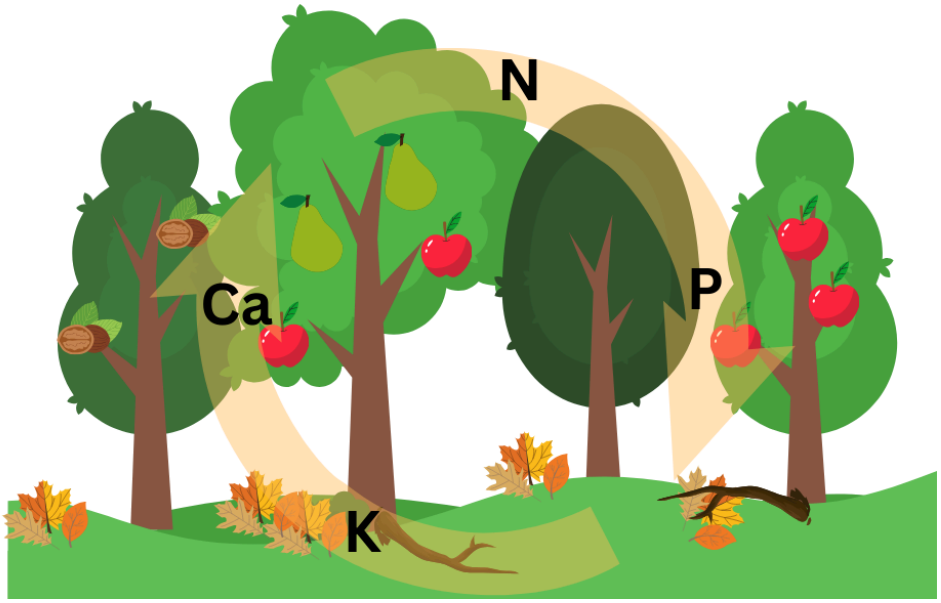
Evaluating self-sufficiency in nutrient cycling (N, P, K & Ca) in temperate complex agroforestry systems (CAS): A case study using five contextualized designs.



Master's Thesis – Resilient Farming & Food Systems

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Abstract:

Nutrient circularity is a key challenge in sustainable agriculture, particularly in temperate Complex Agroforestry Systems (CAS), where the aim is to minimize nutrient inputs while maintaining productivity. This study evaluates the self-sufficiency of nutrient cycling (N, P, K, and Ca) across five CAS designs in the Netherlands, analyzing the extent to which internal nutrient fluxes can compensate for harvest exports. Site-specific soil nutrient stock data, literature values on biomass nutrients of 14 perennial indicator species, and the Rekentool 5.1 a agroforestry yield modelling tool were used. From these a nutrient balance approach was applied to quantify nutrient depletion rates from year 0 to 50 with 20 being the system's maturation year. Results show that N self-sufficiency can be achieved through atmospheric deposition and biological N-fixation, while K emerges as the most limiting nutrient, with high depletion rates due to significant fruit export and low K soil stocks. P and Ca stocks exhibit moderate depletion, with soil initial stock and cut-and-carry mulch from nature areas contributions playing a critical role in nutrient replenishments in production areas. Systems demonstrated K depletion on average at year 25.6, depending on production scenario and specific CAS designs. This is 5.6 years after the system reached maturity. This finding highlights the importance of sufficient initial K soil stocks. Regarding mulch from nature areas, they did not have a significant impact in reducing the K depletion rate leading to some CAS designs still requiring external amendments to maintain long-term sustainability. This study provides essential insights into nutrient management strategies for specific CAS in temperate climates, emphasizing the need for tailored species selection, pruning strategies, and external supplementation to optimize nutrient circularity.

Introduction:

Context

The Netherlands is increasingly challenged by environmental stress caused by nutrient surpluses on its land. High imports of fertilizers and feed to sustain the intensive agricultural system that dominates the country, have resulted in eutrophication, soils, and natural areas (Oenema et al., 2005). Concerns are rising over the sustainability of this agricultural model and its long-term viability (Schoumans et al., 2015; Pepels, 2019; Albrecht & Wiek, 2021). In response, there is growing interest in sustainable agriculture, and Complex Agroforestry Systems (CAS) present promising solutions for nutrient cycling, enhancing biodiversity, improving soil health, reducing GHG emissions and increasing farm resilience (Cardinael et al., 2020; Balasubramanian, 2024). These objectives align closely with the United Nations Sustainable Development Goals (SDGs), particularly Zero Hunger (SDG 2) and Life on Land (SDG 15).

CAS integrates at least three vegetation layers, including perennial plants, trees, shrubs, and sometimes annuals. CAS are systems where through careful planning and species selection of useful tree species and crop trees, the system is able to produce yields as well as ecological benefits (Schroth et al., 2013). The ecological benefits reported include improving soil biota through a higher abundance and diversity of organisms, water cycling through better infiltration and retention, and creating favourable conditions for the cycling of nutrients (Cardinael et al., 2020). CAS are a special type of agroforestry system characterized by a forest-like structure and significant plant diversity in which useful trees and tree crops species attain substantial greater density, compared to natural forest, through planting, selection, and management of useful species from spontaneous regeneration (Schroth et al., 2013). This concept similarly applies to food forests, which have seen a surge in popularity and implementation across the Netherlands. Food forests can be considered a form of agroforestry that mainly focuses on perennials and aims to mimic natural forests ecosystems (Pepels, 2019). Since 2010, when the term gained wider recognition, hundreds of initiatives have emerged in the Netherlands (Roodhof, 2024). The movement has been driven by diverse motives such as building social capital and promoting environmental awareness, which have contributed to its growth (Schuurmans, 2024). In essence, both systems are very similar with their inclusion of perennial trees and tree crops, CAS focuses on creating diverse agricultural outputs while food forests focus more on creating self-sustaining food-producing ecosystems (Albrecht & Wiek, 2021). Both terms overlap on many elements and can be used to describe similar systems, and this paper will refer to the term CAS.

Typical for CAS are the high abundance of trees and non-woody perennials. Research over the past decades has shown that perennials, compared to annuals, can reduce nutrient leaching through their extensive root systems, which also enable them to uplift deep soil nutrients (Sohrt et al., 2017; Raj et al., 2024). Another key element of CAS is the high diversity of plant species which form multi-strata canopies and the mimicking of forest ecosystems (Schroth et al., 2013;

Stanek et al., 2019). High diversity enables plant communities to make more efficient use of available nutrients due to their complementarity and phenological differentiation (Barry et al., 2019; Kim & Isaac, 2022). CAS can take many forms, depending on the goals of the system. Depending on species selection in the design of CAS, the system may improve nutrient uptake through biological nitrogen fixation (Cardinael et al., 2020). Nutrient circularity applies to CAS where the circularity represents the flow of nutrients within the system. Optimizing nutrient circularity is a way of minimizing fluxes from outside the system and improving fluxes from within (Balasubramanian et al., 2024). Regarding circular nutrient use in CAS, it is important to consider the following components: soil, plant litter, plant/tree biomass, the atmosphere and harvest. Fluxes of nutrients cycle through these components at different rates and allow the CAS to function. Effective management practices are also essential for facilitating nutrient cycling. A commonly used management practice is pruning and mulching. Pruning and mulching are management practices of selectively removing branches, stems, or leaves from plants or trees and adding that biomass to the soil to benefit other productive plants (Steinfeld et al., 2024). This management is done more heavily on supporting species of the CAS, they are the more pioneering species which establish the ground for the food producing species to grow with them (Steinfeld et al., 2024).

In contrast, conventional agriculture is defined as agricultural practices that rely on synthetic fertilizers, pesticides and monocultural practices that aim to maximize yields which often lead to soil degradation, nutrient imbalances, and increased greenhouse gas emissions (Sumberg & Giller, 2022). For example, global phosphorus supplies are finite, yet they are mined intensively with high GHG emission rates to meet agricultural demands (Smit et al., 2010). Additionally, rising fertilizer costs are putting financial pressure on farmers worldwide (Brunelle et al., 2015). Regarding Nitrogen, its high usage combined with its mobility in soils has led to heavy leaching in Dutch agricultural soils and extensive environmental damage to the landscape (Oenema et al., 2005). As a result, exploring alternative systems such as CAS that minimize nutrient inputs, promote circular nutrient use, and enhance self-sufficiency are crucial.

Current state of research

Complex Agroforestry Systems (CAS) have shown significant potential in improving nutrient use efficiency, particularly through the ability of perennial plants to access deeper soil layers and redistribute nutrients via litterfall and root systems (Sohrt et al., 2017; Raj et al., 2024). Research highlights that these systems can reduce nutrient losses, thereby lowering dependency on external nutrient inputs and enhancing long-term sustainability (Cardinael et al., 2020; Wolz et al., 2018). While there is extensive research on CAS in tropical regions, studies in temperate regions remain limited (Wolz et al., 2018). Furthermore, quantification of nutrient fluxes and stocks is scare in studies and not well represented at the farm level. Understanding nutrient fluxes and stocks is essential for improving nutrient circularity, particularly in systems with diverse species that have varying nutrient requirements (Mendes et al., 2019).

Nitrogen (N)

Nitogen is one of the most studied nutrients in CAS. It plays a crucial role in vegetative growth and photosynthesis (Kim & Isaac, 2022). In temperate CAS, N-fixing species like black locust (*Robinia pseudoacacia*) and alder (*Alnus glutinosa*) contribute to soil N levels, reducing the need for external fertilizers (Bhardwaj et al., 2017). Studies have explored biological N-fixation, nutrient transfer through prunings, and competition for N among species in CAS (Zingore et al., 2003; Schneidewind et al., 2019; Cardinael et al., 2020; Matos et al., 2020; Kim & Isaac, 2022). However, limited research exists on quantifying N exports and fluxes within temperate CAS, particularly how pruning and mulching impact N cycling (Matos et al., 2020; Kim & Isaac, 2022).

Phosphorus (P)

P management remains a challenge for farmers, as it is of critical importance for plant growth but P rock reserves in mines are estimated to be depleted within approximately 70-140 years (Li et al., 2017). In the Netherlands, agricultural soils have accumulated significant P reserves, estimated at 31 million kilograms (Mkg), with an annual accumulation rate of about 17 kg P per hectare due to nutrient surpluses (Smit et al., 2010; Pepels, 2019). This accumulation has resulted in P surpluses and leaching, contributing to approximately 50% of the total annual P emissions in surface water (Smit et al., 2010). CAS can enhance P availability by mobilizing soil-bound P through interactions with soil biota and recycling via leaf litter and branch decomposition (Zaia et al., 2012; Balasubramanian et al., 2024). Trees with deeper root systems, like poplars, can access subsoil P, redistributing it to surface layers where it becomes available to other crops (Sohrt et al., 2017). However, the exports of P and its necessary replenishment rates of P stocks in temperate climates remain poorly studied.

Potassium (K)

Potassium is an essential nutrient concentrated in harvested products like fruits, nuts, and berries, leading to significant nutrient exports during harvest (Mendes et al., 2019). In sandy soils common in the Netherlands, natural K release is limited, making CAS reliant on organic matter inputs such as litterfall and prunings to replenish K levels (van der Salm et al., 1999; Meiresonne et al., 2007). Potassium is quickly released from decomposing biomass, sometimes in higher quantities than N and P, but its availability can be variable and prone to leaching in sandy conditions (Mahmood et al., 2009; Pardon et al., 2017). Additionally, trees like poplars contribute to K cycling by facilitating root uptake from deeper soil layers (Meiresonne et al., 2007).

Calcium (Ca)

Calcium plays an important role in cell elongation, root growth, and stress tolerance (Burstrom, 1968; Schubert et al., 1990). Calcium helps plants cope with extreme temperatures, salinity, and drought by signaling stomatal closure to reduce water loss during dry conditions (Gupta et al., 2023). These conditions are expected to increase with climate change. CAS can recycle Ca through leaf litter and prunings, which return Ca to the topsoil (Dijkstra et al., 2002; Dauer et al.,

2007). However, long-term quantification of Ca cycling in temperate CAS is limited, and deficiencies have been observed in systems within the Netherlands (Jordy van Eijk, Personal Communications, 2024).

Management practices

Effective management in CAS involves techniques such as *in situ* mulching, which uses prunings, leaf litter, and cuttings to enhance soil nutrient levels (Steinfeld et al., 2024). Syntropic farming, which integrates successional planting with intensive mulching, can boost nutrient cycling, particularly for N, P, K, and Ca (Götsch, 1994; Steinfeld et al., 2023). Research indicates that syntropic practices can enhance nutrient cycling (Froufe et al., 2020; Andrade et al., 2022; Steinfeld et al., 2024). However, not much is known about the potential of mulch to replenish nutrient needs which are exported out of the system through harvest. Finally, these practices require significant labor input, which may not align with farmers' needs and labor availability (Steinfeld et al., 2024). The labor-intensive nature of pruning and mulching can be a barrier, especially for small-scale farmers.

Problem statement

CAS presents a promising sustainable alternative to conventional agriculture by potentially enhancing nutrient management. CAS as a solution requires further studies as the topic is complex, understudied in temperate climates and a relatively new practice in the Netherlands (Wolz et al., 2018). More specifically, research on the nutrient dynamics within CAS of key nutrients like N, P, K and Ca are not complete. Current studies predominantly focus on nutrient losses like leaching but offer limited insights into nutrient flows related to harvest outputs (Raj et al., 2024). Although CAS are known to recycle essential nutrients like N, P, K and Ca through organic matter decomposition, pruning, and mulching, the fluxes of these processes in replenishing nutrient stocks remains poorly quantified, especially under temperate conditions (Balasubramanian et al., 2024; Kim & Isaac, 2022). Understanding these interactions is crucial for optimizing nutrient circularity, maintaining long-term soil fertility, and ensuring the resilience of CAS in the face of changing climates. More comprehensive studies are needed to clarify how these systems can effectively balance nutrient inputs and outputs to support CAS in temperate regions (Dijkstra et al., 2002; Pardon et al., 2017).

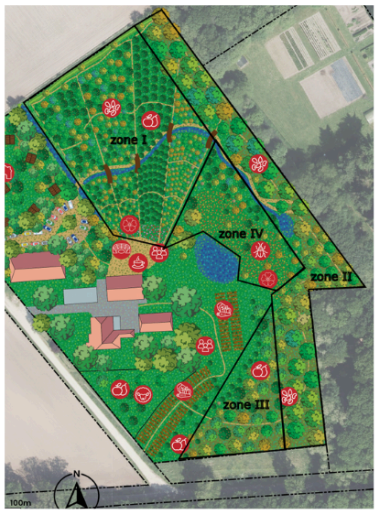
Approach

In order to evaluate this nutrient circularity for N, P, K and Ca, five contextualized CAS designs are assessed. The five CAS are all located in the Netherlands, they were chosen by the Stichting Regeneratie and Jordy van Eijk, supervisor of this study, engineering doctorate candidate at WUR and co-founder of the foundation. The Stichting Regeneratie is a foundation that develops knowledge and practical experience for the professionalization of small-scale complex agroforestry. These designs have not been implemented yet and are considered pilot projects to work with farmers who are willing to do CAS as described in figure.1 and 2. They are considered contextualized as they are specific to a location, climate, soil type and topography, meaning the design cannot be replicated elsewhere. The five designs have the objective of

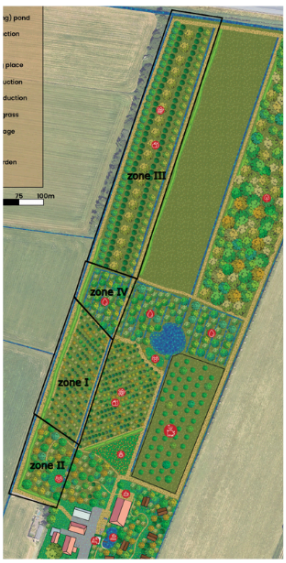
helping Dutch farmers, practitioners, business owners, and more to transition to CAS systems, facilitating the learning process regarding species and management of the systems.



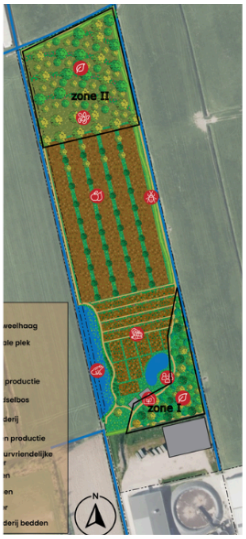
Figure.1: Location of the 5 CAS designs in the Netherlands



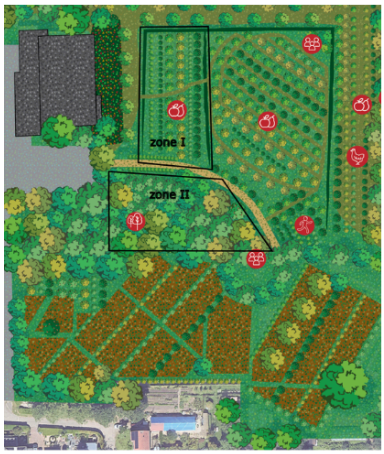
Hoeve t' Marien



Akern



Bonenbos



Eetmerbosch



Middenbos

Figure.2: The 5 farms and their respective zones

The farms were also chosen to differ in their designs, species selection, soil types and more as seen in table.1. All farms have in common that a part of it is dedicated to a form of CAS. What varies is the level of intensity of production, soil type, species chosen or objective that the farmer/owner aims to achieve as seen in table.2. These variables have different categories: either nut, fruit or mixed focus; the soil type can be either sand, loam or clay and the desired level of production is either high, average or low as shown in table.2. Evaluating these variables in the context of the nutrient cycles of N, P, K, and Ca aims to account for the factors that most significantly impact the circularity of CAS and quantify their relative influence. The expected nutrient outputs are quantified for each CAS and calculations are made to assess the depletion rate of the system and therefore the necessary nutrient replenishments. These calculations were done at year 20 (t=20) when it is estimated that the CAS has reached maturity (Bhardwaj et al., 2017). At 20 years the system is expected to be at high production levels for both fruits and nuts. Fruits reaching higher production earlier than nuts, 8-10 years for apples and 26-28

for walnuts for example (Atkinson & Webster, 2001; Ares & Brauer, 2004). This estimation is also in line with the Rekentool 5.1 yield values which reach a plateau at 20 years or earlier depending on the species. The Rekentool 5.1 is a tool developed by HAS University of Applied sciences that provides insight into the financial and yield feasibility of food forests in the Netherlands, its data is based on literature and existing food forest data (HAS Green academy, 2024).

Furthermore, 4 of the farms have zones that are reserved for nature/biomass production. These zones are not food producing and will be mainly composed of supporting species. They have potential in playing an important role in balancing the nutrient needs of the CAS zones as prunings can be taken from the nature/biomass zones to supplement the needs of the CAS zones. This is the case for all farms except Bonenbos as seen in table.1 in zone IV.

Table.1: Spatial and zonal information on the 5 Farms

5 Farm Designs	Total surface	Zone I	Zone II	Zone III	Zone IV	Soil Texture	Types of CAS and their zones
Hoeve t' Mariën	3 ha	0.7 ha	0.5 ha	0.24 ha	0.32 ha	Loamy Sand	I: High productive fruits focus
						Sand	II: Low productive fruits focus
						Sand	III: Low productive mix
						Sand	IV: Biomass focus
Åkern	9 ha	0.6 ha	0.25 ha	1.1 ha	0.2 ha	Loamy Sand	I: High productive fruits focus
						Sand	II: Low productive fruits focus
						Sand	III: Low productive mix
						Sand	IV: Biomass focus
Bonenbos	3 ha	0.24 ha	0.7 ha	NA	NA	Heavy Clay	I: Low productive fruits focus
						Light Clay	II: High productive nuts focus
Eetmeerbosch	3.6 ha	0.25 ha	0.32 ha	NA	NA	Light Clay	I: High productive fruits focus
						Sand	II: Biomass focus

Middenbos	23 ha	1 ha	2 ha	1 ha	0.3 ha	Loamy Sand	I: High productive fruits focus
						Sand	II: High productive nuts focus
						Sand	III & IV: Biomass focus

Table.2 Categories of CAS in the designs in three variables (soil type, production, focus)

Soil Type	Sand
	Loam
	Clay
Production	High 70%
	Average 50%
	Low 40%
Focus	Nuts dominated
	Fruits dominated
	Mixed

Research Questions:

Main Research Question:

To what extent can contextualized CAS designs in temperate climates achieve self-sufficiency in nutrient cycles, and what management practices and design strategies are required to improve their nutrient circularity?

Sub-Questions:

1. What are the nutrient (N, P, K, Ca) exports due to harvesting of produce in five different CAS designs at maturity (20 years)?
2. To what extent can nutrient (N, P, K, Ca) exports due to the harvesting of produce be compensated by the release of nutrients from plant material (e.g., prunings, mulch) from within the system?

Hypotheses:

In addressing the main research question, "To what extent can contextualized CAS designs in temperate climates be self-sufficient in their nutrient cycles, and what management practices and design considerations are required to improve their self-sufficiency?", the results are likely to show that CAS systems can reach partial nutrient self-sufficiency, particularly for N through internal cycling processes, such as biological n-fixation and organic matter decomposition. However, for nutrients like P, K and Ca, the systems may still require some more *in situ* or external inputs to maintain long-term balance, especially in high-production nut and fruit systems. It is expected that these *in situ* inputs can be met through an increased ratio of supporting species that have high levels of P, K and Ca in their leaf litter.

Sub-question 1: What are the harvesting exports in terms of N, P, K and Ca of the CAS?

Harvest exports for N, P, K and Ca will vary across different CAS designs based on species composition, soil type, and management intensity. High-production fruit or nut-focused systems will have higher nutrient exports, especially of N, P, K, due to their high nutrient contents. Nut-focused systems will have higher nutrient exports than fruit systems, especially for N and P (Pepels, 2019). Systems focusing on lower-yielding or mixed-species combinations will have lower nutrient exports, making them more circular without additional inputs.

Sub-question 2: To what extent can these exports (N, P, K and Ca) be sustained by the cycling of internal resources (e.g., prunings, mulch) on the farm?

The ability of CAS to compensate for nutrient (N, P, K, Ca) exports through internal nutrient cycling (e.g., prunings, mulch) will differ based on species selection, soil type, production focus and intensity. It is expected that nutrient replenishment will be more efficient in lower production CAS due to the lower export of nutrients. N replenishment is likely to be more efficient in systems incorporating nitrogen-fixing species like alder and black locust, while P will make up a smaller proportion of the plant/tree biomass (Palm et al., 1995; Balasubramanian, 2024). K replenishment may be challenging in high-yield nut systems due to its significant export in harvested produce (Buwalda & Lenzl., 1992; Pepels, 2019). Ca cycling may be enhanced by calcium-accumulating species such as littleleaf linden, but the replenishment rates may still be insufficient to fully meet the system's needs over time, especially in high-production zones (Dauer et al., 2007). To improve nutrient replenishments it is also expected that the initial nutrient levels in the soil stock will influence if the CAS are getting depleted. CAS with low initial soil stock may face depletion sooner than those with higher soil stock, it is not clear of the role supporting species or prunings have to play in this depletion rate yet. Finally, it is expected to find which species may have higher nutrient content in their mulch which can then contribute to reducing the depletion of specific nutrients.

Methodology

Description of available data:

To quantify the nutrient cycles of N, P, K and Ca, data was collected from available literature as well as on site data. For that it is important to obtain data on nutrient contents of all components and fluxes of the nutrient cycle for each nutrient. The components are the following: Soil + Litter, Tree/Shrub Biomass, Atmosphere and Harvest. The fluxes are litterfall, deposition, weathering, leaching, plant nutrient uptake and volatilization. The difference between fluxes and stocks in a nutrient cycle system is that fluxes represent the movement of nutrients over time (e.g., inputs or outputs per unit of time), whereas stocks refer to the quantity of nutrients present in a specific system component at a given moment. Data from each nutrient N, P, K and Ca have been collected for all the relevant components in Figure.3.

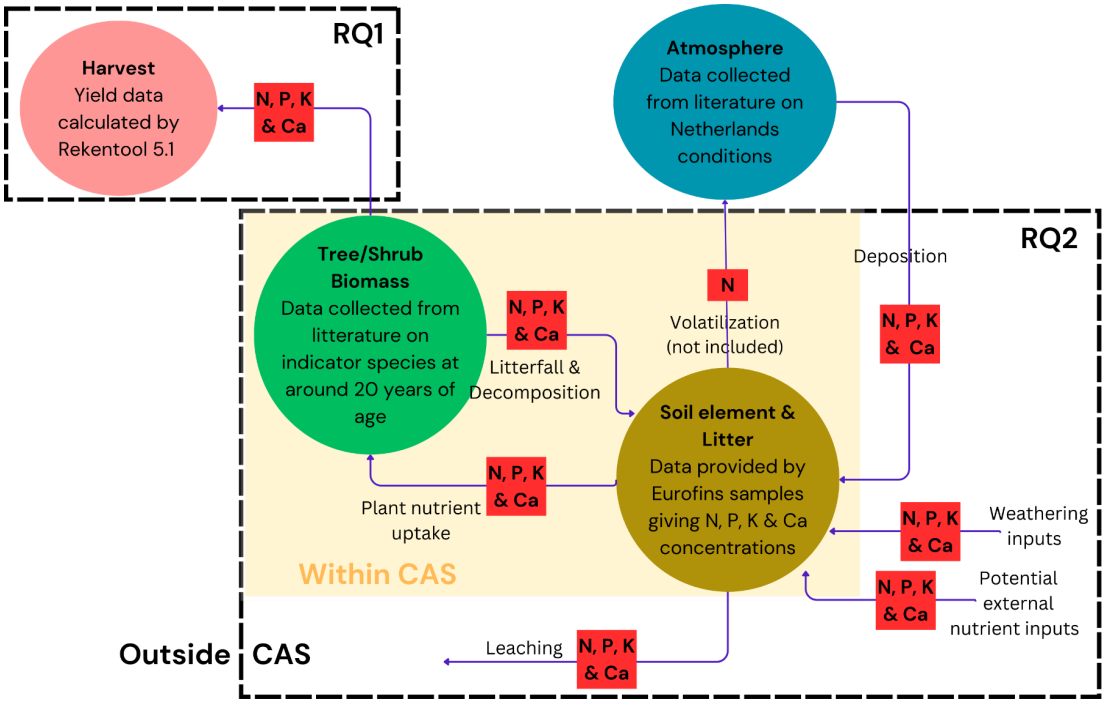


Fig.3: Simplified schematic representation of the CAS nutrient cycle. (The colored circles represent the system's components containing a short explanation of the data used. The purple arrows are the nutrient fluxes and the red boxes indicate which of the 4 nutrients are moving between components. The yellow square gives the delimitation of what is within the CAS, while the dotted line squares indicate what will be included in both sub-research questions.)

Soil nutrient data

A total of 16 soil samples of the topsoil (0-25 cm depth) were analyzed by Eurofins in early 2024 by the Stichting Regeneratie, providing total and available nutrients content in the soil (N, P, K and Ca content). Each of the 5 farms had between 2-4 soil samples taken. The depth of

(0-25cm) is relevant as N is most present in the topsoil (0-10cm) and P is present throughout 0-30cm depth (Pandey et al., 2000). Eurofins is a trusted environmental measurement company that also does soil sample analysis. It is important to state that these soil samples have been taken at t=0 (t: time) of the CAS as the systems have not been planted yet. This data at t=0 is still relevant as it will give us estimates of the current nutrient stocks the soil has for each CAS. The data from the Eurofins also gives the target ranges of similar types of soil for each nutrient which can determine if the soil is in deficit, surplus or has the optimal amount of nutrients. This information has been compiled in an excel table for each of the 5 designs and each nutrient in kg/ha (Annex.1).

Indicator species

A selection of around 14 generic temperate indicator tree and shrub species for the CAS designs were determined (Personal communications, 2024). They were chosen to cover the different functions needed in a CAS. The functions were chosen by Jordy van Eijk, the farmers and inspiration from studies (Stanek et al., 2019; Schwarz et al., 2021). The functions chosen for this study include: primary food producers (fruits and nuts), shrubs and smaller trees to support the multi-strata system, system-supporting species (combination of N-fixing, biomass producers and calcium-accumulating species) and special food-producing species for a diversity of products (edible leaves, small fruits). The list of species varies depending on the focus of the CAS and the desired production level. The soil type does not influence the list of species but was taken into account in the choice of species per CAS (see annex.2). The focus can be either nut, fruit or mixed; and the desired level of production is either high, medium or low as seen in table.2. The focus of the CAS depends on what the farmers want to produce/sell. The production level depends on the yields of the indicator species chosen, which can be found on the Rekentool 5.1. For the production variable, a high production scenario was estimated at 70% of monoculture estimates, a average production at 50% and low at 40% of the monoculture yield as seen in table.2. The specific indicator species chosen for each type of CAS are found in table.3.

Table.3: Indicator species of the different types of CAS possible. In green are the support species while in orange are the food producing species.

	List for the different types of contextualized CAS			
Categories/ Functions	**Fruits focused CAS**	**Nuts focused CAS**		**Mixed CAS**
Primary producing tree + medium	Pear Pyro (*Pyrus*) /Apple M26 (*Malus*)	Hazelnut (*Corylus avellana*)		Pear Pyro (*Pyrus*) /Apple M26 (*Malus*)
Primary producing tree + large	Pear Kirch (*Pyrus*)/ Apple M25 (*Malus*)	Chestnut (*Castanea*)	Walnut (*Juglans*)	Hazelnut (*Corylus avellana*)/ Pear Kirch (*Pyrus*)/ Apple M25 (*Malus*)

Primary producing tree + small + edible leaf	White mulberry (*Morus alba*)
Shrub + producing	Red currant (*Ribes rubrum*) /Autumn olive (*Elaeagnus umbellata*) / Honeyberry (*Lonicera caerulea*)
Support (N-fixing)	Black alder (*Alnus glutinosa*)
Support Biomass	White willow (*Salix alba*)
Support Biomass	Silver birch (*Betula pendula*)
Support Biomass	White poplar (*Populus alba*)
Support Calcium	Littleleaf linden (*Tilia cordata*)

Species adjustments

For some of the species in table.3, some elements on their nutrient content were not available through literature, for instance the nutrient content of woody biomass of less common species such as Autumn olive (*Elaeagnus umbellata*) or honeyberry (*Lonicera caerulea*). For these species, more common species with similar characteristics were chosen as a substitute for lacking data. For instance values of Black locust were used for Autumn olive at it is also a nitrogen fixing species that has a similar woody structure. These species substitutions can be seen in the Annex.3.

Collection of data on nutrient cycle components in CAS

Plant litter, tree & shrub biomass nutrient content data

In this study, the plant litter component and soil component was combined as the decomposition rate was not taken into account as seen in figure.3. The nutrient flux of plant litter was added directly to the nutrient stock of the soil component. The decomposition rate varies depending on many different variables such as lignin/phosphorus ratios, temperatures, soil life, rainfall and more (Yang et al., 2022). Since this study looks at the system's cycling over the long term it was assumed that all plant litter nutrients eventually go back to the soil component regardless of the time it takes for full decomposition (Ventura et al., 2010). Additionally, the amount of plant/tree litter given in kg of dry weight was taken from literature on the 14 indicator species to determine their biomass and nutrient content (see annex.9). As values from literature vary it is important to find values that have common ground. For instance, the leaf litter nutrient data for all species have been taken mainly from studies in temperate climate, and without mineral fertilization when possible. Finally, when determining a leaf litter quantity per surface area, averages for support, food producing and grass yields were determined per hectare. These average values were calculated from agroforestry studies, mainly in temperate climates for support species and grass

yields. For food producing leaf yields, studies from orchards and agroforestry were used (see annex.9). These leaf yields per surface area where then allocated to the surface area of each species in order to determine the amount of leaves litter per species and their respective nutrient concentration.

Similarly, for tree and shrub woody nutrient content, literature values from each species at roughly 20 years of age were taken for biomass content. These estimates were then converted to N, P, K and Ca contents based on other literature data on the specific tree and shrub generic nutrient content per kg of dry weight (see annex.9).

Pruning data

To determine the amount of nutrients that will be pruned from the systems yearly and therefore added back to the soil, an interview with Marenthe Lokin from Den Food Bosch was conducted. She estimated that yearly they pruned around 30-40% (averaged to 35%) of the total biomass of the plant and the prunings were left on the ground to decompose as in syntropic farming systems. The pruning is done yearly in July which means the trees have leaves. From this percentage of pruning it is important to determine a biomass ratio of leaves and branches in order to give more accurate values to the nutrients that are released from the tree to the soil. A percentage of 10% leaves to 90% branches was found in a study on chestnut prunings (Salazar Iglesias et al., 2010), another study indicated that branches and leaves share a similar biomass in pruning residues in *Pinus radiata* agroforestry systems (Bandara et al., 1999) and Jordy van Eijk gave an estimate of 30% leaves to 70% branches which is a conservative average of the two studies and was used in the calculations (Personal Communications, 2025).

Applying this ratio to Lokin's estimate, the 35% total pruned biomass can be further divided into 70% branches and 30% leaves. This results in 25% of the total tree biomass being branches (35% × 70%) and 11% being leaves (35% × 30%). These pruning percentages were assigned to the nature zones of the farms, where pruning can be more intensive due to the absence of food-producing trees. A different percentage was used for pruning in CAS zones in the scenario where internal cycling of pruned material is practiced. In this case, the total pruned biomass (including leaves) was reduced from 35% to 11.5%, as food-producing species should not be pruned too intensively. This 11.5% value aligns with pruning practices for above-ground woody biomass in temperate orchard systems, which prioritize food production (Zanotelli et al., 2013).

Tree quantity data

To determine the amount of trees in each system two approaches were taken. Firstly for the food producing trees, a list with the quantities of each food producing tree that would be ordered for each farm was established. From this list a regrouping work was done to have only the indicator species that were chosen for this study. This modified list (see annex.2) is what this study has used to determine the quantity of food producing trees in each CAS. For the support species, a different approach was done, a percentage of land was determined for supporting species ranging from 12.5% in high producing zones to 80% in more nature dense zones. With these percentages of area dedicated to support trees, they were split equally between the 5

supportive species studied (poplar, willow, birch, alder and linden). The next step was to determine the amount of each supportive tree, this was done by deciding on a spacing that each tree would have at their age of maturity, this spacing rule was also given to food producing trees and the respective spacing can be found in annex.4. This spacing for each species is also crucial for determining the amount of leaf litter element per species mentioned in the above paragraph.

Yield data

Yield estimates at year 20 for the 11 food-producing indicator species and edible leaf species seen in table.3 were taken using the Rekentool 5.1 (HAS Green Academy, 2024). The yields were estimated for the following species: redcurrant, pear (pyro & kirch), mulberry, apple (M26 & M25), autumn olive, walnut, hazelnut, honeyberry and chestnut. For edible leaf yields mulberry and linden were estimated. Once the yields have been determined in terms of species, the corresponding N, P, K and Ca outputs were calculated through literature on the specific generic species. These nutrient values are also taken from studies that were conducted in temperate climate and without fertilizers if possible (see annex.9). For the nut producing species (hazelnut, walnut and chestnut) their shell nutrient content was also collected from literature and included in the yields as an export. The desired yield levels of farmers have been determined in interviews which were used as a benchmark for their desired production level. Three yield scenarios (high 70%, average 50% and low 40%) with the same benchmark as monoculture yields as mentioned in table.2 were used. A soil correction factor which is also in the Rekentool 5.1, was included to these yields scenarios to represent the soil quality variable of each farm. This correction factor is based on an assessment of the overall soil quality of the farms which was determined through the Eurofins measurements. High quality soils got a higher soil correction factor while lower quality soils got a lower value (annex.5). The combination of these 2 factors gave a conservative estimate of the yields to be expected in the CAS designs as the final percentage given to the monoculture yield varied from 70% to 16% as seen in annex.5.

Harvest export data for years 1-19

Harvest output from years 1-19 before the CAS systems reach maturity are important to include in this study. The yields vary for each species from year 1 to 20 and these yield variations per year are given in the Rekentool 5.1. These yields per species were allocated to the amount of food producing trees in the system to determine the amount of nutrient exports that would have already left the system before the calculation at year 20 can be done. This value gives a more accurate representation of the gradual harvested nutrients exports.

Weathering and atmospheric deposition data

While substantial gaps remain in understanding deep root-soil interactions, such as rock weathering and nutrient acquisition, weathering is increasingly recognized as vital to nutrient cycling in agroforestry systems (Isaac et al., 2019). Incorporating weathering of soil and atmospheric deposition in CAS is essential for representing the nutrient cycle, especially in nutrient-sensitive regions like the Netherlands. Weathering of soil provides a slow-release,

background supply of certain nutrients, such as calcium measured at 0.01 to 0.018 kmolc/ha/year in 3 forest sites close to the 5 CAS designs (van der Salm et al., 1999). These inputs may offset some leaching losses, though moderate due to the nutrient-poor sandy and loamy soils typical of the Dutch landscape (Anderson, 1988; van der Salm et al., 1999). For P and K they were also given weathering values 0.1 and 2.57 kg/ha/y respectively based on average results of two studies (van der Salm et al., 1999; de Vries et al., 2021). Regarding N, it is not significantly released through weathering due to the sandy nature of the Netherlands and therefore not accounted for in the study. N volatilization was not accounted for in this study as values are not high in forest areas in the Netherlands. Instead, N is highly introduced through atmospheric deposition with high levels of N deposition up to 50 kg N/ha/y have been recorded in certain regions (Dise & Wright, 1995; van der Salm et al., 1999). The value of 27.83 kg/ha/y was taken for this study from an average of 4 measurements in oak forests in the Netherlands (van der Salm et al., 2006). Regarding P (0.13 kg/ha/y) and K (1.75 kg/ha/y) depositions are considered low with Ca (5kg/ha/y) being slightly higher due to its presence in wet and dry depositions (de Vries et al., 2021). All of these values for each nutrient can be found in annex.6.

Leaching data

Leaching is a significant concern in the Netherlands, particularly for nutrients like N, P and Ca, due to the predominance of sandy soils with low buffering capacity as seen in table.1. High atmospheric N deposition leads to increased nitrate leaching, especially in sandy soils that have low organic matter content and poor nutrient retention (Dise & Wright, 1995). Nitrogen leaching rates can range between 30 to 45 kg N/ha/year, particularly in areas with high rainfall and poor soil structure (Dise & Wright, 1995; van der Salm et al., 2006). K, while less mobile than N, still exhibits notable leaching losses in acidic, sandy soils, with rates estimated at around 10-20 kg K/ha/year (de Vries et al., 2021). Calcium leaching is exacerbated by acidification from nitrogen and sulfur deposition, leading to the loss of up to 50% of calcium inputs from weathering and deposition (Dise & Wright, 1995; de Vries et al., 2021). In contrast, P is relatively immobile in Dutch soils due to strong adsorption to soil particles, resulting in minimal leaching, except under highly acidic conditions or heavy rainfall events (van der Salm et al., 2006). Given the high leaching potential for N, K, and Ca in Dutch soils, it is essential to quantify these losses to enhance nutrient use efficiency in CAS. For this study values of 20.74; 0.05; 2 and 7 kg/ha/y of N, P, K and Ca respectively were taken from multiple studies in the Netherlands (de Vries et al., 2021; van der Salm et al., 2006). All of these values for each nutrient can be found in annex.6.

Calculations

Nutrient equations

Nutrient stock calculations were performed, focusing on N, P, K and Ca. The calculations relied on quantitative data that had already been collected and additional data that was collected as mentioned above. The calculation determines the nutrient stock in the system (ΔNtr) at maturity when including the annual inputs and outputs of the system (equ.1). This calculation is done for each of the 5 sites and for each of the 4 nutrients. The calculation includes all the different

components, interactions and fluxes of nutrients from the CAS nutrient cycle as shown in figure.3. The equations used are written below.

Equation.1:

$$\Delta Ntr(t = 20) = Nstock\,(t = 0) + \sum^{1-20} Nannual\ input\ flux - \sum^{1-20} Nannual\ output\ flux$$

To project the system further in time when the system would reach depletion, the equation was repeated from t=0 until the stock was depleted (ΔNtr≤0 at t=i) (equ.2). The amount of years needed (i) determined the depletion rate of the nutrient stock of the system and therefore the necessary nutrient replenishments (Pepels, 2019). The different steps of the nutrient calculations can be seen in the following flowchart in figure.4. Finally, to visualize the fluxes and nutrient stocks of the nutrient cycle as seen in figure.3, the cycle will be drawn at year 20 (t=20) when it is estimated that the CAS has reached maturity.

Equation.2:

$$Depletion(t) = \Delta Ntr(t = 20) - \sum_{i}^{21} Nannual\ input/output\ flux - \ldots - \sum_{i}^{t} Nannual\ intput/output\ flux$$

t= time in years
i= amount of years till N stock ≤0
N= nutrient (N, P, K or Ca) in kg
ΔNtr= nutrient stock after inputs and outputs have been accounted for
Depletion(t)= time in years where N stock is ≤0

Another calculation was done to determine the nutrient soil depletion ratio which is the final nutrient stock at year 50 (in the high scenario) minus the initial nutrient stock at year 0 all divided by the initial nutrient stock. If soil depletion ratio is positive there is a depletion of the nutrient, if it is 0 there is self sufficiency and if it is negative there is a surplus of nutrients.This soil depletion ratio is important to determine how much the soil depletion rate is in relation to the initial soil nutrient stock. Additionally, a nature/food surface area ratio was calculated by dividing the nature area of each farm by the specific CAS studied. This allows for a comparison between the amount of prunings from nature area and the amount of area dedicated to food production. These two ratios will be important in determining the cause of nutrient depletion or surplus in each of the CAS.

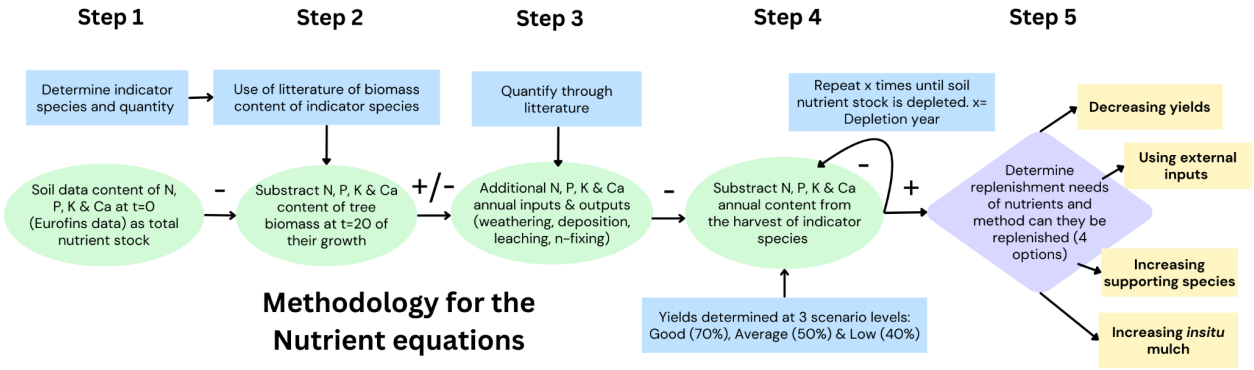


Figure.4: Flowchart of the 5 steps in the methodology for the nutrient equation. The green circles are the quantities of nutrients in kg from inputs/outputs or stocks. The blue squares represent the source of the data used. The purple lozenge represents the final objective of the equation and the yellow rectangles are 4 possible methods to replenish the nutrient deficit.

Results:

The analysis of nutrient flows in the five CAS was structured around two central research questions: (1) the quantification of nutrient losses (specifically N, P, K, and Ca) via harvested produce, and (2) the evaluation of nutrient compensation from on-farm plant materials. This section gives answers to the questions through several visual representations such as donut diagrams, stacked bar charts, and line graphs. The quantities of nutrients are given for certain figures (fig.5, 6 and 7) per CAS to visualize the total exports per system which highlights the unique features of each CAS. Figures that are farm specific also give the total nutrient quantities. All other figures are given per ha for all CAS to have the nutrients inputs and outputs standardized.

Research Question 1:

Total yearly nutrient output per CAS at year 20

Firstly, the nutrient content of the harvested yields are given for each CAS for each of the 3 scenarios studied (fig.5, 6 and 7). The nutrient contents are given in kg for each of the 11 CAS, they are not per hectare to visualize the total outputs of each CAS. In the high scenario the total N exports vary from 1.73 kg in Mariën III to 43.05 kg for Middenbos II. For K the total exports are the highest with values ranging from 3.19 kg in Åkern II to 50.09 kg in Mariën I. P yields are relatively low with values ranging from 0.38 kg for Mariën III to 6.63 kg for Middenbos II. Similarly for Ca the yields are low with values ranging from 0.74 kg for Mariën III to 8.04 kg for Middenbos II. These N, P, K and Ca yields for each CAS decrease for the average (fig.6) and low scenario (fig.7) in a proportional way for most CAS. The only one where the decrease is less significant is Bonenbos I & II. This is due to the soil correction factor being the lowest of all the CAS and therefore the yields being less impacted than the other farms (annex.5).

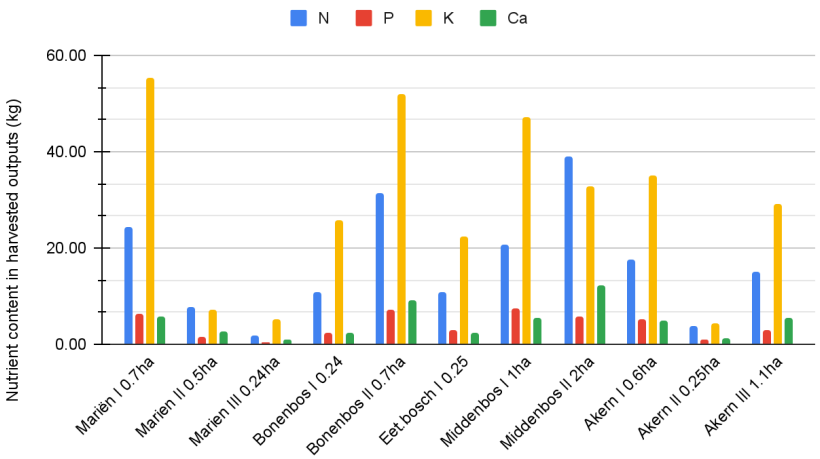


Figure.5: High scenario yields of each CAS for all nutrients

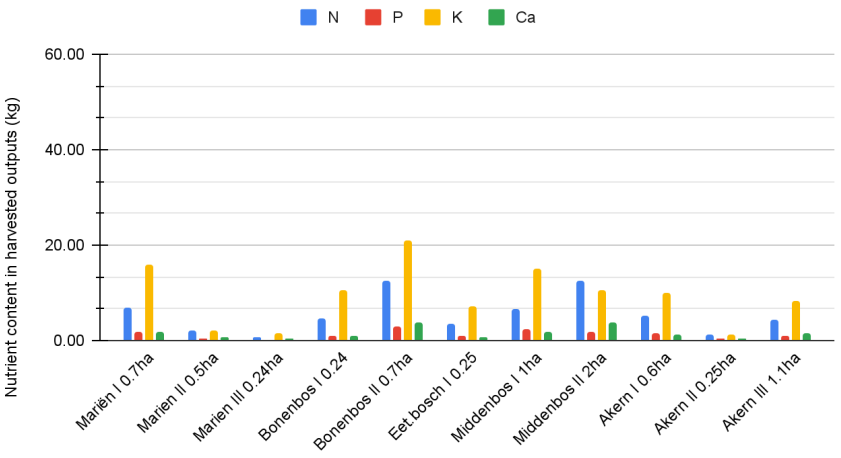


Figure.7: Low scenario yields of each CAS for all nutrients

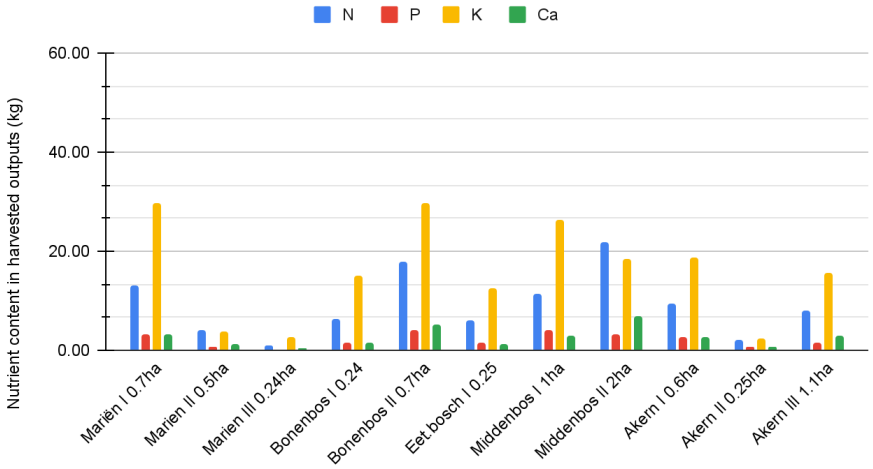


Figure.6: Average scenario yields of each CAS for all nutrients

Harvest nutrient per hectare

To have a more standard representation of the nutrient exported from the 5 farms, the yields were adjusted to the size of each farm. In the table below, the combined yields from the food producing CAS are shown with the values showing the range from the low scenario to the high scenario (table.4). Bonenbos and Eetmeerbosch have the highest nutrient exports per hectare regardless of their smaller size compared to the other farms. This is due to their high production focus. Middenbos has the lowest exports while being the largest farm in terms of size with N exports being half those of Eetmeerbosch per hectare and K exports being only a third. Values in the most high producing farm per hectare (Eetmeerbosch) ranged from 13.6 to 42.8 kg N/ha; 3.53 to 11.12 kg P/ha; 28.53 to 89.88 kg K/ha and 3.07 to 9.66 kg Ca/ha (table.4). Finally, this table highlights the variation in production levels of the farms as their designs and plant selections are unique.

Range of 3 scenarios	**Mariën**	**Bonnenbos**	**Eetmeerbosch**	**Middenbos**	**Åkern**
N (kg/ha)	6.73-23.55	18.07-44.83	13.6-42.85	6.31-19.89	5.34-18.68
P (kg/ha)	1.58-5.52	4.08-10.12	3.53-11.12	1.41-4.44	1.32-4.62
K (kg/ha)	13.40-46.91	33.26-82.86	28.53-89.88	8.48-26.7	10.05-35.17
Ca (kg/ha)	1.85-6.46	4.95-12.34	3.07-9.66	1.87-5.88	1.68-5.89

Table.4: Nutrient quantities in exported harvest from low to high production scenario in 5 farms per hectare

Nutrient concentration in yearly outputs per farm

It is also important for each of the 5 farms to know their nutrient outputs of all their food producing zones. This information allows to see which nutrients are being exported out of the system at maturity (year 20 onwards) and in which concentrations compared to other nutrients (fig.8). Figure.8 shows these concentrations through donut diagrams for the best case scenario. The other two scenarios are nearly identical and therefore not included in the figure. We see that K is the largest output of the system representing percentages ranging from 58.5% to 62% of the total yields. N is the next biggest output representing 25.5 to 28.2% of the total outputs. P and Ca are both the lowest with values ranging from 6% to 9.3% for P and 5.9% to 7.6% for Ca. We see in figure.8 that these ratios do not vary strongly regardless of the farm and the nutrient quantities that are exported (as shown in fig.5, fig.6 and fig.7).

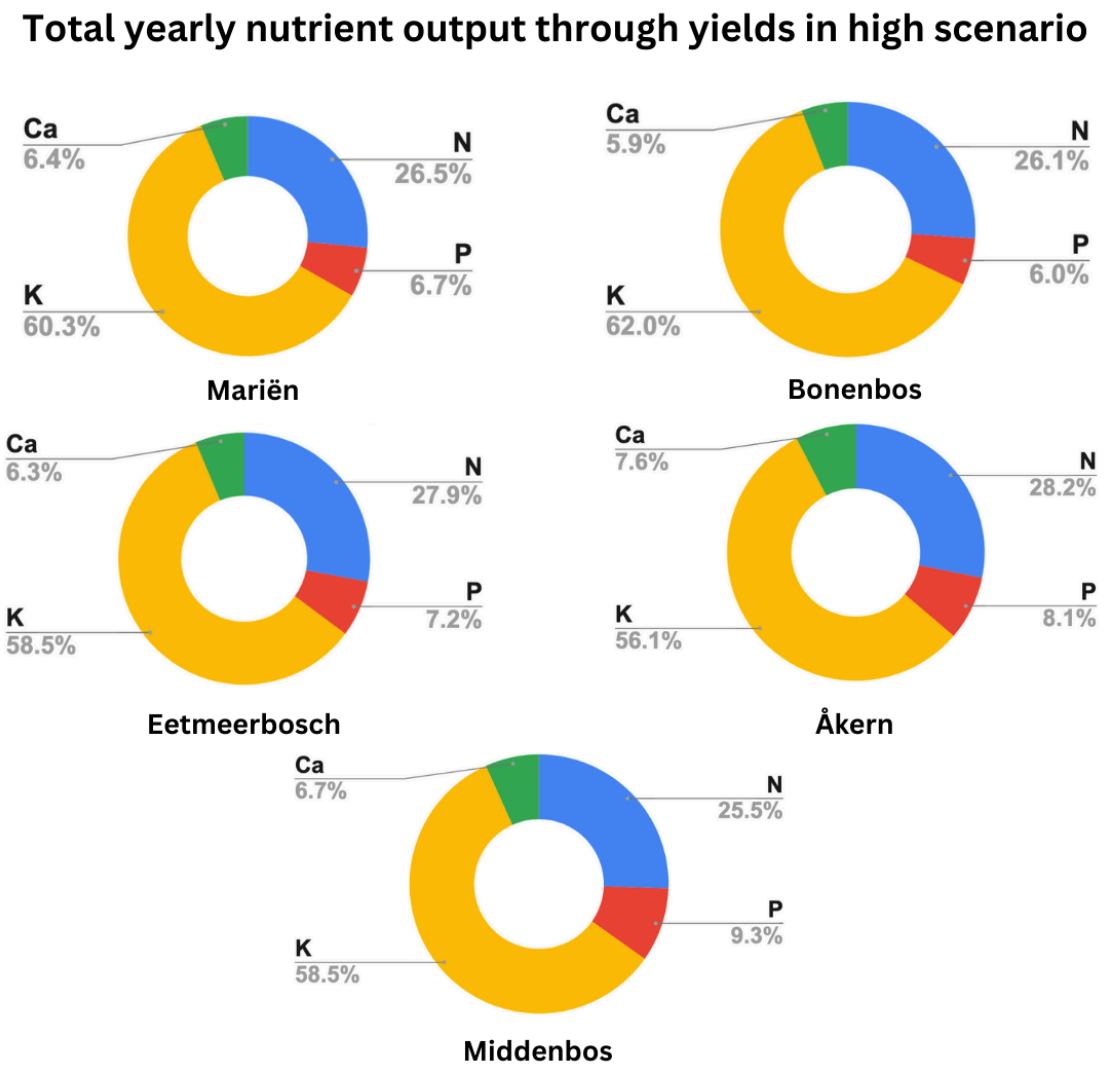


Figure.8: Total yearly nutrient concentration of outputs based on kg of nutrients in food yield per farm in the high scenario

Nutrient output in different harvest groups (fruits, nuts, edible leaves)

A key result for the five farms is determining the nutrient content of edible exports fruits, nuts, and leaves since CAS can have varying focuses, including mixed, fruit, or nut production. This result may highlight the nutrients concentrated in each of these groups. These results are shown in stacked column charts of figure 9, 10 and 11 taken from the high scenario. A first observation is that the fruits have a high concentration of K with values ranging from 2.6 kg to 48.9 kg per CAS with an average of 23 kg of K per year per CAS (fig.9) (For individual species nutrient content per kg of harvest see annex.7). N represents nearly half of K fruit yields while P and Ca represent approximatively a tenth. These values are not negligible as fruits have the biggest nutrient output of the three groups. Regarding nuts, the main nutrients of this group are N and K representing a significant proportion of the outputs (fig.10). The quantities of N range from 0 to 11.7 kg per CAS (as some CAS do not have any nut production) with an average of

4.5 kg across all CAS. For K in nuts the outputs range from 0 to 8.75 kg per CAS with a slightly smaller average of 3.15 kg per CAS. Ca outputs are half of potassium with an average of 1.67 kg per CAS and P is minimal with an average of 0.74kg per CAS. Finally with leaves output (fig.11), Ca is the most abundant nutrient in this output with values ranging from 0.3 to 3 kg per CAS with an average of 1 kg across all CAS. These quantities are small but are double the values of N and K and 4 times those of P.

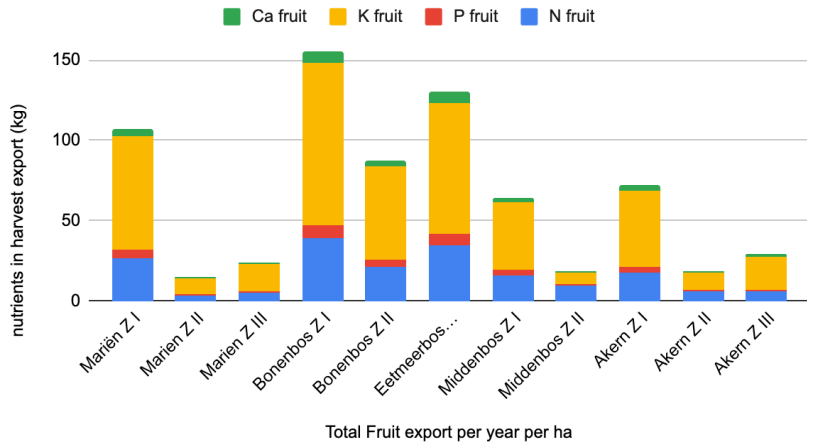


Fig.9: Nutrient content of the fruit group in all CAS in high scenario

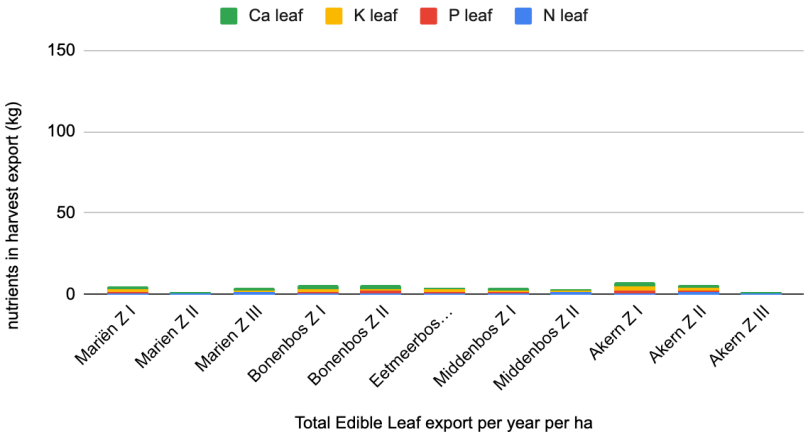


Fig.11: Nutrient content of the edible leaf group in all CAS in high scenario

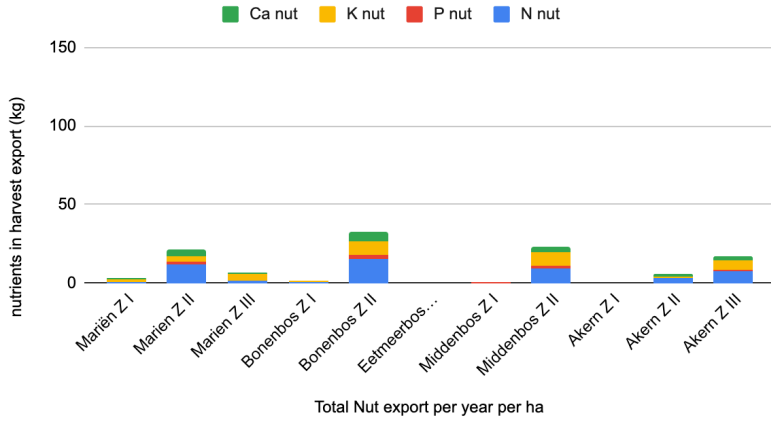


Fig.10: Nutrient content of the nut group in all CAS in high scenario

When combining the results from the first research question, it is observed that the high K content in fruits (fig.9), correlates with the high K nutrient exports seen in the concentration of the harvested produce (fig.8), underscoring the critical challenge of maintaining K balance in these agroforestry systems regardless of the yield scenario.

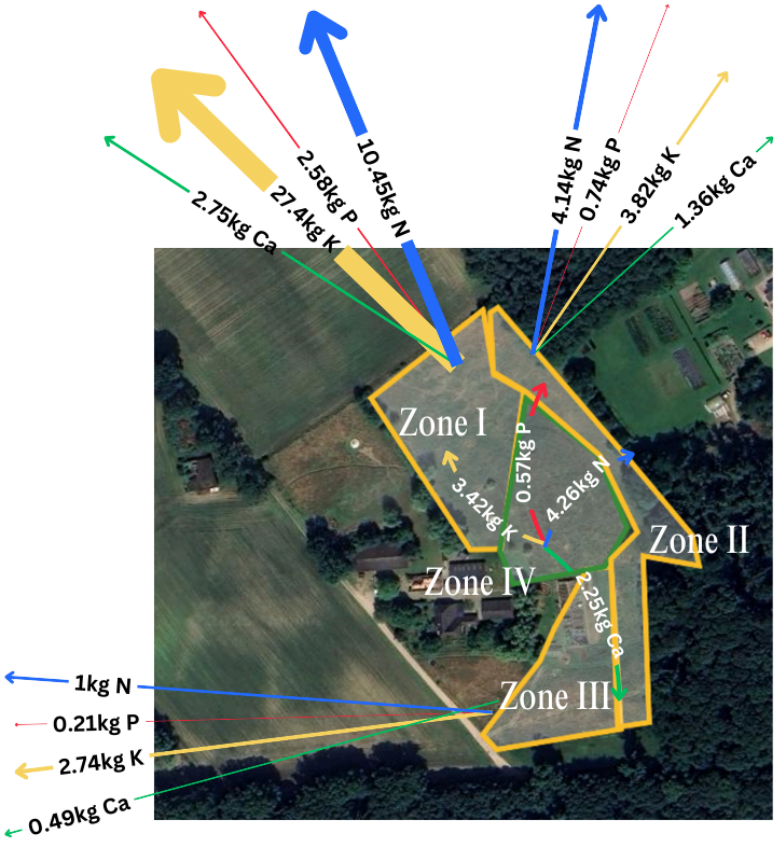
The integration of these findings paints a comprehensive picture of nutrient dynamics within the CAS. It is established that all five farms share a common pattern of nutrient loss, with K being disproportionately removed through harvested produce, a phenomenon linked to the high fruit content. The final figures of nutrient partitioning among plant components provides additional insight, revealing that while fruits are the primary conduit for K export, nuts and leaves serve more as exports for N and Ca, respectively.

Collectively, these results not only answer the first research question regarding nutrient losses through food yields but also lay the groundwork for addressing the second question on nutrient compensation through internal recycling. The consistent nutrient partitioning patterns observed across the different farms and yield scenarios underscore the potential for management practices that optimize the use of plant residues such as leaves to partially counterbalance the nutrient losses, particularly for K. The subsequent sections will further explore the extent to which these internal nutrient contributions can compensate for the deficits created by high-yield harvests, thereby informing potential strategies for sustainable nutrient management in CAS.

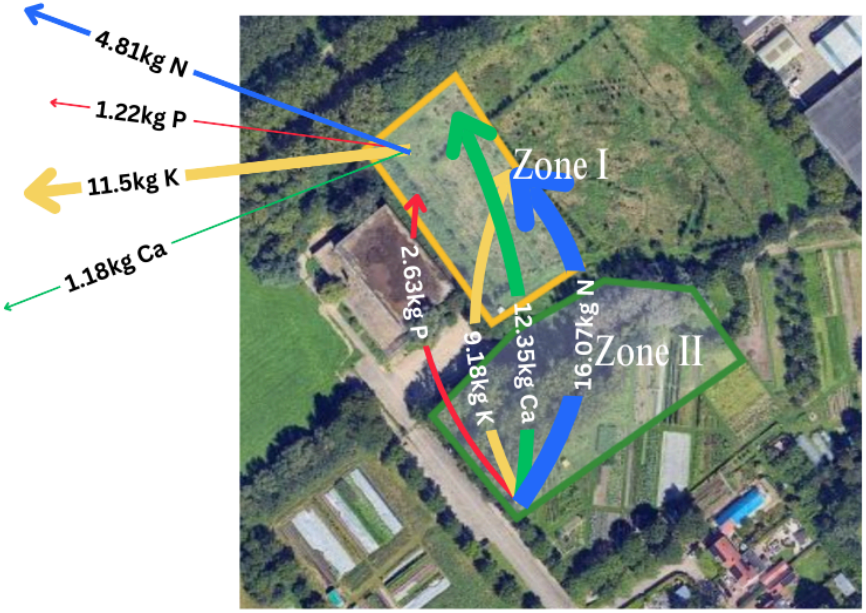
Research Question 2:

Yearly leaves & prunings from nature areas

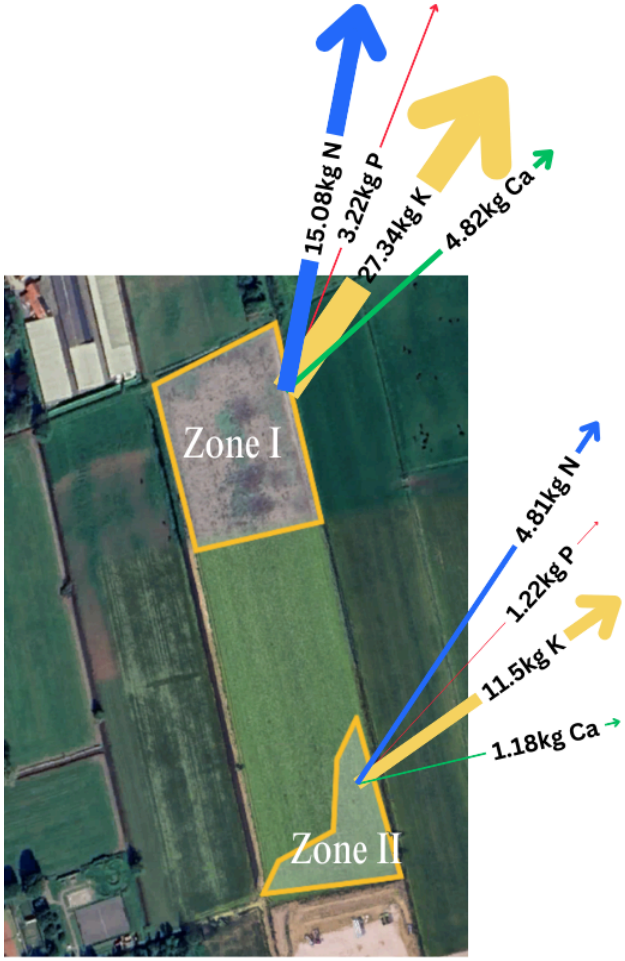
To compensate for the exports that exit the CAS as output, there are prunings from nature zones on 4 of the 5 farms which can be reallocated to the food producing CAS zones. This comes as an “external” input into the CAS system and can therefore compensate for the outputs highlighted in research question 1. In this study, half the amount of prunings from nature areas were allocated to CAS zones, these pruning nutrient contents can be seen in the below figure which highlights the nutrient’s being transferred from one zone to another in all 5 farms (fig.12). Additionally, figure.12 indicates the yearly nutrient outputs from harvest in the average scenario to have a visual comparison between the exports of nutrients and the inputs from nature zones. We can observe in all farms a stronger export of N and K compared to P and Ca, high production zones such as Mariën I, and Bonenbos I for instance display the highest export of K and N with quantities of 27.4 kg K; 10.45 kg N and 27.34 kg K; 15.08 kg N respectively. The nutrient imports from nature zones vary strongly across the farms. Mariën IV has the lowest quantities of nutrients with 4.26 kg; 3.42 kg; 2.25 kg and 0.57 kg of N, P, K and Ca respectively. On the higher side Middenbos’s two nature zones (III and IV) account for the biggest nutrient flux across all farms 57.16 kg; 8.88 kg; 33.2 kg and 43.52 kg of N, P, K and Ca respectively. It is important to note that these inputs from nature areas are spread equally across all zones and are therefore less per zone than the numbers indicated per arrow. For the case of Middenbos the nutrient reallocation from nature zones gave Middenbos I and II 28.6; 4.4; 16.6 and 21.8 kg/year of N, P, K and Ca respectively to both.



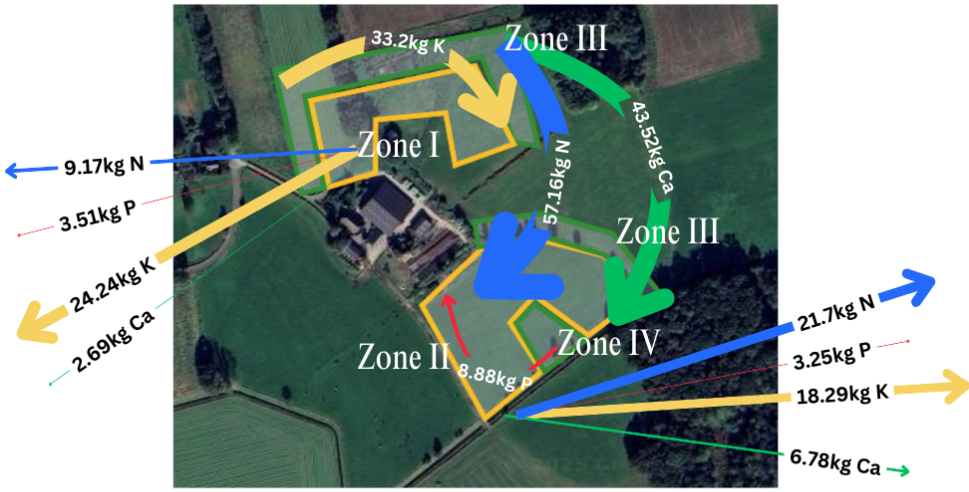
Hoeve t' Marien



Eetmerbosch



Bonenbos



Middenbos

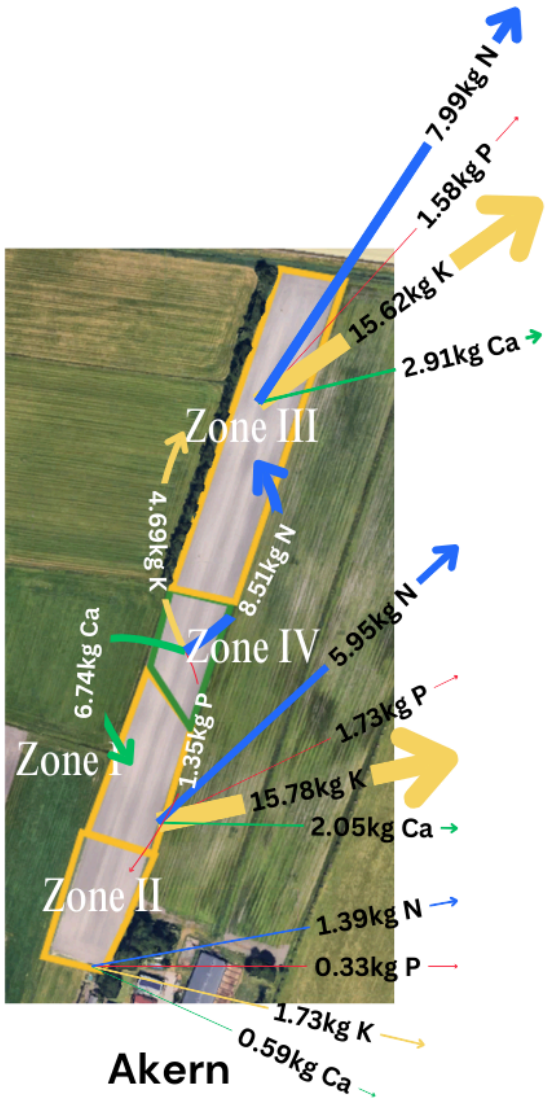


Figure.12: Fluxes of nutrient from CAS and nature zones across the 5 farms. CAS zones are delimited in yellow while nature zones are in green. The arrows represent the fluxes of nutrients in the average scenario in kg. The arrow's colors are nutrient dependent blue=Nitrogen; red=Phosphorus; yellow=Potassium and green=Calcium. The arrow's size is also relevant to the quantity of nutrients flowing through that arrow. The larger the arrow, the more the nutrients are being moved. The nature zones have the quantities in white and the arrows are curved to differentiate from the CAS fluxes which are in black text and straight arrows. Finally, the fluxes from the nature zones are spread to CAS zones evenly which is not represented in this figure. Only the total flux of nutrients from the nature zone is represented to avoid overcrowding the figure. Regarding Middenbos farm, the nutrients from nature zones III and IV were combined for clarity.

Internal cycling of nutrients from food producing zones

In this section, the internal pruning nutrient content from the food producing CAS zones are compared to the harvest exports in high and average scenario (fig.13, fig.14, fig.15, fig.16 and fig.17). These prunings are from the food producing zones and not from the nature zones. The low scenario was excluded to enhance clarity as the internal nutrient needs were always met for all nutrients in all farms. This indicates that in the low yield scenario, all CAS systems exports can be met with the yearly nutrients from within the system. The yearly additional fluxes from weathering, N-fixing, deposition and leaching were not included in this section as to isolate internal prunings which were sufficient to cover the harvest exports. It is important to compare the internal cycle of nutrients from CAS zones with yearly harvests in order to determine if the harvest can be met and if it is a realistic objective.

Across Mariën, Middenbos and Åkern, all nutrient output needs are met by the internal cycling of nutrients in the high scenario (fig.13, fig.16 and fig.17). For Bonenbos and Eetmeerbosch, the internal cycling from pruning is not enough for K in the high scenario. It is met for all the other nutrients but for K it its only enough in the average scenario of outputs (fig.14 and fig.15). These figures highlight the potential self-sufficiency of the CAS in the high or average scenario as the pruning inputs from within the zone cover the harvest outputs in all 4 nutrients. However, these results may still lead to soil depletion as the nutrients from internal pruning cycling come from within the zone and are bound to be depleted. The use of pruning and mulch from outside the CAS, in this case the nature zones can be considered an external input and act as nutrient replenishment to the exports of the CAS. This is shown in the next section where the prunings of nature zones are used instead of the CAS zones.

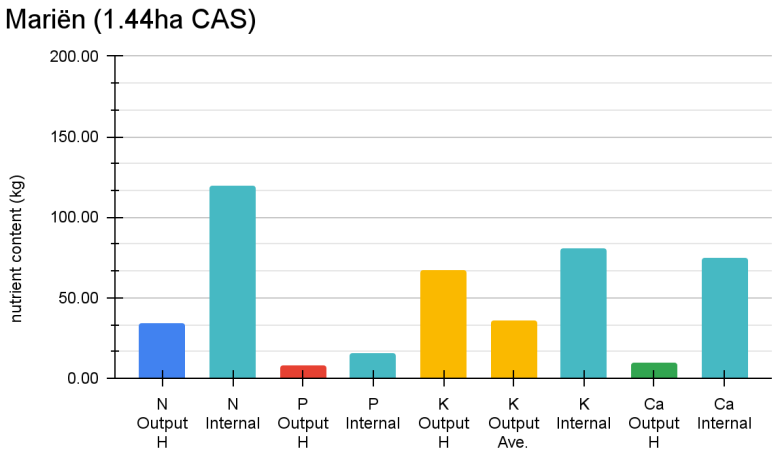


Figure.13: Mariën harvest output and internal cycling of pruning nutrients in high and average scenario

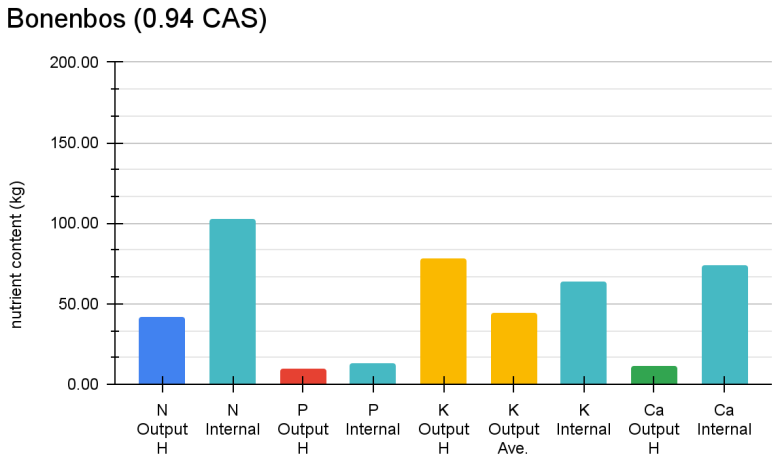


Figure.14: Bonenbos harvest output and internal cycling of pruning nutrients in high and average scenario

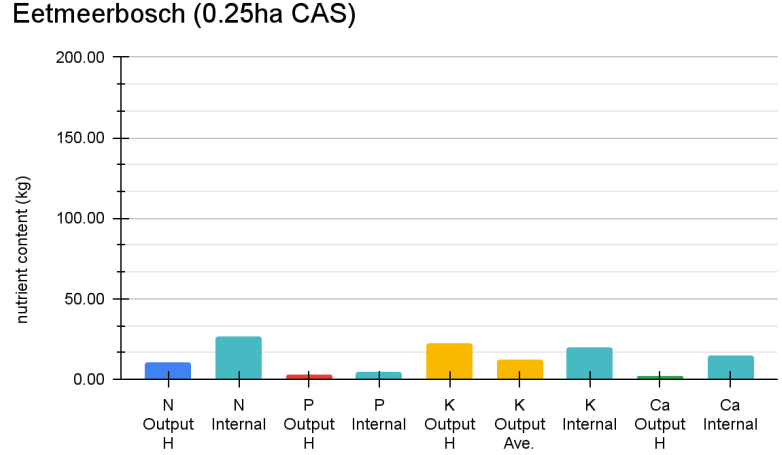


Figure.15: Eetmeerbosch harvest output and internal cycling of pruning nutrients in high and average scenario

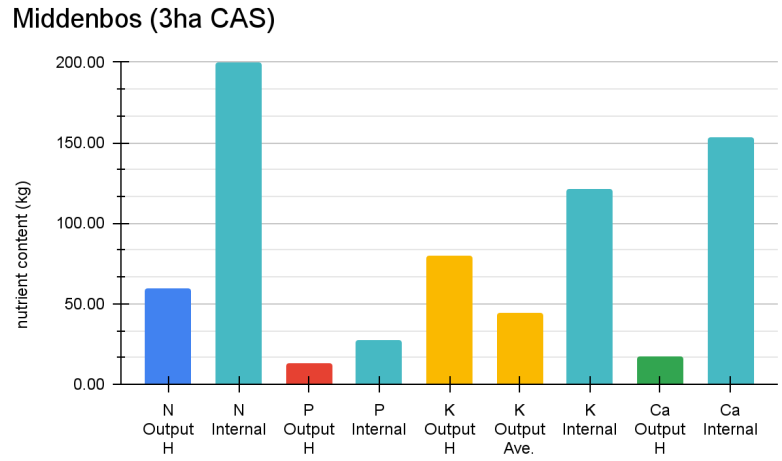


Figure.16: Middenbos harvest output and internal cycling of pruning nutrients in high and average scenario

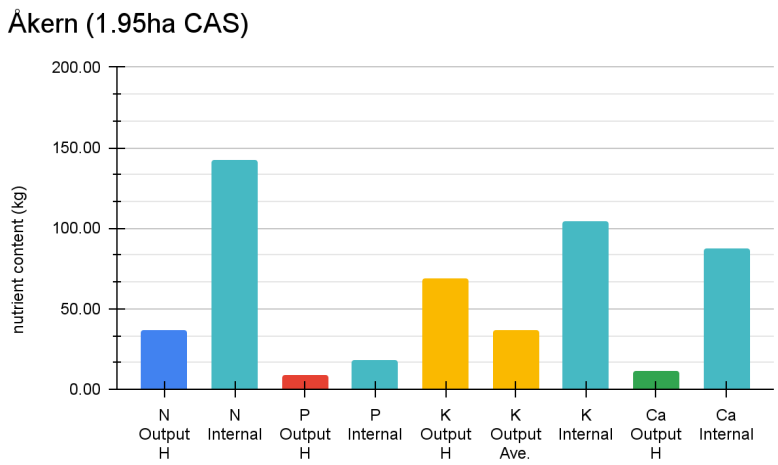


Figure.17: Åkern yield output and internal cycling of pruning nutrients in high and average

Legend:

H: High scenario; Av.: Average scenario; L: Low scenario



Nature zone pruning and mulching reallocation

The allocations of nutrients from nature areas in comparison with the different scenarios of exports are presented below. These findings are central to answer the second research question as they provide the export of the systems for the 3 scenarios (high, average and low) in comparison to the nutrient content that is provided from nature zone prunings (leaf, grass and woody biomass included). Additionally the fluxes from leaching, N-fixation, weathering and atmospheric deposition are included in these figures to have a complete observation of the fluxes (fig.18, fig.19, fig.20, fig.21 and fig.22). In this section, total inputs refer to the mulching from nature zones as well as the sum of all the fluxes mentioned above. In this part we present the results in order of the 5 farms as this gives a more case specific lens on each system.

Firstly, Mariën's nature areas have significant outputs of N and K with values ranging from 33.9 to 9.7 kg and 67.6 to 19.3 kg respectively across the scenarios (fig.18). The total inputs of N are the highest with a value of 32.6 kg each year. This shows that the N total inputs cover the exports of all yield scenarios and therefore no N depletion should occur and instead a slight surplus will accumulate yearly. However, for P, K and Ca there is no yield scenario where the total inputs match the exports. The gap is the biggest with K which has a yearly input of 7.51 kg. Ca even has a negative total input of 0.80 kg per year due to Ca leaching values being high. Mariën is therefore never fully self-sufficient in any of the 3 scenario.

Secondly, Bonenbos is a specific farm as it is the only one in this study with no nature zone and therefore no external mulch inputs. Therefore the external inputs are solely based on N-fixation, atmospheric deposition and weathering. These total inputs are sufficient for N as they are larger than the N exports in the average and low scenario. The N yearly input is of 24 kg while the N export of the best scenario is of 36 kg. For the other nutrients, all scenarios exports are higher than the total input. For Ca the situation is similar to Mariën with negative total input. Bonenbos is therefore never fully self-sufficient in any of the 3 scenarios (fig.19).

For Eetmeerbosch, there are varying results per nutrients, for N the total inputs are very high compared to the exports with a total input of 23.7 kg compared to an export of 8.6 kg in the best scenario which is nearly 3 times the needed N (fig.20). For P the total input is also sufficient to cover the exports in all scenarios with total inputs of 2.68 kg compared to an export of 2.2 kg in the best scenario. K needs are not met for the best and average scenario but are in the low scenario. The K total input is of 9.8 kg while the low scenario output is of 6.57 kg, whereas for high and average exports, they are of 20.7 and 11.5 kg respectively. Ca total inputs are similarly to N significantly higher than any of the output scenarios with a value of 11.9 kg compared to an export of 2.1 kg in the best scenario. This Ca can be traced back to the the prunings of nature areas (fig.12) while exports do not contain high calcium content (fig.8). Therefore N, P and Ca will be in slight surplus over time and Eetmeerbosch is only fully self-sufficient in the low scenario.

For Middenbos, there are two nature zones (Middenbos III and IV) which contribute significantly to the total nutrient inputs. N and Ca export needs are met in all scenarios with 137.6 and 38.3 kg respectively. The exports in the best case scenario are only 55.6 and 17 kg of N and Ca respectively which is less than half of what the inputs provide yearly. This will lead to a surplus of both N and Ca. For P the total input meets only the average and low scenario with a yearly value of 9.4 kg while the export is of 12.2 and 6.8 kg in the best and average scenarios respectively. In Middenbos the K needs are only met in the low scenario with K inputs of 40.2 kg while the exports are of 42.5 and 24.3 kg for the average and low scenarios respectively. Middenbos is therefore only fully self-sufficient in the low scenario (fig.21).

Finally, for Åkern the N total inputs are self sufficient for all scenarios with a yearly input of 36.6 kg compared to an export of 28.6 kg in the best scenario. The P and K needs are not met in any scenarios with the inputs being 1.7 and 9.2 kg respectively and the exports being 1.9 and 17.7 kg in the low scenario. For Ca the needs are met only in the low scenario with an input of 3.4 kg compared to an export of 3 kg. Åkern is therefore not self sufficient in any scenario but has a slight surplus of N (fig.22).

Mariën (1.44ha CAS) (0.32ha Nature)

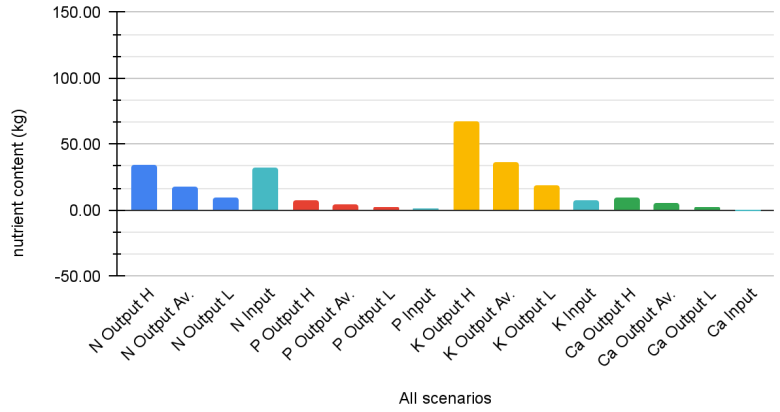


Figure.18: Mariën farm all nutrient outputs and inputs per scenario

Eetmeerbosch (0.25ha CAS) (0.32 Nature)

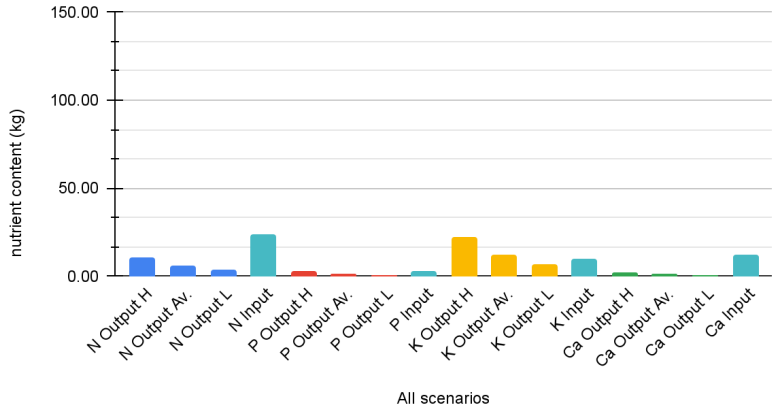


Figure.20: Eetmeerbosch farm all nutrient outputs and inputs per scenario

Bonenbos (0.94 CAS) (0ha Nature)

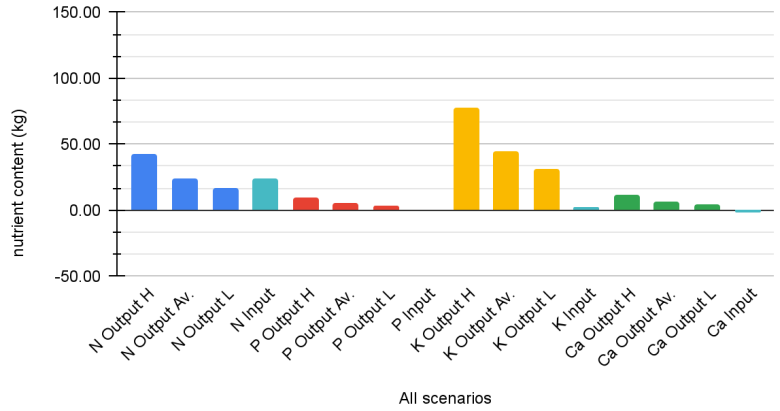


Figure.19: Bonenbos farm all nutrient outputs and inputs per scenario

Middenbos (3ha CAS) (1.3ha Nature)

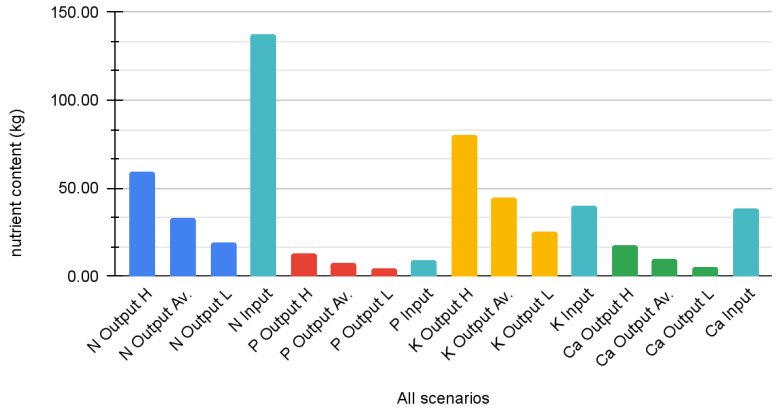


Figure.21: Middenbos farm all nutrient outputs and inputs per scenario

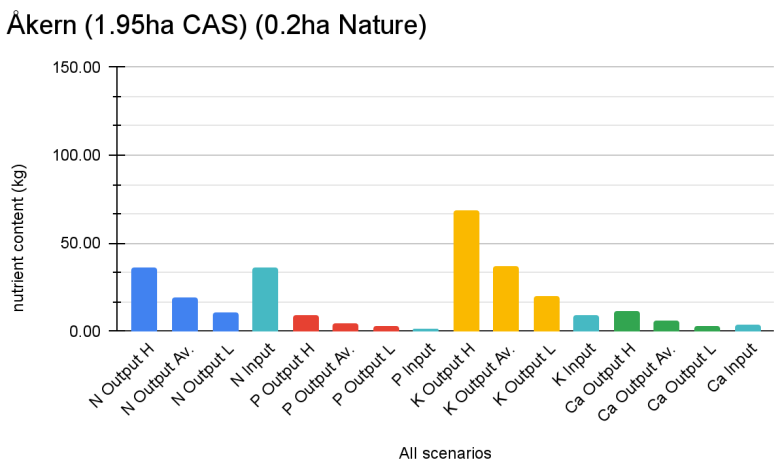


Figure.22 Åkern farm all nutrient outputs and inputs per scenario

Legend:
H: High scenario; Av.: Average scenario; L: Low scenario



Depletion rate

For each CAS, projections were made to determine when would a certain nutrient be depleted (see equation.2). This calculation is repeated yearly until year 50. Table.5 represents the soil nutrient depletion rate if no pruning is added, whether internal or external. The color coding of the tables indicate in green, nutrients who would be considered self sufficient or non-depleting as they are still in the soil stock by year 50+. In yellow are the nutrients who have passed the estimated maturity stage of the CAS of 20 years. And in orange are the nutrients who have been depleted before the CAS could have reached maturity. For all scenarios the N , P and Ca stocks are not depleted for more than 50 years, for certain CAS the N rate even goes up due to N-fixation and/or N deposition. This indicates that there is self-sufficiency and no depletion will occur in all systems for certain nutrients.

For K, the results are more complex with certain CAS being depleted very early on, such as Eetmeerbosch I at year 9, 12 and 16 for the high, average and low scenarios respectively. In the high scenario, only one CAS reach 20 years without having a depletion of K (Middenbos II). In the average scenario 7 CAS reach the 20 year mark without being depleted. For the low scenario,3 CAS zones (Mariën II, Middenbos II and Åkern II) can be considered non-depleting. No farm is entirely self sufficient regardless of the scenario as some zones may be self sufficient but not the neighbouring zones of the farm.

These same depletion tables were created for management scenarios where prunings from nature zones were allocated to the CAS zones (table.6). For N, P and Ca there is also no depletion regardless of pruning reallocation. For K the depletion years are near identical in the CAS zones to those of the no-external pruning results (table.5). The same color coding as table.5 apply for table.6. Furthermore, compared to the non-pruning scenario, in table.6 we see that some of the nature zones have nutrients depleted out of them after a certain amount of years. For instance, Eetmeerbosch II and Åkern IV don’t make it till year 20 without depleting their K stocks at years 11 and 18 respectively. For Middenbos III and IV the K depletion year is at year 18 and 21 respectively. Mariën IV is the only nature zone that reaches 50 years without depletion which is due to its low support species surface area and a higher initial K soil stock than the other nature zones (see annex.1 and 2). These nutrients depletion for nature zones do translate in a further year for nutrient depletion in some CAS such as Eetmeerbosch I extending its K depletion year by 1 in all scenarios (table.5 and 6). However the effect of external pruning on K soil depletion years are minimal for the CAS zones.

Table.5: Year of Nutrient depletion in all scenarios without external pruning input for each CAS. The green boxes represent nutrients who are self-sufficient or non-depleting as they are still in the soil stock by year 50+. In yellow are the nutrients who have passed the estimated maturity stage of the CAS of 20 years. And in orange are the nutrients who have been depleted before the CAS could have reached maturity. In green text are the nature zones.

CAS/ Year of Depletion	N, P, Ca all scenarios	K High scenario	K Average scenario	K Low scenario
Mariën I	50+	11	15	22
Mariën II	50+	30	49	50+
Mariën III	50+	20	30	48
Mariën IV	50+	50+	50+	50+
Bonenbos I	50+	14	20	25
Bonenbos II	50+	17	24	32
Eetmeerbosch I	50+	9	12	16
Eetmeerbosch II	50+	50+	50+	50+
Middenbos I	50+	17	24	35
Middenbos II	50+	27	42	50+
Middenbos III	50+	50+	50+	50+
Middenbos IV	50+	50+	50+	50+
Åkern I	50+	10	14	19
Åkern II	50+	20	31	50+
Åkern III	50+	16	21	31
Åkern IV	50+	50+	50+	50+

Table.6: Year of Nutrient depletion in all scenarios with external pruning from nature zones for each CAS (in green text are the nature zones) The green boxes represent nutrients who are self-sufficient or non-depleting as they are still in the soil stock by year 50+. In yellow are the nutrients who have passed the estimated maturity stage of the CAS of 20 years. And in orange are the nutrients who have been depleted before the CAS could have reached maturity. In green text are the nature zones.

CAS/ Year of Depletion	N, P, Ca all scenarios	K High scenario	K Average scenario	K Low scenario
Mariën I	50+	11	15	22
Mariën II	50+	30	49	50+
Mariën III	50+	20	30	49
Mariën IV	50+	50+	50+	50+
Bonenbos I	50+	14	20	25
Bonenbos II	50+	17	24	32
Eetmeerbosch I	50+	10	13	17
Eetmeerbosch II	50+	11	11	11
Middenbos I	50+	17	24	36
Middenbos II	50+	27	43	50+
Middenbos III	50+	18	18	18
Middenbos IV	50+	21	21	21
Åkern I	50+	11	14	20
Åkern II	50+	21	32	50+
Åkern III	50+	16	22	32
Åkern IV	50+	14	14	14

K depletion from year 0 to 50

For K in particular, the depletion of the soil's stock was calculated yearly based on the exports of the system from year 1 to 50 as the soil depletion often occurred before the 20 year mark. This was done firstly without the addition of pruning from nature zones (fig.23, 24, 25) and then a second time while including the prunings from nature zones (fig.26, 27, 28). These figures represent a more accurate soil depletion rate of K in all scenarios to tables 8 and 9 as the rate of depletion and initial soil stock at t=0 on the x-axis are visible.

When no pruning was added, in figure.23 (high scenario) a decline in K soil stock after year 6 is observed. This is due to the yields of the food producing plants starting to produce higher quantities of food at that time. The decrease in the following years is constant in all CAS once the peak production of food has been achieved for most species which ranges between year 8 to 20 according to the Rekentool 5.1 values. This constant decline can also be seen in the average and low scenario (fig.24 and 25) as the peaks of food production are reached at the same time but with different intensity which is seen by the less steep decline in the K soil stock for all CAS.

Regarding specific CAS, the more high producing CAS experience a steeper K soil decline, compared to lower producing CAS. For instance, Mariën I which has the fastest K depletion rate is a high producing system while Mariën II a low production zone has a much slower K depletion rate (fig.23). These patterns for Mariën and other high producing CAS are similar across the 3 scenarios high, average and low production. Regarding the specific date where the K soil stocks reach 0 kg are on average at 17.4 ± 16; 25.6 ± 15 and 30 ± 10 years for the high, average and low scenarios respectively (the average and standard deviations uses 50 as a value for CAS which are 50+ in table.5 which gives a conservative estimate). The specific year of K soil depletion of each CAS are best seen in table.5.

Now for the situation where pruning from nature areas are incorporated yearly to the CAS zones, a steady K soil depletion can also be observed across all scenarios (fig.26, 27 and 28). There is a difference from the no pruning added scenario in the early stage (year 6) where there is a slight increase in soil K stock before it declines. This slight increase is due to pruning from nature zones being reallocated to the CAS zones at year 6 and not before as the pruning quantities of a young nature zone were not calculated in this study. After this peak at year 6 the K soil stocks of all CAS follow a very similar decline pattern as the situation with no pruning reallocation. The difference is minimal and can't be seen on the graph but more in table.6 where the years of K depletion can be slightly later. On average the K soil stocks reach 0 kg at year 17.6 ± 10; 26 ± 13 and 30.3 ± 15 for the high, average and low scenarios respectively (the average and standard deviations uses 50 as a value for CAS which are 50+ in table.6 which gives a conservative estimate). These years can be considered near identical to the ones of the no pruning scenario in table.5.

Additionally, the K depletion was also quantified from year 0 to 50 for the nature zones (fig.29). We see slight increases of K stock in the initial 5 years due to inputs such as weathering and deposition, but once pruning starts being reallocated the K stocks decline and all reach a depleted stage before year 50 except Mariën IV. Middenbos III has the steepest decline as it is the largest nature zone and contributes to the largest amount of prunings. On average the K depletion year for the nature zones is at 22.8 years. This value is the same across all scenarios as the pruning quantities are not production scenario dependent.

Nutrient replenishment needs per CAS

There are different methods to replenish this K depletion in order for the K soil stock to be stable and not in decline. These methods range from using external K amendments, increasing mulching quantities and reducing K exports of the system. For farmers to decide which methods suits them best it is important to first determine the quantities of K that are needed to be replenished. These quantities can be seen in table.7 for all the CAS and all the scenarios. High producing CAS zones like Mariën I have the highest need of K replenishments with 54.28 kg of K needed yearly to meet the export deficit. In certain cases this K replenishment value can be much lower such as in Mariën III which is a low production zone with values of 1.41kg of K in the low production scenario (table.7). These K replenishment values can also serve as an indicator for practitioners depending on how much K they are willing to add to the CAS systems depending on their labor availability for mulching or fertilizing costs.

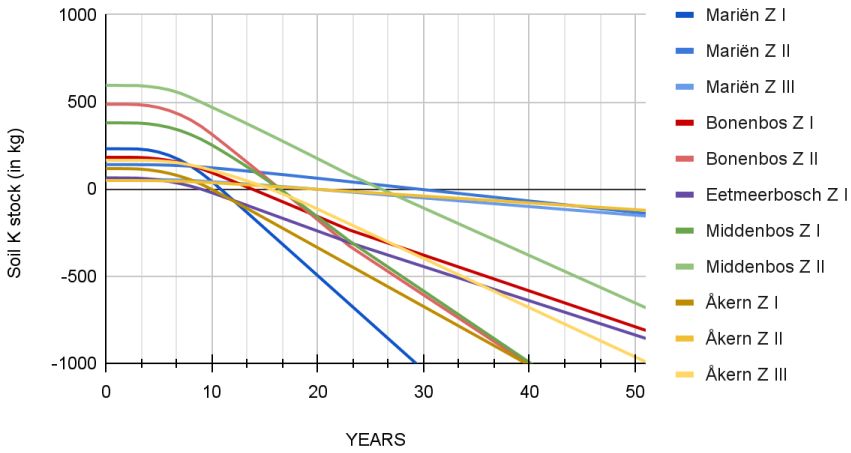


Figure.23: High scenario soil K depletion with no additional pruning for all CAS

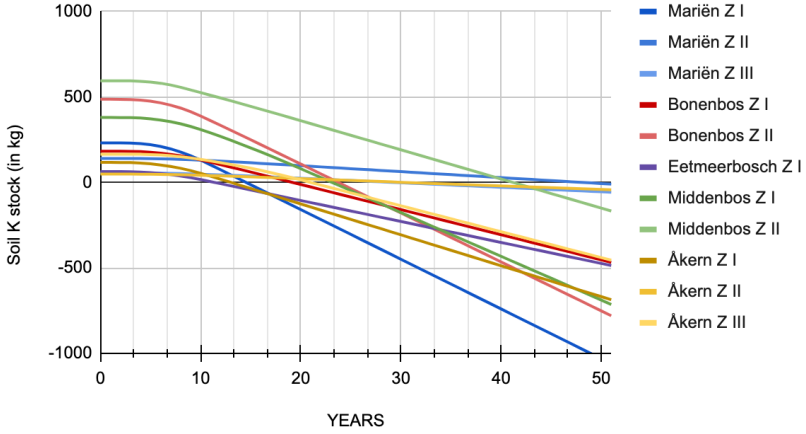


Figure.24: Average scenario soil K depletion with no additional pruning for all CAS

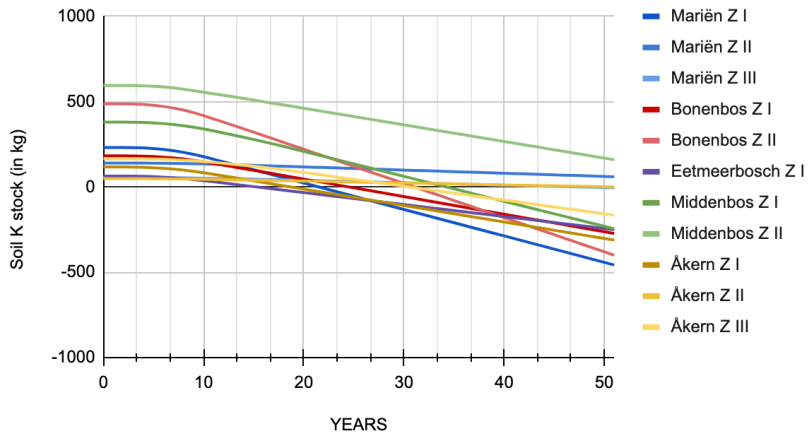


Figure.25: Low scenario soil K depletion with no additional pruning for all CAS

The color or each CAS was selected to have similar color gradient per farm for a easier visual comparison within each farm.

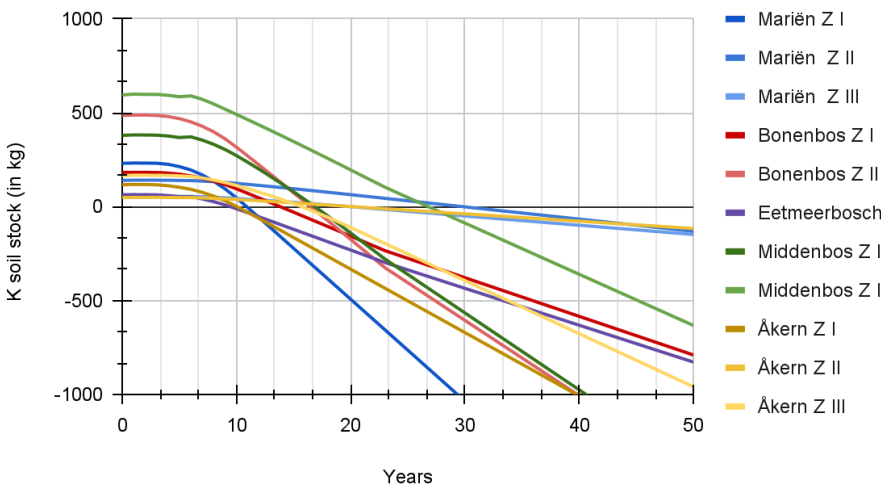


Figure.26: High scenario soil K depletion with additional pruning from nature zones for all CAS

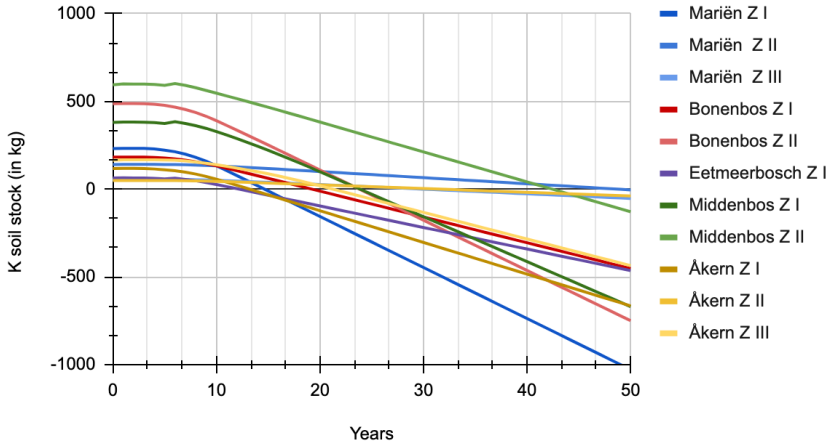


Figure.27: Average scenario soil K depletion with additional pruning from nature zones for all CAS

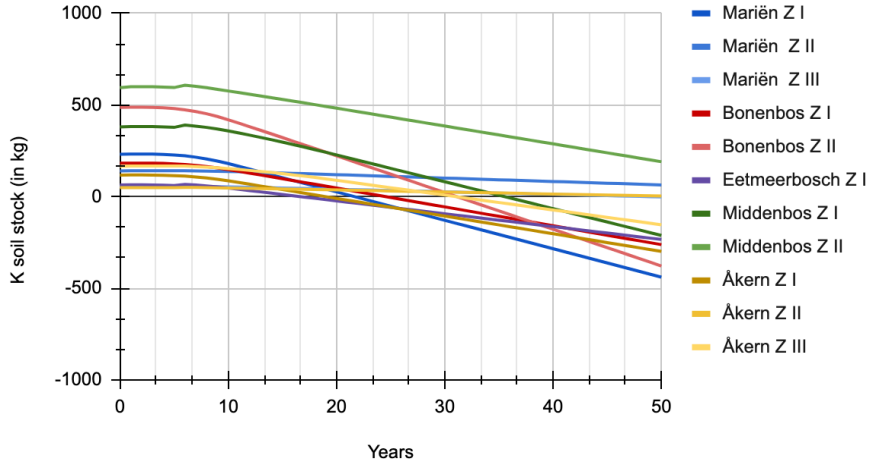


Figure.28: Low scenario soil K depletion with additional pruning from nature zones for all CAS

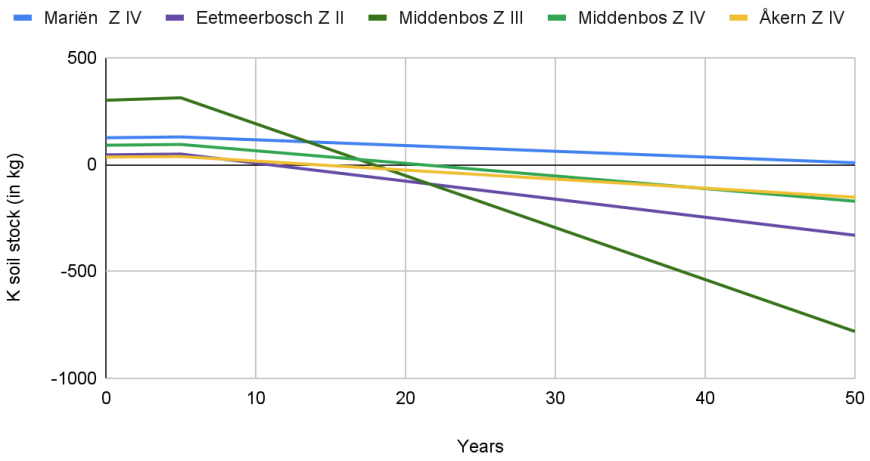


Figure.29: K soil depletion in nature zones from pruning reallocation

K needs in kg	Mariën Z I	Mariën Z II	Mariën Z III	Mariën Z IV	Bonenbos Z I	Bonenbos Z II	Eetmeerbosch Z I	Eetmeerbosch Z II	Middenbos Z I	Middenbos Z II	Middenbos Z III	Middenbos Z IV	Åkern Z I	Åkern Z II	Åkern Z III	Åkern Z IV
High	54.28	6.51	4.94	2.68	20.59	40.09	19.65	8.44	40.98	27.28	24.28	5.90	33.75	3.90	28.29	4.23
Average	29.08	3.49	2.65	2.68	14.71	28.63	12.28	8.44	25.61	17.05	24.28	5.90	18.08	2.09	15.15	4.23
Low	15.51	1.86	1.41	2.68	10.29	20.04	7.02	8.44	14.64	9.74	24.28	5.90	9.64	1.11	8.08	4.23

Table.7: K replenishment needs in kg per year in 3 scenarios for all CAS once maturity has been reached. The color scale represents the quantities needed with white being low K needs and red the higher K needs.

Soil nutrient stock vs. nature area: drivers of nutrient depletion or self-sufficiency

After seeing the depletion rate of the soil nutrient stock in the above section and the pruning inputs from nature zones compared to outputs, it is important to compare which of those two variables are responsible for either the nutrient depletion or nutrient self sufficiency of these systems. For this a bubble graph serves as a comparison between the nature/food surface area of each CAS compared to the nutrient soil depletion percentage for each of the 4 nutrients. In the following 4 figures (fig.30, fig.,31, fig.32 and fig.33), the further the CAS is on the x-axis the higher the amount of nature area is allocated and therefore the amount of mulch. A value of 1 on the x axis indicates a 1:1 ratio of nature area of that CAS compared to the food area on the farm. The further the CAS is on the y-axis the higher the nutrient depletion between the initial soil stock and the stock at year 50. If the y-value percentage is positive there is a depletion of the nutrient, if it is 0 there is self sufficiency and if it is negative there is a surplus. It is important to add that the position of each CAS on the x-axis does not vary between all figures as they have the same variable.

Firstly in figure.30 which gives this comparison for N we see that a few farms are in N surplus such as Middenbos I and II, Åkern II, Eetmeerbosch I and Mariën III. These CAS are also on the more right hand side of the bubble chart indicating a higher nature area to food producing ratio. On the other hand some CAS are more in the positive on the y-axis especially Bonenbos I and II, Mariën I and others (fig.30) indicating a slight N depletion of 10-15%. Finally, all the nature producing zones (in green) are in slight N depletion. Regarding the initial N stock, Eetmeerbosch has the highest in both I and II followed by Bonenbos, while Hoeve t' Mariën is on the lower end of the spectrum. When conducting a linear regression analysis using the N-depletion percentage as response variable and nature/food area as explanatory variable, a weak significance was found (p-value=0.01) (see annex.8).

In figure.31 we can first see that all CAS are in a state of P depletion. There is not much difference between the CAS compared to N with P depletion values ranging in a similar percentage range. One difference is Mariën II which has a lower depletion rate by 5% in P compared to N. Regarding the initial P stock, this time Bonenbos has the highest amount of P followed by Mariën II and III. It is interesting to note that the initial P stock can vary greatly between CAS on the same farm as seen between Mariën III and IV. Similarly to N a weak significance was found between P soil depletion percentage and nature/food surface area with a p-value<0.1 (p-value=0.067) (see annex.8).

In figure.32 for K, there is a similar pattern with all CAS being in the negatives for the depletion ratio. However, the value of that depletion is much more significant with K depletion values in CAS ranging from 173% to 1100% for Middenbos II and Åkern I respectively. There is no clear

correlation between the y and x variables (see annex.8) as some CAS have very high depletion ratios while having high nature/food area such as Eetmeerbosch I. Regarding the initial K soil stock, Bonenbos has the highest K stock again nearly doubling all other CAS stocks. Åkern has lowest K stocks overall, but has varying K depletion percentages. It is important to note that the K initial soil stocks are according to the Eurofins target range considered low in most CAS with an average of 317 kg of K per ha across all zones. Some of the CAS with the lowest depletion rates such as Middenbos II and Mariën I have “quite low” K soil stocks according to Eurofins target values (see annex.1). There is no clear correlation between nature area and depletion % as some CAS have high nature area and high depletion (e.g. Eetmeerbosch I) while others with low nature areas have lower depletion percentage (e.g. Åkern III). No significance was found through the linear regression analysis.

For Ca in figure.33 we see some CAS that have negative soil depletion percentages such as Middenbos II and Eetmeerbosch I. The other CAS are all in Ca depletion with all relatively similar ratios regardless of the nature/food surface area. An interesting observation is that the nature zones are having higher depletion rates of Ca then most of the CAS (fig.33). This is the case for Middenbos III and IV as well as Åkern IV. It is also important to point that there are no clear correlation between nutrients as some CAS may be very high on the depletion ratio on a specific nutrient but low for another, as is the case with Eetmeerbosch I in K and Ca respectively (fig.32 and fig.33). Additionally, Bonenbos has the highest initial Ca stock again followed by Eetmeerbosch. Finally, compared to other nutrients, it is in Ca where the nature zones (e.g. Åkern IV, Middenbos III and IV) have the highest depletion compared to food producing CAS which would be due to the high amount of Ca in leaves and prunings which are leaving these nature zones. No significance was found through the linear regression analysis (see annex.8).

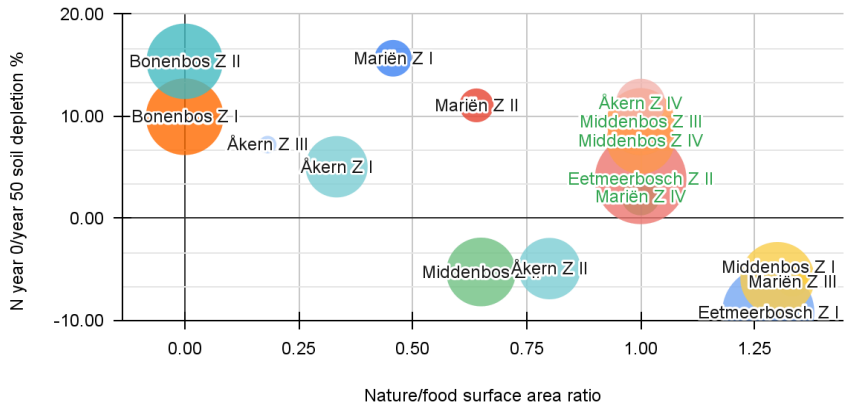


Figure.30: Nitrogen soil depletion % and initial N stock in relation to nature area ratio for all CAS. (Bubble size represents initial soil nutrient strock per ha. In green text are the nature zones.

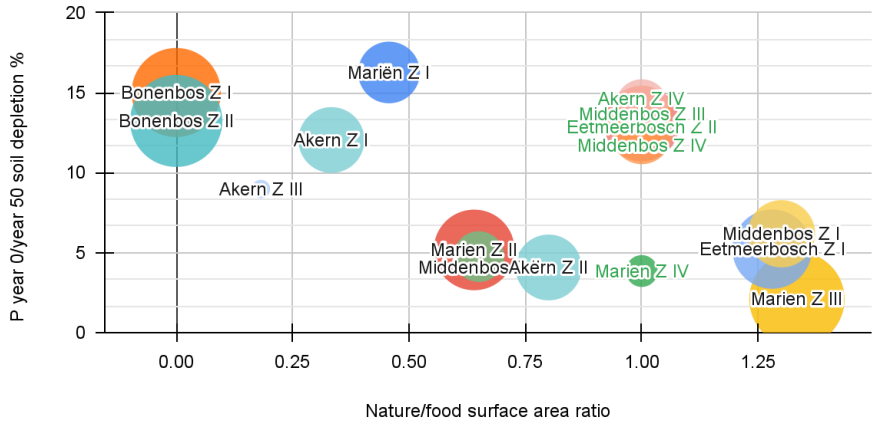


Figure.31: Phosphorus soil depletion % and initial P stock in relation to nature area ratio for all CAS (Bubble size represents initial soil nutrient strock per ha. In green text are the nature zones.)

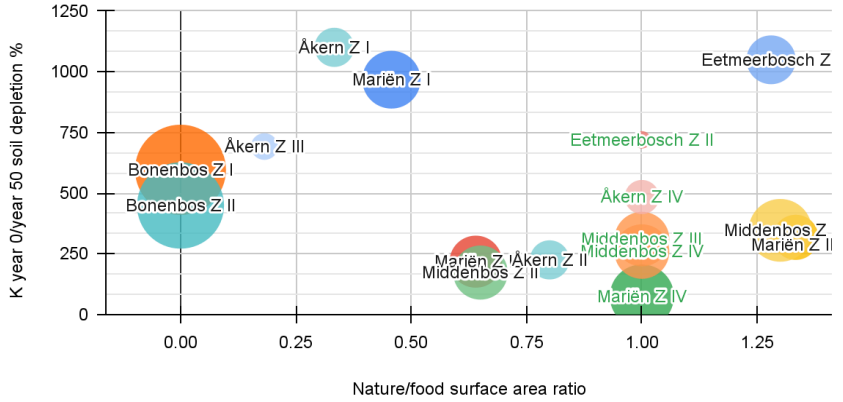


Figure.32: Potassium soil depletion % and initial K stock in relation to nature area ratio for all CAS (Bubble size represents initial soil nutrient strock per ha. In green text are the nature zones.)

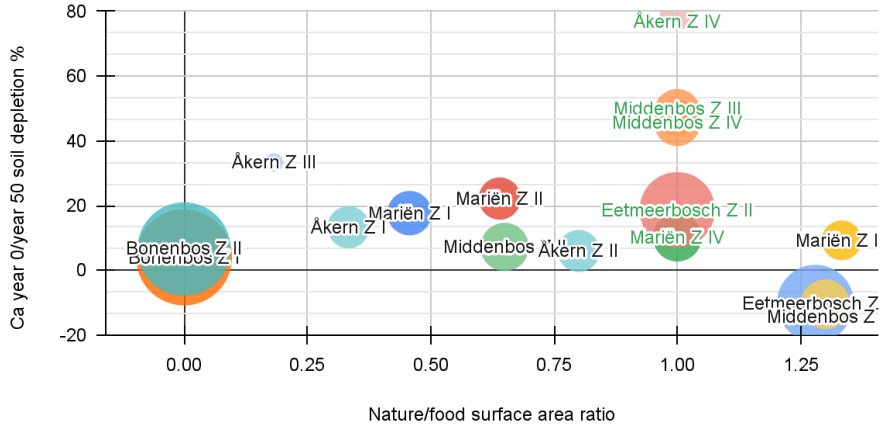


Figure.33: Calcium soil depletion % and initial Ca stock in relation to nature area ratio for all CAS (Bubble size represents initial soil nutrient strock per ha. In green text are the nature zones.)

Design solutions on K-demanding and K-giving species

An approach for practitioners to the K depletion issue would be to shift focus in terms of species selection, this can be done in two ways, by first prioritizing least K demanding species or by focusing on high K giving mulching species. The two tables give the first 5 species that this study used that are either K demanding (table.8) or K-giving (table.9). A first observation is the high K content of hazelnut and its shell, showing that there is a big export of K when hazelnuts are produced. On the other hand, blueberries (used as honeyberry replacement) have a low K export, which could have high yields without draining too much of the K soil stocks (table.8). Regarding mulch input, ryegrass had the highest K content with 2 cuts per year with 15 g K/sqm/y while mulberry only produces 2.67 g K/sqm/y. A tailored selection of these species can enhance the K availability in the soil while still keeping high harvest values in terms of kilos and high K enrichment from pruning and mulching materials.

Most K-demanding	g/kg/food	Least K-demanding	g/kg/food
1. Hazelnut + shell	43.44	**1. Blueberry (similar honeyberry)**	0.86
2. Pear	11	**2. Autumn Olive**	1.846
3. Mulberry	7.18	**3. Currant**	2.985
4. Apple	4.57	**4. Chestnut + shell**	3.04
5. Walnut + shell	4.23	**5. Walnut + shell**	4.23

Table.8: Selection of most and least K demanding species per kg of food produced

Most K-giving mulch	g/kg woody prunings	g/kg leaves	g/sqm leaves	g/sqm prunings	Total K g/sqm
1. Rye grass (2 cuts/year)	NA	26.65	15.01	NA	15.01
2. Walnut	2.98	9.01	1.16	7.74	8.90
3. Willow	0.93	16.50	4.18	3.85	8.03
4. Poplar	0.62	15.00	3.80	2.40	6.20
5. Mulberry	0.02	20.67	2.668497	0.001225	2.669722

Table.9: Selection of most K giving species per kg prunings and leaves produced

Discussion:

Reflection on results

Nutrient losses due to harvesting and their implications

The findings of this study highlight potassium (K) as the most heavily exported nutrient across all five CAS farms, accounting for 58.5% to 62% of total nutrient losses, followed by nitrogen (N) (25.5–28.2%), phosphorus (P) (6–9.3%), and calcium (Ca) (5.9–7.6%). This nutrient loss pattern is predominantly influenced by the high K concentration in fruit yields, as confirmed by nutrient partitioning data. This aligns with previous agroforestry research demonstrating significant K losses in fruit-dominated systems (Buwald et al., 1982). In terms of quantities of nutrients exported out of the farms, these values varied as each farm is unique in its design and species selection. In comparison with maize, a more common crop grown in monoculture systems, the N, P, K yields are on average 123.5 kg N/ha, 20.6 kg P/ha and 32.4 kg K/ha (BąK et al., 2016). The nutrient composition in CAS is different but is significantly higher in monoculture for N and P (table.4). For K the CAS has higher exports due to the higher K content in fruits, highlighting the high production of CAS at maturity in comparison to monocultural systems.

The study demonstrated that for N, P and Ca there is a potential for self sufficiency in all the farms regardless of the production scenarios. For N there is in some CAS with slight surplus coming from N-fixing species or deposition (e.g Eetmeerbosch). For P there is still a depletion in all farms as the exports are bigger than the inputs but the rate is much slower due to the quantities of P in export being one of the lowest as mentioned above. This depletion would occur past year 50 which was not quantified in this model but could possibly reach 2000 years as seen in other studies (Pepels, 2019). For Ca in some CAS there is depletion if the nature zones do not bring in significant mulch (e.g Mariën). But in some CAS there can be surplus as the pruning and mulch contains more Ca then the exports of the system leading to a slight surplus in the food producing CAS zones (e.g Middenbos).

A key challenge identified in this study is the substantial gap between nutrient exports and on-farm inputs, particularly for K. This is especially critical for farms with low initial soil K stocks, such as Åkern and Mariën, where nutrient depletion occurs rapidly, often in the first 10-15 years. Nutrient availability is further limited as nutrients imported through leaf litter depend on the mineralization of organic material (Pardon et al., 2017). Additionally, certain CAS, including Eetmeerbosch I, Mariën I, and Åkern I, are K-depleted regardless of the yield scenario, indicating that even internal pruning contributions and nature zone inputs are insufficient to maintain K stocks. These CAS will require targeted K amendments to prevent long-term depletion and soil degradation. Similar findings have been reported by Szott & Kass (1993), who argued that pruning and mulching alone are insufficient to sustain long-term nutrient balances in agroforestry systems without supplementary inputs. This study supports this argument, as even nature zones supplying prunings deplete their own nutrient reserves, reinforcing the need for external supplementation.

Regarding the contextualized designs, some variables were found to not be significant in the nutrient cycling, for instance the soil type (sand, loam or clay) was not directly correlated to the depletion rates but more the initial nutrient soil stock. Similarly the nut, fruit or mixed focus was not a strong influencer of depletion as the export quantities had similar nutrient ratios across all farms (fig.8). A variable that was correlated to the depletion of nutrients in the soil was the quantity of production, with high production zones having a faster depletion than low production zones (fig.23, 24, 25).

Additionally, this study finds that prunings from nature zones have nearly no impact on slowing K depletion rates. This finding is not entirely in line with research, which shows that prunings can contribute significantly to nutrient cycling, especially N and K, yet can still contribute to nutrient depletion due to high export rates (Palm et al., 1995; Matos et al., 2020; Balasubramanian, 2024). In our study, the initial K soil stock is more significant than pruning quantities in determining nutrient depletion. Most CAS and nature zones in this study have low to quite low K soil stocks according to the Eurofins target value range (317±175 kg K/ha on average), making K depletion an inevitable challenge in many CAS designs. As a result, CAS with already low initial K stocks will struggle to maintain productivity over time unless external amendments or strategic species selection are implemented.

Additionally, the efficiency of nutrient return from biomass recycling depends on species selection and management strategies, as Steinfeld et al. (2024) demonstrated that pruning and mulching enhanced nutrient cycling capacity in Brazilian agroforestry systems. These findings suggest that optimizing pruning regimes and species composition which was not done in this study could improve nutrient retention in temperate CAS, while additional external supplementation might still be necessary.

Further research by Lokin with HAS University of Applied Sciences (2024) highlights that nutrient deficiencies in CAS extend beyond N, P, and K. Samples taken from apples, pears, redcurrants, and hazelnuts in five Dutch CAS systems (5-7 years old) indicated widespread N deficiencies, likely caused by high soil P concentrations inhibiting nitrate uptake (Lokin, 2024). In addition, iron, boron, and copper deficiencies were observed in the food products, suggesting that internal recycling may not always supply all essential nutrients (Lokin, 2024). While these micronutrients were not analyzed in this study, their deficiency further underscores the limitations of internal nutrient cycling alone and the need for more holistic nutrient management approaches.

Findings from Pepels (2019) indicate that while some food forests maintain productivity for millennials without fertilization, nut-based systems tend to experience faster nutrient depletion of around 400-600 years. While our study emphasizes fruits as the largest contributor to K depletion, this is likely due to the higher proportion of fruit-bearing trees in the selected CAS designs. Nonetheless, K depletion from nut trees is important to consider, especially as they reach maturity later than fruits and may produce higher yields in the later years beyond the Rekentool 5.1’s 20-year values.

K amendments being a strong recommendation for all of the farms, a possible source is organically amended rock mineral powder, a by-product of mining activities with a fast release rate in the first 45 days after being added (Basak et al., 2021). This supplementation method could be more practical in CAS with high K depletion with needs of above 40 kg of K per year such as Mariën I, Bonenbos II or Middenbos I (see table.7), to maintain expected yields and support the correct functioning of the CAS without deficiencies.

Choosing low K-demanding food species and high K-giving species

The K content of nuts can be explored as a potential solution for farmers regarding using shells as a nutrient amendment rather than exporting them out of the system. This research indicates that hazelnuts are the most K-demanding produce, with an export of 43.44 g/kg DW (table.8). A significant portion of this K is found in the hazelnut shell (86.5 g/kg DW), which is often removed from farms (Azizov et al., 2021). Establishing on-farm hazelnut processing units to retain shells and incorporate them into the system could help return a significant portion of K to CAS. This solution is supported by research showing that crop residues, nutshells, and pruning biomass can be valuable organic K sources if managed effectively (Andrews et al., 2021).

Additionally, ryegrass has been identified as the most K-giving species in this study, contributing 15.01 g/sqm/y when two cuts were done (see table.9). This K could be more effectively utilized by CAS if farmers implement more frequent mowing, without increasing the surface area allocated to ryegrass (Wan et al., 2024). CAS practitioners could mitigate K depletion by incorporating low K-demanding food species while integrating high K-releasing species into the pruning cycle. This dual approach could help extend the longevity of CAS soil nutrient stocks.

Social relevance of this study

With the increasing popularity of CAS across the Netherlands, understanding nutrient depletion risks and mitigation strategies is crucial for practitioners (Albrecht & Wiek, 2021; Roodhof, 2024). As more farms adopt CAS principles, deficiencies in K, N, and other nutrients will likely become more apparent in the coming years. Addressing these challenges proactively allows farmers to maintain soil fertility, sustain long-term productivity, and avoid unexpected declines in yields. By implementing effective nutrient management strategies such as selecting appropriate species, optimizing pruning cycles, and considering targeted amendments, CAS practitioners can tailor solutions that suit their specific systems. This study provides a foundation for informed decision-making to prevent nutrient imbalances before they severely constrain food production and system functioning.

Reflection on methodology

The methodological approach employed in this study offers a comprehensive framework for quantifying nutrient flows in Complex Agroforestry Systems (CAS). A key strength of the method is that it successfully integrates nearly all relevant nutrient flows within the system, ensuring that each value is derived from either an academic source or a validated expert tool such as

Rekentool 5.1. This reliance on scientifically established sources enhances the robustness and credibility of the nutrient budget calculations, reducing the risk of subjective estimations or arbitrary assumptions as recommended by previous studies (Pepels, 2019).

Additionally, the methodological design of maintaining similar species across the five CAS sites, but with varying quantities, presents a comparative framework for assessing differences in species-specific nutrient cycles. This approach allows for meaningful comparisons between different agroforestry designs while minimizing confounding variables related to species composition. Furthermore, the inclusion of different production zones with distinct tree compositions and productivity levels enhances the depth of analysis, enabling a clearer understanding of how tree species and planting densities influence nutrient flows within these systems. Planting densities influence on nutrient cycling was a recommendation from previous studies on investigating the spatial arrangements of trees in agroforestry systems (Cardinael et al., 2020; Andrade et al., 2022). Another notable strength of this approach was the use of averaged data from multiple studies for species-specific nutrient concentrations. This practice helped to mitigate the impact of outlier values that may have emerged from individual studies with atypical environmental conditions or methodological differences, leading to a more balanced and representative dataset.

Beyond the comparative strength of the model, another methodological advantage is that it allows for each of the five farms to have its own independent evaluation of nutrient cycling, closely linked to its specific design. This action based research enhances the practical applicability of the results, as farmers and practitioners can directly relate nutrient flows to their respective agroforestry setups (Personal communications, 2024). Instead of being overly theoretical or generalized for CAS systems, this approach makes the findings more actionable by providing case-specific insights, making it easier to identify system-specific challenges and potential nutrient management strategies.

Despite these strengths, some methodological challenges were encountered, which highlight areas for improvement in future research. One major limitation was the inconsistency in available literature on the nutrient content of specific species, particularly when attempting to gather comprehensive data for multiple plant components such as fruits, woody biomass, and leaves. The variability in sources often required compiling data from multiple studies conducted in different climatic conditions, soil types, and management systems. This limitation was also observed in similar studies where data was gathered from agricultural, forestry, ecology and lithology fields which all have different approaches (Pepels, 2019). While this approach provided necessary input values, it also introduced potential sources of error, as nutrient concentrations can be highly context-dependent. Future studies could benefit from conducting primary measurements of nutrient content in key agroforestry species components to improve the specificity and accuracy of input values.

There are also some elements in the method that indicate that the values are too conservative, this is the case with the spacing allocated to supporting species which is determined at their age of maturity (see annex.4). This decision has made the model limited in fully representing the

syntropic aspect of chopping densely planted pioneer trees as they grow to reduce tree density over time (Götsch, 1994). The calculations of this study do not include the nutrients from those chopped trees which are not included in the mature system and therefore may lead to a lower more conservative estimate of the nutrients included from plant biomass.

Another area of improvement for future studies is to include deeper soil levels of nutrients, in this study the data available on soil samples only gave us data from the first 25 cm of the soil. This top layer does contain the most nutrients but does not give a full picture of the soil nutrient content and the ability of perennials to access those deeper soil nutrients are not quantified in this study (Cardinael et al., 2020; Raj et al., 2024).

To further improve the accuracy of nutrient estimations in CAS, future research should prioritize direct sampling of plant components from similar food forests. Specifically, conducting leaf nutrient analyses for the 13 selected species, measuring woody biomass nutrient content, and including branch nutrient content would provide a more detailed picture of nutrient storage and fluxes in tree components. This is particularly relevant as branch nutrient composition differs from trunk composition, yet branches were not explicitly accounted for in this study (Salazar Iglesias et al., 2010). Incorporating these additional measurements would provide a more precise dataset and allow for better calibration of nutrient cycling models within CAS as done in previous studies (Lokin, 2024).

It is important to note that many perspectives on quantifying the nutrient cycling have not been accounted for in this study and would be needed in future research on the nutrient cycles in CAS. The element of biomass growth, nutrient availability for plant uptake, the decomposition rate of litter and how fast it can be uptaken by the CAS, the role of mycorrhiza in decomposition and nutrient cycling are all key elements of CAS that have been mentioned in other studies but was not undertaken which would strengthen all further research on this field (Pepels, 2019; Cardinael et al., 2020; Kim & Isaac, 2022; Steinfeld et al., 2024).

Finally, it is important to emphasize that the nutrient cycle model developed in this study does not aim to provide exact nutrient quantities within CAS systems, but rather to present a scale of nutrient fluxes and stocks within these systems. Given the complexity and variability of agroforestry environments, precise nutrient quantification at the system level remains a challenge. Instead, this model serves as a diagnostic tool to highlight relative nutrient balances, potential depletion risks, and areas for nutrient input optimization. By providing an overview of nutrient movement rather than absolute values, the model offers a valuable decision-making framework for CAS practitioners seeking to enhance the circularity of their systems.

Overall, while the methodology provided a strong foundation for assessing nutrient dynamics in CAS, improvements in data specificity, site-matching of literature sources, inclusion of deeper soil nutrient stocks, and the integration of direct sampling efforts could further enhance the accuracy and applicability of future research in this field.

Conclusion:

This study has highlighted the challenges of nutrient depletion, particularly for K, which remains the dominant nutrient export across all CAS farms, regardless of system variability. While the specific nutrient export rates differ among farms, K consistently represents the majority of losses, making its depletion a critical management concern. The study also highlights a positive outlook on the other 3 nutrients N, P and Ca which in all scenarios and all CAS are still present in the soil after 50 years. Highlighting the possible self-sustaining capacity of the CAS in regards to these nutrients. Findings confirm that internal cycling through pruning and nature zone inputs alone cannot sustain long-term nutrient balances. The study underscores the importance of initial soil nutrient stocks, species selection, and external amendments in maintaining productivity.

Practical management strategies such as hazelnut shell recycling, optimized ryegrass utilization, and supplementary nutrient inputs have been identified as key approaches to mitigating depletion risks. These nutrient management strategies have been highlighted in this study as possible solutions but further research is needed to identify the extent of these methods in achieving self-sufficiency in CAS. Furthermore, as CAS adoption increases across the Netherlands, farmers must proactively address nutrient deficiencies to ensure sustainable, resilient food systems. By understanding the risks associated with nutrient depletion and implementing targeted interventions, CAS practitioners can enhance soil fertility and maintain productivity over the long term. Future research should continue exploring tailored nutrient management approaches while incorporating the limitations addressed, emphasizing site-specific solutions that align with CAS practitioners' ecological, economic and agronomic goals.

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ANNEX:

Annex:1: Soil analysis of the 5 farms and their respective CAS from the Eurofins sample

CAS	Soil sample ID	CAS zone	Soil Type	Bulk density (kg/m3)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (kg/ha)	N target range (kg)	P target range (kg)	K target range (kg)	Ca target range (kg)
Bonenbos	AJz1 Bonenbos	CAS II	Light clay	1316.00	8520	3000	695	13485	5050 - 7580	2155 - 3015	595-990	12225 - 15560
	AJz2 Bonenbos	CAS I	Clay	1320.00	8710	2880	760	14455	4860 - 7290	2160 - 3025	600-1000	13015 - 16560
Åkern	AKz1 Åkern	CAS I, II & IV	Sand	1320.00	6670	2115	195	2320	6440 - 9660	2160 - 3025	300-500	2605 - 3310
	AKz2 Åkern	CAS III & IV	Loamy sand	1381.00	4180	1490	150	1105	5080 - 7620	2260 - 3165	295-495	2725 - 3465
	AKz3 Åkern	NA	Sand	1285.00	7710	1695	350	3710	7300-10950	2105-2945	340-565	4240-5395
Hoevet Mariën	Alz1 t Mariën	CAS II	Sand	1504.00	4060	2740	355	2410	3130 - 4690	2460 - 3445	340-565	2965 - 3775
	Alz2 t Mariën	CAS I & II	Sand	1475.00	4650	2010	330	2585	3780 - 5660	2415 - 3380	340-565	2910 - 3700
	Alz3 t Mariën	CAS IV	Sand	1485.00	4710	1540	390	3125	3450 - 5170	2430 - 3405	340-565	2930 - 3725
	Alz4 t Mariën	CAS II & III	Sand	1476.00	4390	3125	230	2095	3900 - 5840	2415 - 3380	320-535	2910 - 3705
Eetmeerbosch	AXz1 Eetmeerbosch	NA	Loam	1377.00	7920	2540	200	8180	4960-7440	2255-3155	520-865	8930-11365
	AXz2 Eetmeerbosch	CAS I	Light clay	1249.00	11180	2520	255	8705	6990-10490	2045-2860	560-935	10180-12960
	AXz3 Eetmeerbosch	CAS II	Light clay	1282.00	11090	2390	140	8300	6670-10000	2100-2940	500-835	9430-12000
Middenbos	AMz1 Middenbos	CAS I & III	Loam	1382.00	8190	2155	380	3240	5420 - 8130	2260 - 3165	350-580	3930 - 5000
	AMz2	CAS	Sandy	1362.0	6950	1410	215	2875	5560-	2230-	330-5	3305-4

	Middenbos	III	loam	0					8340	3120	45	205
	AMz3 Middenbos	CAS II & IV	Sandy loam	1335.00	7340	1940	300	2815	6300-9450	2185-3060	315-525	3035-3865
	AMz4 Middenbos	NA	Sandy loam	1385.00	5960	1905	325	2395	5430 - 8140	2265 - 3175	310-515	2730 - 3475
DenFoodBosch	DFB1		Sand	1463.00	1810	580.00	135.00	800.00	1640-2460	225-285	130-215	1155-1470

Legend:

Target range from Eurofins	
Low	
Quite low	
Good	
Quite high	
High	

Annex.2: Amount of plants of each species in each of the CAS as designed by Jordy van Eijk

Species planted	**Mariën Z I**	**Mariën Z II**	**Mariën Z III**	**Mariën Z IV**	**Bonenbos Z I**	**Bonenbos Z II**	**Eetmeerbosch Z I**	**Eetmeerbosch Z II**	**Middenbos Z I**	**Middenbos Z II**	**Middenbos Z III**	**Middenbos Z IV**	**Åkern Z I**	**Åkern Z II**	**Åkern Z III**	**Åkern Z IV**
Red currant	453	0	0	0	113	100	461	0	492	1200	0	0	250	55	0	0
Pear (Pyro)	24	0	0	0	19	50	22	0	18	0	0	0	50	0	0	0
Pear (Kirch)	0	0	3	0	2	0	0	0	8	0	0	0	0	0	30	0
Mulberry	37	0	0	0	9	30	14	0	28	0	0	0	50	10	0	0
Apple M26	191	27	12	0	57	80	37	0	78	0	0	0	50	10	30	0
Appl	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0

e M25																
Autumn Olive	50	0	0	0	40	50	13	0	18	250	0	0	25	10	0	0
Walnut	0	21	0	0	0	30	0	0	0	40	0	0	0	3	24	0
Hazel	12	0	10	0	2	30	0	0	3	120	0	0	0	0	50	0
Honeyberry	174	0	0	0	25	100	60	0	65	0	0	0	250	55	0	0
Chestnut	0	10	0	0	0	0	0	0	0	30	0	0	0	0	0	0
Linden	23	20	24	15	10	28	0	0	40	146	256	72	24	20	44	51
Willow	6	5	6	4	2	7	33	32	10	37	64	18	6	5	11	13
Alder	4	3	4	3	2	5	7	22	7	25	44	13	4	3	8	9
Birch	4	3	4	3	2	5	0	0	7	25	44	13	4	3	8	9
Poplar	6	5	0	4	2	7	0	32	10	70	64	18	6	5	11	13

Annex.3 Substitution species for indicator species and the respective component changed.

Indicator species	**Substitute species**	**Element of substitution**	**Justification**	**Source**
Autumn olive (*Elaeagnus umbellata*)	Black Locust (*Robinia pseudoacacia*) & Black alder (*Alnus glutinosa*)	Biomass and leaves nutrient content (Black Locust), Calcium in biomass (Black alder)	Both N-fixating, similar growth rate and climate preferences	Personal communication, Jody van Eijk, 2024
White mulberry (*Morus alba*)	Hazelnut (*Corylus avellana*)	Biomass nutrient content	Similar woody structure and growth rate	
Redcurrant	Hazelnut (*Corylus*	Biomass nutrient	Similar woody	

(*Ribes rugrum*)	*avellana*)	content	structure and growth rate	
Honeyberry (*Lonicera caerulea*)	Blueberry (*Vaccinium corymbosum*) & hazelnut (*Corylus avellana*)	Fruit (blueberry) and biomass nutrient content (hazelnut)	Similar berries and woody structure as hazelnut	

Annex.4: Spacing given for each species based on their maximum growth size.

Species	**Spacing**	**Plants per ha at full growth**	**Explanation**	**Source**
Redcurrant	3x3	1111	Shrub	From previous planting, and food forest designing experience of Jordy van Eijk (Personal communications, 2025)
Pear (Pyro)	3x3	1111	Dwarf size fruit tree	
Pear (Kirch)	6x6	278	Full size tree with minimal management	
Mulberry	6x6	278	Full size tree with minimal management	
Apple M26	3x3	1111	Dwarf size	
Apple M25	6x6	278	Full size tree with minimal management	
Autumn Olive	4x2	1250	Will be pruned to stay on 2m wide strips	
Walnut	10x10	100	Will be left to grow at full size	
Hazel	4.5x4.5	494	Denser than shrubs	
Honeyberry	3x3	1111	Shrub	
Chestnut	10x10	100	Will be left to grow at full size	
Alder	6x6	278	Crowned upwards	
Linden	2.5x.25	1600	They are kept small	
Willow	5x5	400	They get pollarded so they grow less wide	
Poplar	5x5	400		
Birch	6x6	278	Crowned upwards	

Annex.5: Correction factors (%) from Rekentool 5.1 monocultural yields given to each CAS for each scenario

Farms	**Mariën**			**Bonenbos**			**Eetmeerbosch**			**Middenbos**			**Åkern**		
Yield % from monoculture for 3 scenarios	70	50	40	70	50	40	70	50	40	70	50	40	70	50	40
Soil correction factor	80	60	40	100	80	70	90	70	50	90	70	50	80	60	40
Final % of the monocultural yields	56	40	16	70	40	28	63	35	20	63	35	20	56	30	16

Annex.6: All yearly inputs and ouputs of the CAS and their values (excluding harvest and prunings)

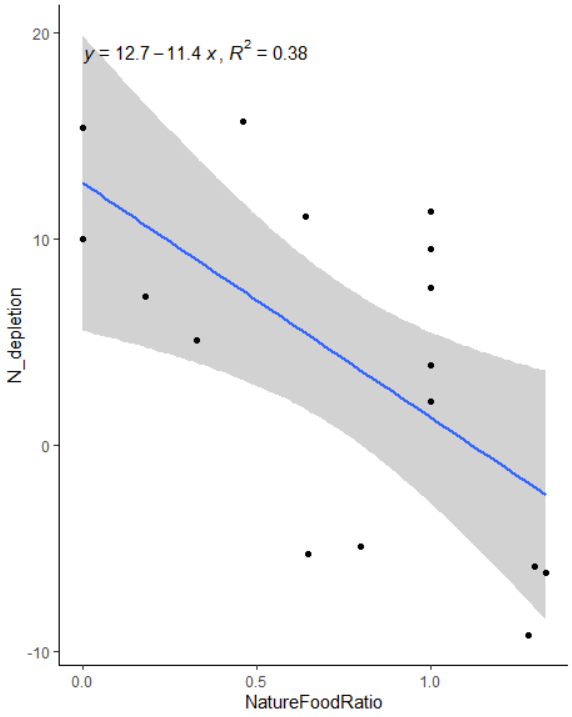
Inputs (+) and outputs (-)	**Nitrogen/kg/ha/y**	**Phosphorus/kg/ha/y**	**Potassium/kg/ha/y**	**Calcium/kg/ha/y**	**Sources**
Weathering (+)	0	0.1	2.57	0.27	All sources can be found in the Annex.9
Deposition (+)	27.83	0.13	1.75	5	
Leaching (-)	20.74	0.05	2	7	
N-fixing Alder (+)	175	NA	NA	NA	
N-fixing Autumn olive (+)	187.5	NA	NA	NA	

Annex.7: Nutrient content per kg of harvest from all food producing indicator species.

Nutrient content per kg	**N-content g/kg**	**P-content g/kg**	**K-content g/kg**	**Ca-content g/kg**
Apple	1.4	0.335	4.575	0.285
Pear	3	0.75	11	0.75
Mulberry	8.3	2.35	7.18	1.21
Hazelnut + shell	16.57675	2.733375	43.442125	9.908625
Walnut + shell	16.664	2.71822	4.2334	5.51492

Chestnut + shell	3.46	0.6375	3.04375	0.595
Blueberry (similar honeyberry)	1.12	0.13	0.86	0.12
Autumn olive	6.4	0.3615	1.846	0.29065
Currants	2.25	0.515	2.985	0.44

Annex.8: Linear model regression analysis for N,P,K and Ca between their soil depletion percentage and the nature/food surface area.



Call:

lm(formula = N_depletion ~ NatureFoodRatio, data = Victor)

Residuals:

Min	1Q	Median	3Q	Max
-10.5693	-3.8543	-0.9776	5.7917	9.9452

Coefficients:

	Estimate	Std. Error	t value
(Intercept)	12.710	3.334	3.812

NatureFoodRatio -11.356 3.863 -2.940

Pr(>|t|)

(Intercept) 0.00191 **

NatureFoodRatio 0.01076 *

Signif. codes:

0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

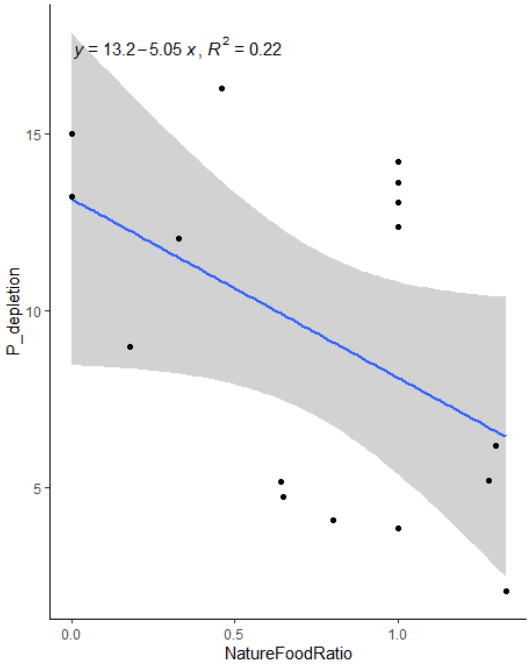
Residual standard error: 6.654 on 14 degrees of freedom

Multiple R-squared: 0.3817,

Adjusted R-squared: 0.3375

F-statistic: 8.642 on 1 and 14 DF, p-value: 0.01076

- **SIGNIFICANT AT p<0.1 THRESHOLD, NOT SIGNIFICANT AT p<0.05**



Call:

lm(formula = P_depletion ~ NatureFoodRatio, data = Victor)

Residuals:

	Min	1Q	Median	3Q	Max
	-5.1290	-4.2855	-0.1708	4.4304	6.1052

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	13.162	2.193	6.001	3.25e-05	***
NatureFoodRatio	-5.050	2.541	-1.988	0.0668	.

Signif. codes:

0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

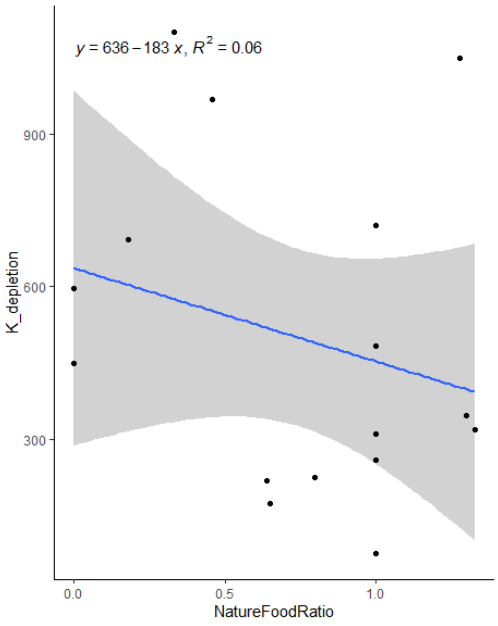
Residual standard error: 4.377 on 14 degrees of freedom

Multiple R-squared: 0.2201,

Adjusted R-squared: 0.1644

F-statistic: 3.951 on 1 and 14 DF, p-value: 0.06676

- **SIGNIFICANT AT p<0.1 THRESHOLD, NOT SIGNIFICANT AT p<0.05**



Call:

lm(formula = K_depletion ~ NatureFoodRatio, data = Victor)

Residuals:

Min	1Q	Median	3Q	Max
-377.7	-211.3	-62.9	133.5	647.5

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	635.9	162.4	3.915	0.00156 **
NatureFoodRatio	-182.9	188.2	-0.972	0.34760

Signif. codes:

0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

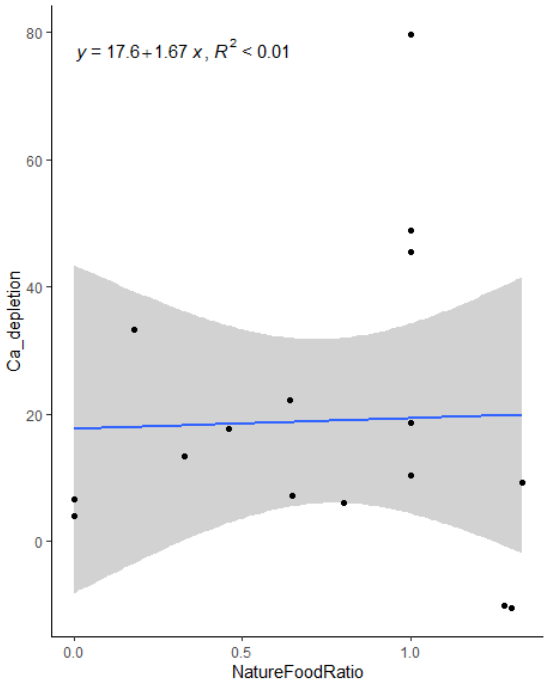
Residual standard error: 324.2 on 14 degrees of freedom

Multiple R-squared: 0.0632,

Adjusted R-squared: -0.003709

F-statistic: 0.9446 on 1 and 14 DF, p-value: 0.3476

- **NOT SIGNIFICANT**



Call:

lm(formula = Ca_depletion ~ NatureFoodRatio, data = Victor)

Residuals:

Min	1Q	Median	3Q	Max
-30.282	-11.855	-6.931	6.469	60.364

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	17.63	12.05	1.463	0.165
NatureFoodRatio	1.67	13.96	0.120	0.906

Residual standard error: 24.05 on 14 degrees of freedom

Multiple R-squared: 0.001021,

Adjusted R-squared: -0.07033

F-statistic: 0.01431 on 1 and 14 DF, p-value: 0.9065

- **NOT SIGNIFICANT**

Annex.9: Sources for all the components and species used in the calculations.

Source	**Type of data collected**	**Species or Variable covered**
(Cheng & Raba, 2009)	Food and woody biomass nutrient content	Apple
(Hummer & Barney, 2002)	Food nutrient content	Apple, currant (red & black)
(Buwalda & Meekings, 1990)	Food nutrient content	Pear
(Jiang & Nie, 2015)	Food nutrient content	Mulberry
(Ercisli & Orhan, 2007)	Food nutrient content	Mulberry
(Müller et al., 2020)	Food nutrient content	Hazelnut
(Özenç et al., 2014)	Food nutrient content	Hazelnut
(Wei & Zhai, 2010)	Food nutrient content	Hazelnut
(Azizov et al., 2021)	Shell nutrient content	Hazelnut shell
(Demirbas, 2008)	Shell nutrient content	Hazelnut shell %
(Korkmaz et al., 2024)	Food nutrient content	Walnut
(Lavedrine et al., 2000)	Food nutrient content	Walnut
(USDA, 2019)	Food nutrient content	Walnut, Chestnut
(Morales et al., 2022)	Shell nutrient content	Walnut shell %
(Queirós et al., 2020)	Shell nutrient content	Walnut shell
(Morana et al., 2017)	Shell nutrient content	Chestnut shell %
(Rodrigues et al., 2015)	Shell nutrient content	Chestnut shell
(USDA, 2022)	Food nutrient content	Blueberry (used for honey berry)
(Ahmad et al., 2006)	Food nutrient content	Autumn Olive

(Khanzadi, 2012)	Food nutrient content	Autumn Olive
(Han et al., 2011)	Leaf nutrient content & leaf quantity of food species/ha	Apple & Apple Orchard
(Jivan & Sala, 2014)	Leaf nutrient content	Apple
(Lokin, 2024)	Leaf nutrient content	Apple, Pear, Hazelnut, Walnut, Currant
(Neto et al., 2009)	Leaf nutrient content & leaf quantity of food species/ha	Pear & Pear Orchard
(Iheshiulo et al., 2019)	Leaf nutrient content	Honeyberry
(Drossopoulos et al., 1996)	Leaf nutrient content	Walnut
(Bhattarai & Tomar, 2009)	Leaf nutrient content	Walnut
(Ponder, 1983)	Leaf nutrient content	Walnut
(Kim et al., 2001)	Leaf nutrient content	Mulberry (White)
(Levickienė et al., 2018)	Leaf nutrient content	Mulberry
	Leaf nutrient content	Grass
(Brink et al., 2006)	Leaf nutrient content	Ryegrass
(Walia & Dick, 2016)	Leaf nutrient content	Ryegrass
(Smith et al., 1985)	Leaf nutrient content	Ryegrass
(Rytter & Ericsson, 1993)	Leaf nutrient content	Willow
(Uri et al., 2003)	Leaf and woody biomass nutrient content	Alder
(Hrdlička & Kula, 2024)	Leaf nutrient content	Alder
(Yuldashev et al., 2021)	Leaf nutrient content	Little leaf linden and Birch
(Özyazici & Açikbaş, 2020)	Leaf nutrient content	Little leaf linden
(Hagen-Thorn et al., 2004)	Leaf and woody biomass nutrient content	Little leaf linden
(Seastedt et al., 1983)	Leaf nutrient content	Black locust (used for Autumn olive)
(Berg & Staaf, 1987)	Leaf nutrient content	Birch

(Salazar Iglesias et al., 2010)	Leaf and woody biomass nutrient content	Chestnut
(DesRochers et al., 2006)	Leaf nutrient content	Poplar
(Pardon et al., 2017)	Leaf quantity support species per ha	Poplar arable alley cropping fields
(Zhang, 1999)	Leaf quantity support species per ha	Poplar intercropping
(Wotherspoon et al., 2014)	Leaf quantity support species per ha	Poplar and Walnut Agroforestry
(Dold et al., 2019)	Leaf quantity support species per ha	Oak Silvopasture
(Ramananjatovo et al., 2024)	Leaf quantity food species per ha	Apple agroforestry
(Graß et al., 2020)	Grass quantity in agroforestry per ha	Grass/clover AFS 2 cuts
(Ehret et al., 2015)	Grass quantity in agroforestry per ha	Grass/clover AFS
(Larsen et al., 2018)	Woody biomass nutrient content	Willow
(Côté & Camiré, 1985)	Woody biomass nutrient content and N-fixing rate	Alder
(Hytönen & Saarsalmi, 2009)	Woody biomass at mature age and nutrient content	Willow, Alder and Birch
(Paschke et al., 1989)	Woody biomass nutrient content, N-fixing rate and woody biomass content tree at mature age (walnut)	Alder, Autumn olive (n-fixing rate), Walnut
(Sorrenti et al., 2017)	Woody biomass nutrient content	Apple, Pear
(Tappeiner & John, 1973)	Woody biomass nutrient content	Hazelnut (used also for currant)
(goodman et al., 2013)	Woody biomass nutrient content	Walnut
(Bañados et al., 2006)	Woody biomass nutrient content	Blueberry (used for honey berry)
(Li et al., 2013)	Woody biomass nutrient content	Black locust (used for Autumn olive)
(Morhart et al., 2013)	Woody biomass nutrient content	Poplar
(Čihák et al., 2014)	Woody biomass content tree at mature age	Linden
(Johansson & Karačić, 2011)	Woody biomass content tree at mature age	Poplar
(Winzer et al., 2017)	Woody biomass content tree at mature age	Apple and Pear
(Monarca et al., 2009)	Woody biomass content tree at mature age	Hazelnut (also used for Autumn

		olive)
(Jacobs et al., 2009)	Woody biomass content tree at mature age	Chestnut
(Nemeth et al., 2017)	Woody biomass content tree at mature age	Blueberry (used for honey berry & currant)
(de Vries et al., 2020)	Weathering, Leaching, Atmospheric Deposition	NA
(van der Salm., 1999)	Weathering	NA
(Van der Salm., 2006)	Atmospheric Deposition, Leaching	NA