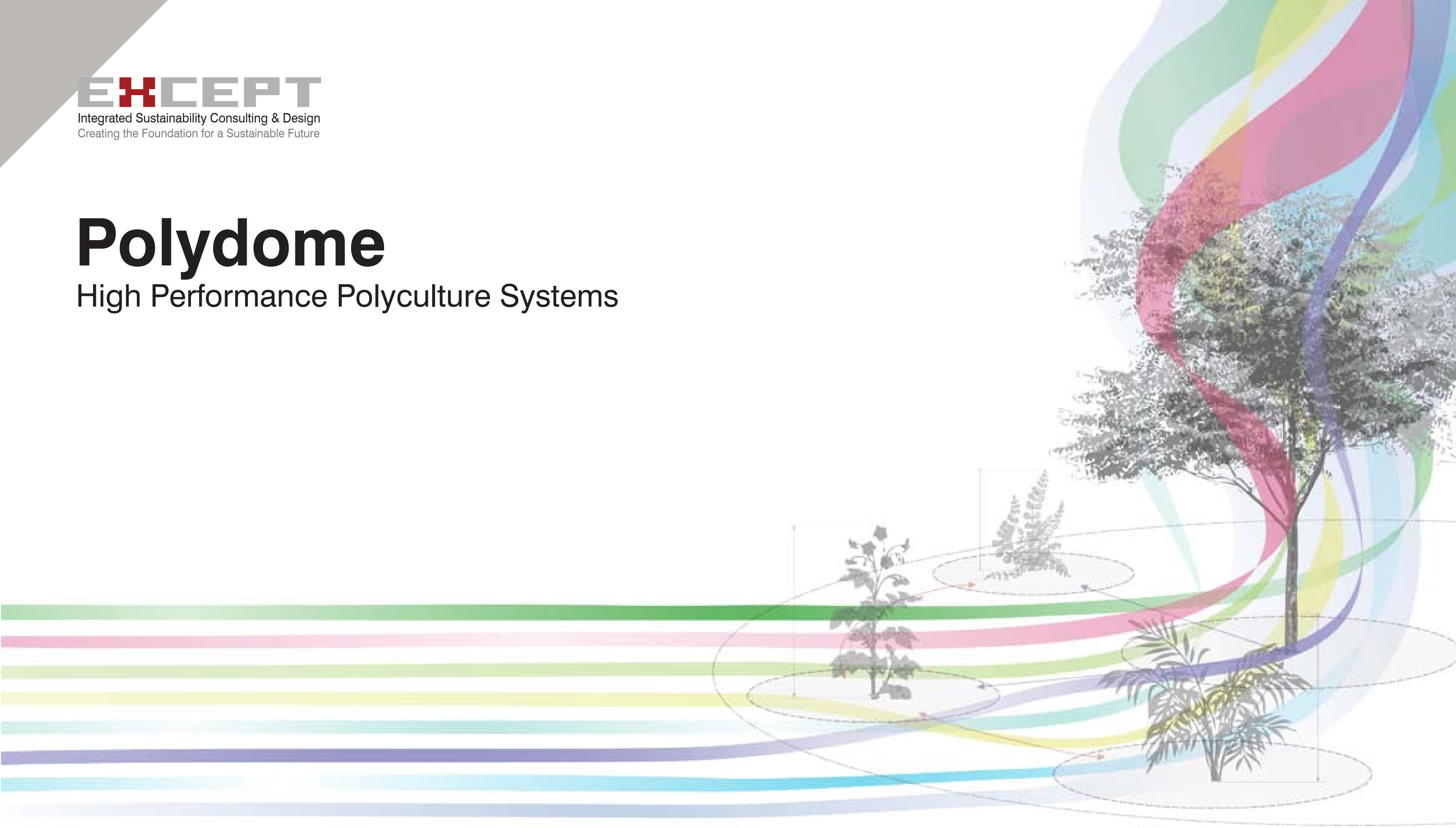
EXCEPT
Integrated Sustainability Consulting & Design
Creating the Foundation for a Sustainable Future

Polydome

High Performance Polyculture Systems



Stichting Innovatie Glastuinbouw Nederland

InnovatieNetwerk
Grensverleggend in Agro en Groen

Printed on:

FSC FOREST STEWARDSHIP COUNCIL

Certified paper.

Version 2.4 - April 15th 2011

ISBN: 978-90-5059-449-3
InnovatieNetwerk Rapportnummer: 11.2.264

Voorwoord SIGN/InnovatieNetwerk

De landbouw is sinds de jaren zestig in de vorige eeuw massaal overgeschakeld op monoculturen. Schaalvergroting en specialisatie waren de credo's om de wereldbevolking efficiënt van voedsel te voorzien. Dat heeft een enorme verhoging van de wereldvoedselproductie opgeleverd. Gaandeweg zien we echter steeds meer de negatieve gevolgen van schaalvergroting en ontkoppelde productiesystemen. Massale aanplant van gewassen kan leiden leidt tot ontbossing, in monoculturen neemt de ziektedruk toe waarvoor chemische gewasbescherming nodig is en intensieve veehouderij gaat gepaard met mest- en mineralenoverschot in ons land.

Schaalvergroting komt voort uit reductionistisch denken. Als we last hebben van schimmels, dan gebruiken we fungiciden, bij vraat van insecten insecticiden. Kunstmest is de oplossing voor een schrale bodem terwijl we een overschot aan organische mest hebben. Stap voor stap neemt de input aan chemische bestrijdingsmiddelen, kunstmest en energie zo toe.

Naast schaalvergroting is specialisatie een belangrijke ontwikkeling: een rozenkweker heeft een heel andere kas dan een potplanten- of tomatenkweker. Telers die afhankelijk zijn van één product hebben echter te lijden van sterke schommelingen op de afzetmarkten. Vanwege hun grootschaligheid moeten ze aan partijen leveren, die voor verdere verkoop en distributie zorg kunnen dragen.

De positieve kant van de Nederlandse glastuinbouw is de extreem hoge productiviteit per vierkante meter; die een reëel perspectief biedt bij een groeiende wereldbevolking. Met programma's als Kas als energiebron is de sector bovendien een voorloper op het gebied van verduurzaming. Ze gebruikt meer en meer natuurlijke middelen om ziekten en plagen in de hand te houden, die niet uit kunnen blijven bij monoculturen.

Wie daarop doorborduurt, komt uit bij een fundamenteel andere benadering: om biodiverse landbouwsystemen te ontwikkelen, die inherent duurzaam zijn doordat de verschillende teelten elkaar positief beïnvloeden. Deze integrale studie van Except legt de grondslag voor kassen, die een grote variëteit aan producten voortbrengen: van kruiden, groente en fruit tot paddenstoelen, honing, kippen en vis.

Dat biedt tal van voordelen: voor ziekten en plagen is een biodiverse kas minder interessant. Bepaalde plantencombinaties blijken te leiden tot gezondere planten. Compostbereiding en paddenstoelenteelt dragen bij aan een hoger CO_2 gehalte in de kas, waardoor de planten beter groeien. Het afval van de ene teelt is de basis voor de volgende. Vanwege het grote aantal producten is het mogelijk direct aan de retail of restaurants te leveren. De rentabiliteit ziet er beter uit dan van reguliere tuinbouwbedrijven, al zijn met name de inkomsten en de hoeveelheid arbeid nog onzekere factoren. Zo'n kassencomplex is ingewikkeld te managen, maar de mogelijke voordelen zijn zo groot, dat we deze route zeker verder gaan verkennen.

Ger Vos
InnovatieNetwerk

Nico van Ruiten
Voorzitter SIGN

SIGN/InnovationNetwork Foreword

Since the 1960s, agriculture worldwide has undergone a mass conversion to monocultures. Scale increases and specialization became the creeds of efficient production. These practices greatly expanded global food output. Over time, however, the negative effects of large, decoupled production systems started to become evident. Large scale farms can lead to deforestation, monocultures of plants require chemical protection from pests and diseases, and intensive livestock production has caused the manure and mineral surplus in our country.

Expanding the scale of agriculture results in reductionist thinking. If we have problems with mold, we apply fungicides. Insecticides are used for insect control. Fertilizer is seen as the solution to poor soils despite our surplus of organic manure. At every step of the way, we rely on the input of chemical pesticides, fertilizers, and fossil energy.

Besides scale increases, we have also seen the rise in specialization. A rose grower has a very different greenhouse from a potted plant producer or tomato grower. Growers who are dependent on a single product can suffer economically from severe market fluctuations. Because of their large-scale output, they are also dependent on third parties for product distribution and sales.

One of the positive sides of Dutch greenhouse horticulture is the extremely high productivity per square meter, which offers a real prospect for meeting the demands of a growing world population. With programs such as Energy Producing Greenhouses, the sector has also made inroads into becoming sustainable. Increasingly, natural approaches are used for disease and pest control.

While elaborating on these themes, this report comes from a fundamentally different approach: to develop bio-diverse farming systems that are inherently sustainable because the various crops are mutually supportive. In this comprehensive study, Except provides a basis for a greenhouse system that will produce a large variety of products: from herbs, fruits, and vegetables to mushrooms, honey, chickens, and fish.

This offers many advantages. Bio-diverse greenhouses are more resistant to the spread of pests and diseases. Certain combinations of plants appear to result in healthier plants. Mushroom compost preparation and cultivation will contribute to a higher CO_2 levels in the greenhouse, improving plant growth. The wastes of one product can be used as the input for the next. Due to the large number of products, it is possible to sell directly to the retail or restaurant supply. The profitability looks better than regular horticulture, though exact income and labor requirements still remain uncertain. Such a greenhouse is complicated to manage, but the potential benefits are so great that we will definitely continue to explore this route.

Ger Vos
Innovation Network

Nico van Ruiten
Chairman, SIGN
Foundation for Innovation in
the Dutch Horticulture Sector

Reading Guide

This report consists of two primary sections:

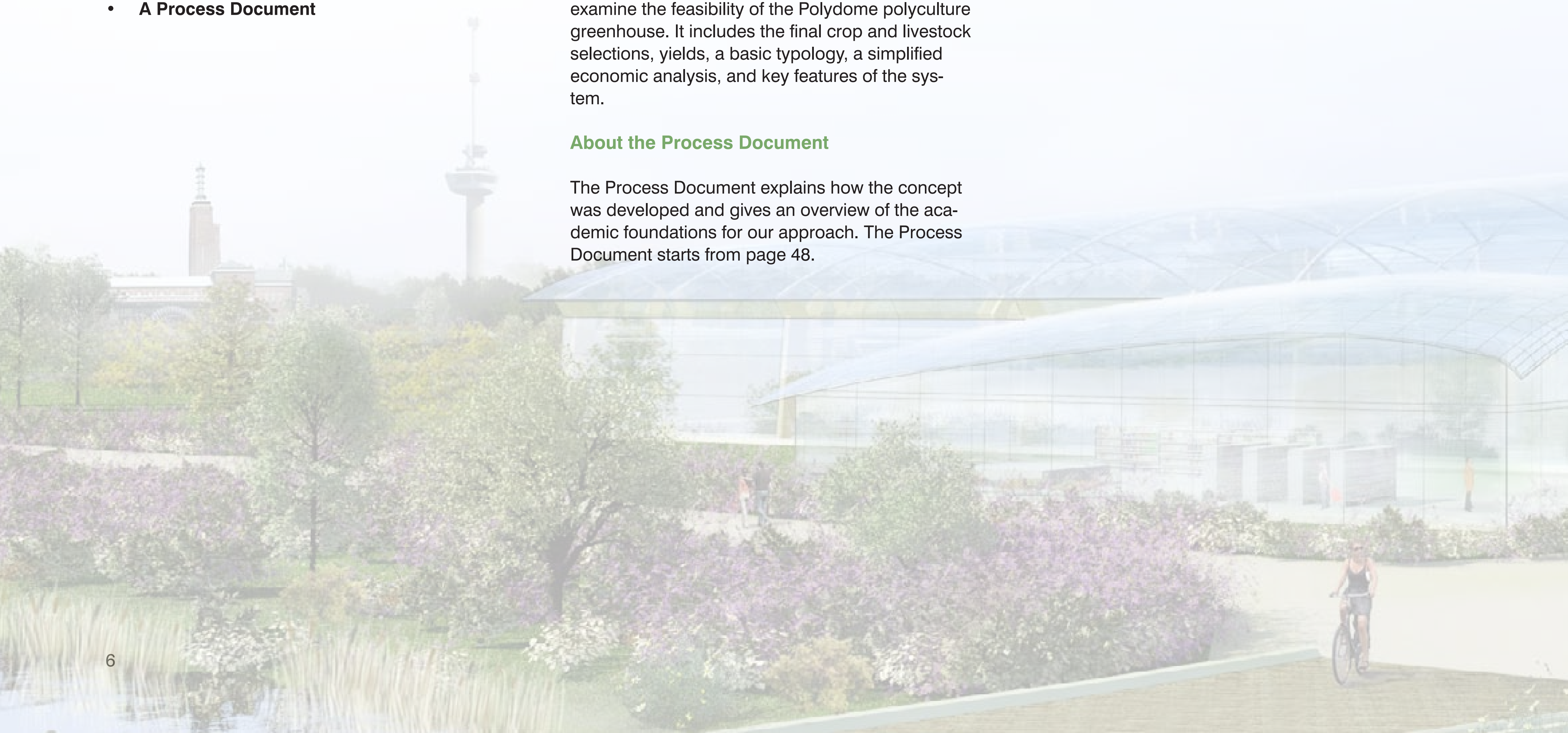
- **A Concept Overview**
- **A Process Document**

About the Concept Overview

The Concept Overview describes the main features of the modeled “test case” that we used to examine the feasibility of the Polydome polyculture greenhouse. It includes the final crop and livestock selections, yields, a basic typology, a simplified economic analysis, and key features of the system.

About the Process Document

The Process Document explains how the concept was developed and gives an overview of the academic foundations for our approach. The Process Document starts from page 48.



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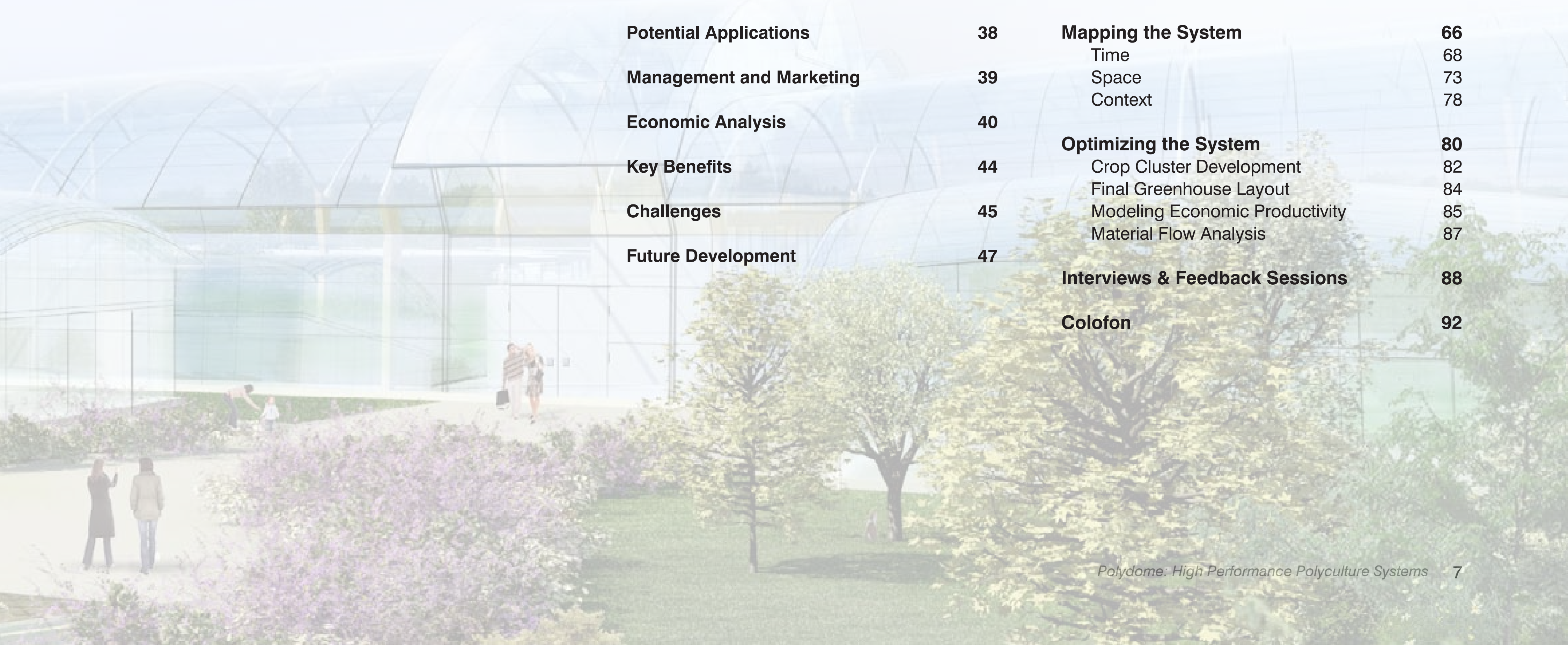

Introduction

Imagining Sustainable Agriculture

Agriculture is central to human existence: to our nourishment, livelihoods, and cultures. Advances in agriculture have driven human civilizations for millennia.

Nevertheless, agriculture is also currently the single greatest source of negative impact that humans have on the planet. It consumes enormous quantities of resources, displaces vast areas of natural ecosystems, and generates enough pollution to dramatically alter global nutrient and atmospheric cycles.

One of the primary challenges we face in the coming few decades is to reinvent and redeploy agriculture as a sustainable industry.

The United Nations estimates that by the year 2050, we might have as many as 14 billion people living on our planet. This is roughly twice our current population. Our planet isn't getting bigger, and our standards of living, including the complexities of our diets, have only continued to increase. We must begin to think creatively about how to double the output of food production.

Agricultural systems will need to efficiently produce healthy and nutritious food as well as provide economic value and satisfying employment. They will need to do this without placing an unmanageable burden on our natural environment.

In this report we describe an approach that we believe could evolve into an innovative and truly sustainable form of agriculture: a new greenhouse production method called Polydome.

The Polyculture Greenhouse
Polydome is a polyculture system, which means that unlike most existing forms of greenhouse production, it has many crop and livestock species growing at once. In the model we describe here, we have included around 50 plant crops, two mushroom crops, chickens, a fish aquaculture component, and several cultivated insect populations (honey bees, worms, and support habitats for other beneficial insects). Rather than trying to maintain absolute control over the process of cultivation, as is currently the case in greenhouse agriculture, the Polydome system is designed to function more like a natural ecosystem, with self-supporting plant and animal interactions.

Such a polyculture system is capable of greatly reducing the environmental impact associated with food production, maintaining the high levels of productivity characteristic of Dutch greenhouses, and also providing a number of economic and social benefits.

Environmental Benefits
On the level of physical impacts, Polydome allows "wastes" created within the system to be reused

internally. For example, plant waste is reused as mulch or fish feed, while animal wastes are processed into nutrient supplements. It also reduces the need for certain costly technological interventions. Rather than shading plants using mechanical screens, shade-loving plants are intercropped below plants with a high demand for direct sunlight. In a similar fashion, supplemental CO_2 is provided by mushroom cultivation, chickens, and composting rather than by CO_2 generators or the combustion of fossil fuels. Our design also takes advantage of temporal and spatial stacking, companion planting, and a number of other approaches that allow for greater production density than in any other cultivation method.

A Community Asset

On a socio-economic level, our model shows that this system is highly profitable. It allows for high-density production, the capture of several high-value niche markets, and savings on a significant number of technological inputs.

Furthermore, because even a small-scale Polydome system produces a broad range of consumable products, it is ideally suited to the emerging production demands of urban, peri-urban, and distributed agriculture.

Where a typical meal currently consists of elements that have been produced in many different countries and shipped from around the world, this single system could provide a large part of local food needs for an entire community. Profits can also be increased by shrinking the length of the logistical chain associated with moving product from production to retail.

Lastly, Polydome is designed to last a minimum of 30 years. This means that an investment can be made in its physical structure and appearance, ensuring that it provides a positive aesthetic contribution to the built environment.

An Opportunity for Innovation

This study was primarily commissioned to explore new pathways for Dutch greenhouse innovation. The Netherlands is the world's leader in greenhouse technology and efficient greenhouse production. However, few innovations have appeared in recent years to signal a new direction for the sector's development. The Polydome system represents a potentially exciting direction for the Dutch greenhouse sector: a way to expand and develop in an environmentally sustainable and economically beneficial way.

Beyond Monoculture

The Economic and Environmental Reasons for Diversification

Worldwide, agricultural production is dominated by monocultures: huge areas of single-species production.

From a satellite's perspective, whole countries can sometimes appear to be single swaths of wheat, corn, or rice. Herds of cattle can be so numerous that from neighboring hills they appear to be ant colonies.

This monoculture approach has changed the face of our planet and the structure of the global economy, often in unexpectedly negative ways.

The Green Revolution completely changed agricultural practices between the 1940s and late 1970s. The major trends in this period were: the introduction of High Yielding Varieties (HYV) of crops, significant increases in chemical use (pesticides, fungicides, synthetic nutrients), increased mechanization, and the introduction of large irrigation projects.

Increases in crop yield per hectare as a result of these changes were truly impressive, and the Green Revolution is often credited with having helped avoid widespread global famine. However, the intensive practices introduced in this period have also resulted in the negative economic and environmental impacts of modern agricultural production.

The move towards large-scale monocultures was both a driver and a consequence of the Green Revolution's trends. Mechanical planting and harvesting is much easier to implement on a large single-crop field. But these large single-crop swaths also increase the need for environmentally and economically costly pesticides and fertilizers. In a monoculture system, plants grow in increasingly depleted soil, while pests are provided with vast, uninterrupted fields of their favorite food.

In the face of ever greater agricultural demand, we must find a new path - one that goes beyond highly mechanized and chemically-reliant monoculture production. However, we can't afford to sacrifice profitability or efficiency. As we move forward, we must first examine the problems of the existing system to avoid repeating its mistakes.

The Cost of Monocultures

Modern Agriculture & the Economy
The arguments for monoculture farming usually center on economics. The primary line of reasoning is that a single crop allows for greater economy of scale and higher efficiency in growth and processing.

Contrary to this reasoning, however, there are also many economic disadvantages of monoculture farming. Even on the level of basic economic logic, when growing only one crop, there is always the risk that the particular crop will fail or that there will be an oversupply on the market.

While it is true that large-scale monocultures offer a certain kind of efficiency gain in terms of crop production, they also cause major efficiency losses:

- through disconnected energy and material cycles.
- through greater demand for costly chemical inputs, such as pesticides and fertilizers.[1]
- as a result of sub-optimal crop density: it is actually possible to produce twice as much food per area than even the most concentrated grain field when using an intercropped and vertically stacked system.
- as a result of inefficient use of space and time: a single crop with a single life cycle experiences non-productive or fallow periods. These could easily be filled in with other productive elements rather than leaving that space or time unused.
- in terms of supply chain length and the demand for transport. Rather than supplying local communities with a diversity of food, large scale monocultures are attuned to supplying the global market with a particular commodity. This approach has resulted in the enormous growth in the number of "food miles" associated with every meal. It also reduces the earnings received by food producers, as every additional link in the chain between them and the consumer cuts into profit margins.

Modern Agriculture & the Environment
Modern agricultural practices have also resulted in some critical global problems:

- Roughly 70% of the world's terrestrial surface is at least partly devoted to agricultural uses,[2] with 40% dedicated purely to crops and

1 *7% of crops were lost to pests at the start of industrial agriculture (1948) compared to around 13% now. This has occurred despite a 20-fold increase in chemical pest control measures. From: Hawken, P., Lovins, A., and Lovins, H.L, (1999), "Natural capitalism: creating the next industrial revolution", New York: Little, Brown, and Company.*

2 *Esty, Daniel C., M.A. Levy, C.H. Kim, A. de Sherbinin, T. Srebotnjak, and V. Mara. 2008. 2008 Environmental Performance Index. New Haven: Yale Center for Environmental Law and Policy.*

pasture land.[3] Our need for agricultural output is estimated to double by 2050. At our current efficiency of production, not enough land remains in order match that need.

- Deforestation associated with agriculture[4] and the chain of activities involved in the production and consumption of livestock[5] are each individually responsible for higher greenhouse gas emissions than the transport sector, which contributes to around 18% of emissions globally.

- Two-thirds of global freshwater withdrawals are used for irrigation.[6] Fifteen to 35% of withdrawals deplete water tables faster than they are naturally replenished.[7]

- Excessive use of fertilizers and pesticides has contributed to the pollution of many water sources, causing both water toxicity and eutrophication (excess nutrients in water, leading to algal blooms and low oxygen conditions).

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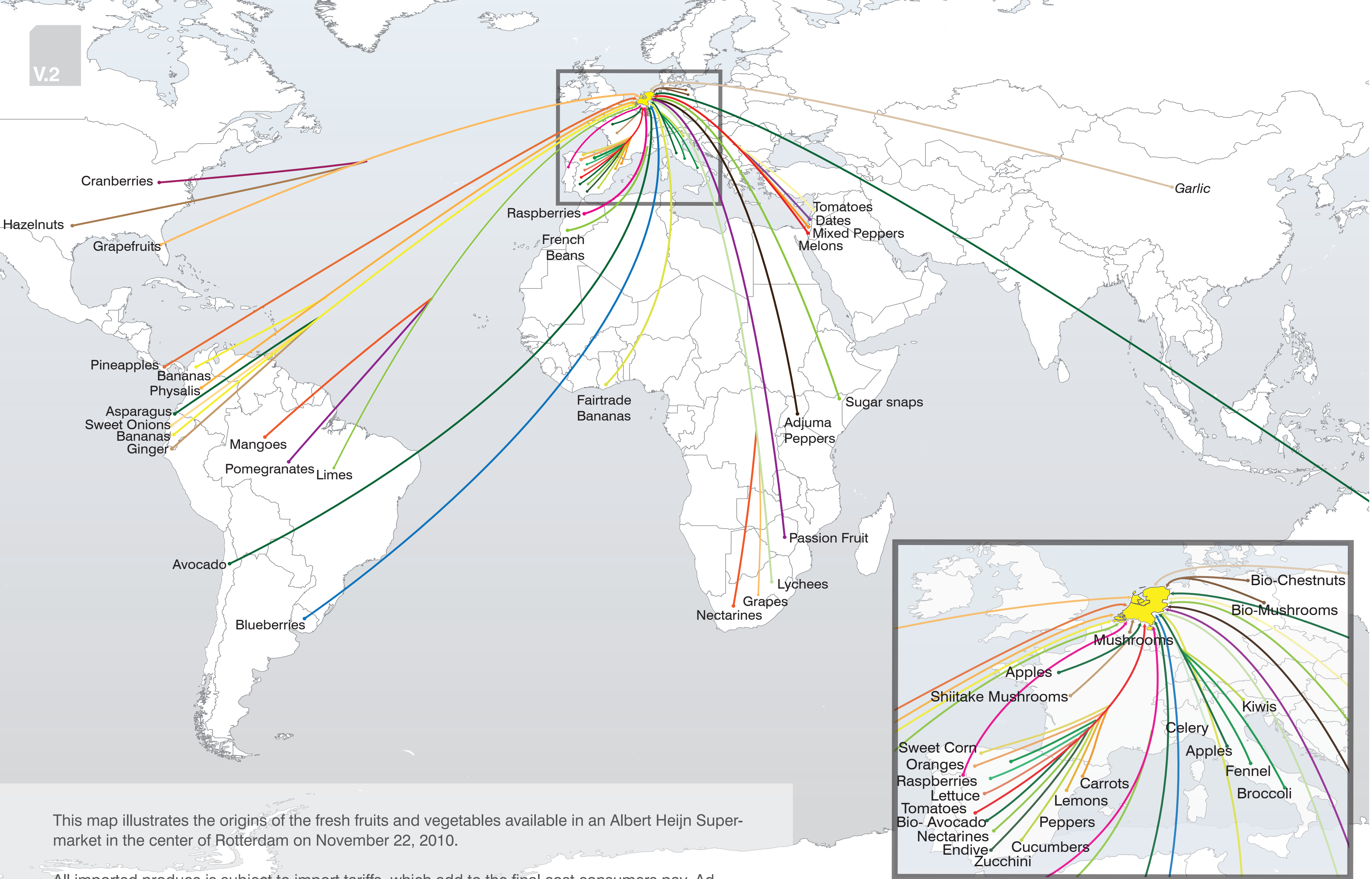
3 *FAO Staff (1995). FAO Production Yearbook 1994 (Volume 48 ed.). Rome, Italy: Food and Agriculture Organization of the United Nations.*

4 *Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N.H., Verardo, D. J., & Dokken, D. J. (2000). Landuse, land-use change, and forestry. Cambridge: Cambridge University Press.*

5 *Steinfeld, Henning et al., 2006. Livestock's Long Shadow: Environmental Issues and Options, U.N. Food and Agriculture Organization, Rome.*

6 *U.N. Food and Agriculture Organization, Aquastat. http://www.fao.org/nr/water/aquastat/water_use/index.stm*

7 *World Business Council on Sustainable Development. 2009. Water, version 2. Facts and Trends.*



This map illustrates the origins of the fresh fruits and vegetables available in an Albert Heijn Supermarket in the center of Rotterdam on November 22, 2010.

All imported produce is subject to import tariffs, which add to the final cost consumers pay. Additionally, the "food miles" and embedded energetic costs of transport can be high, particularly if crops are shipped by air freight.

- Improper soil management and irrigation are leading to widespread desertification, salinification, and erosion of soils.
- A great deal of modern agriculture is now reliant on non-renewable resources, such as fossil fuels (required for the manufacturing of chemicals and the operation of machinery), and phosphorus, a finite mineral deposit.

Certainly, monocultural production is not the only source of agriculture's environmental burden, however, it either exacerbates or is directly related to many of these problems.

Modern Agriculture: A Reductionist Approach
On a fundamental level, monocultural production leads to disconnected material flows. A single plant or animal has a demand for specific inputs (nutrients, water, gases) and produces certain kinds of outputs. When there are many plants and animals together, the wastes of one become the inputs of another, creating a closed material cycle. For example, manure from cattle enriches fields so that livestock can continue to graze on the emerging grasses.

When we separate the different elements of such interacting systems into distinct units, the material flows between them are suddenly disconnected and thrown out of balance. Manure from monocultural animal production facilities is suddenly located too far from any field farming to be worth the cost of transport. Instead of being used as a valuable source of nutrients to replenish the soil, it becomes a waste product, much of it ending up accidentally in water streams. Meanwhile, farmers with field crops rely increasingly on chemical fertilizers made of fossil fuels.

This separation of agricultural crops and livestock into distinct units reflects an underlying trend in modern food production. Our basic approach to agriculture in this latest era has been reductionist: we have attempted to simplify it to its basic elements and control these elements to the best of our ability. To each problem we have responded with a unique technological solution - pests get pesticides, weeds get herbicides. As part of this controlled strategy, rather than using naturally occurring inputs, we have tried to synthesize each input with chemical precision. We now feed natural gas to our crops and concoctions of bone meal and enhanced soy to our cattle.

One of the problems with this approach is that we didn't necessarily know what all the important flows were in the system to begin with, so it is difficult to reconstruct them "correctly."

In a natural ecosystem, healthy soil organisms can improve nutrient uptake by up to ten fold.[8] We exchange this uncharted complexity in favor of more sterile soils which require ten times the application of synthetic chemicals. Likewise, in ecological farming, completely eradicating pests is seen as a mistake; without at least some pests, you can never cultivate a population of predators to keep them in check.

8 *Hawken, P., Lovins, A., and Lovins, H.L, (1999), "Natural capitalism: creating the next industrial revolution", New York: Little, Brown, and Company*

By stripping it of all its complexity, and assuming that we can fill the gaps with synthesized inputs, we create new problems along the way.

A New Way Forward
None of this is to say that we should idealize the simpler approach to agriculture of our agrarian past; a time when most people toiled from morning to night in order to manage their small subsistence farms. Pre-industrial farming left much to be desired in terms of yields, labor requirements, and most other factors against which successful agriculture can be measured, including environmental impact.

It is clear that aside from reducing our reliance on monocultures, we also need to increase the efficiency of agricultural output per unit of fresh water, land, and energetic input. We must find ways to be more productive, meeting the demands of an ever-increasing population, while reducing the impact of our growing footprint. This challenge requires a new way of thinking.

The Polydome concept shows how we can move away from monocultures without regressing into the past. By combining the unique benefits of greenhouses with the many untapped opportunities of polycultures, we create a system that maximizes production density and diversity to a greater degree than any other food production system.

Beyond Monoculture

Greenhouses are a very interesting framework for developing sustainable agricultural solutions. They offer many benefits over traditional outdoor farming, including:

- environmental control for light, temperature, water, and gas concentrations.
- structural framework for logistical and support systems (robots, railings, etc).
- growing season extension or year-round growing capability

Polycultures offer the environmental and economic benefits of reducing damaging and costly chemical inputs. When crops are mixed together, or intercropped, not only do they draw different nutrients from the soil and attract different beneficial soil microorganisms, but they also interrupt the easy spread of pests, in a phenomenon known as pattern disruption. Growing multiple crops also allows the capture of multiple “high-value” product niches and the ability to more flexibly respond to changes in demand.

The Polydome concept illustrates the foundation for an efficient and modern polyculture system, and provides many opportunities for economic, environmental, and social advancement. Though such a system may be unusual compared to present-day greenhouse designs, we believe it represents a promising direction for long-term, sustainable innovation.

Greenhouse Technology

Dutch greenhouse technology is widely recognized as the most advanced in the world. The Netherlands continues to be a global leader in this sector with ambitious goals for improvement. In 2006, the Energy-Producing Greenhouse Transition Programme was launched, with the objective of ensuring that greenhouses built from 2020 onwards be entirely energetically self-sustaining.

Because the physical design of greenhouses is such an active area of research, it is not something we focused on in the development of the Polydome concept. However, any Polydome system will necessarily rely on a combination of existing and emerging energy technologies in order to satisfy the goals of energy self-sufficiency and CO_2 neutrality. Here we present a quick overview of some of the technologies at the forefront of the discussion.

Closed Greenhouses
Most greenhouses are vented during the warmer months of the year to get rid of excess heat and humidity. Closed greenhouses are not vented, which means they accumulate rather than dissipate heat. Cold ground water is pumped through heat exchangers in the greenhouse, cooling the air by absorbing the heat. The now-warm water is pumped back into the ground, where it retains its elevated temperature for many months, acting as a heat battery. In winter, this warm water can be pumped back up to heat the cold greenhouse air.

This approach can provide a total energy savings of around 30% relative to annual demand (the rest consists of electricity needs). A closed greenhouse collects more heat than it needs for its annual heating, which means that it can also export energy to heat neighboring residential areas.

Not venting also leads to higher internal CO_2 concentrations, which can boost yields by over 20% (as shown in a demonstration site operated by company Themato). Reduced exposure to pests also results in lower agrichemical use, while lower rates of evaporation lead to less water consumption.

FiWiHex
Fine Wire Heat Exchangers, or FiWiHexes, are one of the technologies that allow closed greenhouses to work. Using a heat exchanger with a multitude of fine wires increases the surface area available for heat transfer, ensuring a fast and efficient exchange of heat.

Geothermal Heating
Depending on the specific location of a greenhouse, deep well geothermal energy can also be an option for greenhouse heating. One company claims to provide 80% of its total energy in this way.

Integrated Solar Technologies
A variety of solar technologies for greenhouses are in conceptual development or pilot testing stages.

Thermal solar technologies focus on collecting heat (in ways similar to the closed greenhouse approach). Integrated solar photovoltaics are used to generate electricity. The pilot project Elkas was the first greenhouse in the world to produce electricity relying fully on solar technology.

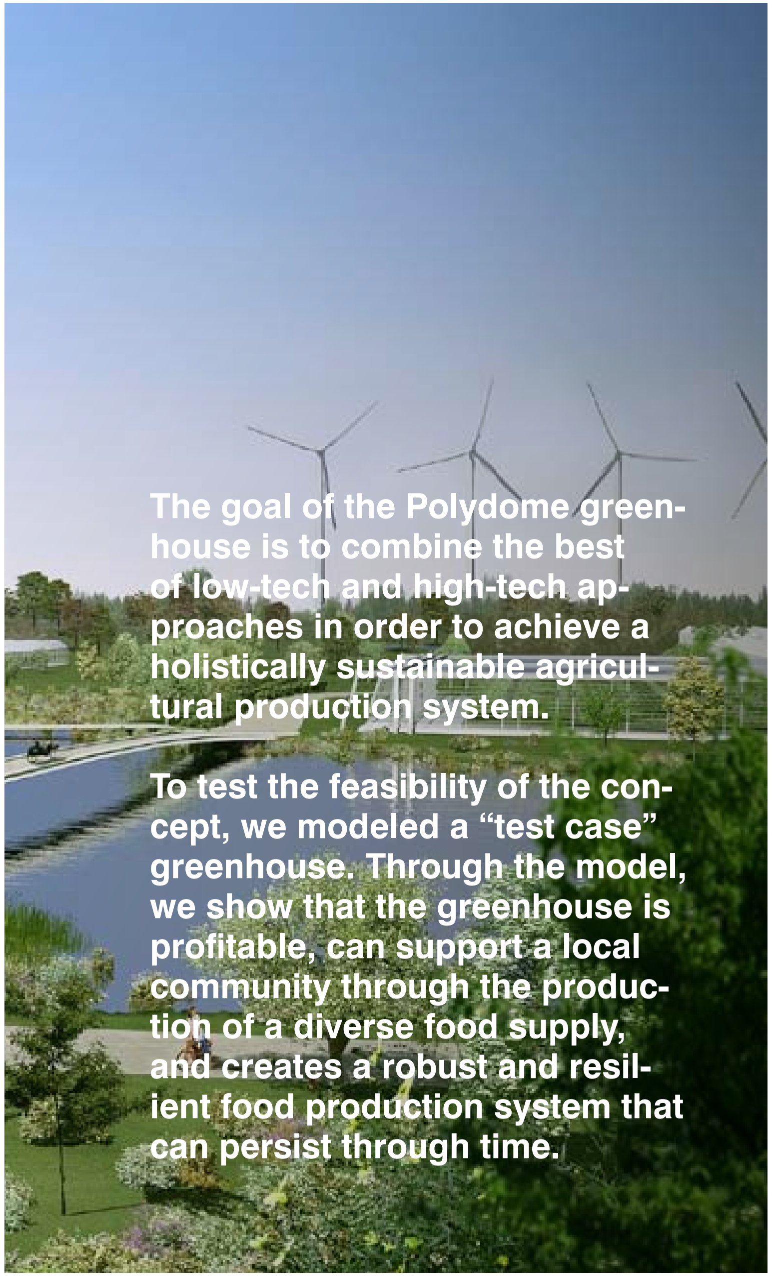
The Daylight System, developed by Technokas, is a unique approach that uses fresnel lenses to convert direct sunlight into electricity while allowing indirect light to be used for plant growth. The lenses focus direct light onto a strip of photovoltaics, and the entire system is water cooled further generating a source of heat capture.

Biogas CHP
Currently, Dutch greenhouses have the capacity for around 3000 MW of Combined Heat and Power (CHP) systems to efficiently generate heat, electricity, and CO_2. The use of CHPs has reduced original greenhouse energy demand by 20 - 30%. However, conventional CHP plants are still dependent on fossil fuel combustion.

With access to sources of biomass (livestock manure, tree coppicing, green waste from cities, etc.), greenhouses can also generate sufficient biogas to power bio-CHP plants on their terrain. Several companies are exploring this route.

Sensor Technologies & LED lighting
A number of innovations in greenhouse operation will eventually lead to greater efficiency and energy savings. Advanced sensor technologies can provide more accurate feedback for when environmental controls are needed. High power LED lighting could offer greater control over the fraction of light spectrum used, while cutting energy demand.


Polydome Concept
Overview



The goal of the Polydome greenhouse is to combine the best of low-tech and high-tech approaches in order to achieve a holistically sustainable agricultural production system.

To test the feasibility of the concept, we modeled a "test case" greenhouse. Through the model, we show that the greenhouse is profitable, can support a local community through the production of a diverse food supply, and creates a robust and resilient food production system that can persist through time.

The case study presented here is a rough approximation of what a Polydome greenhouse might look like in terms of species composition, key flows, basic technological requirements, and economic yield.

We have considered a small, one-hectare model greenhouse containing several modules. There are perennial and annual crops grown in soil; a hydroponic system for fast-growing greens and herbs; a fish aquaculture system; a mushroom module; chickens; and a vermiculture composting system. All nutrient flows are designed to interlink in a cyclical fashion. The system is structured to maximize efficiency over space and time, but not at the cost of environmental damage. This one-hectare model could easily be multiplied to reach any desired size.

Because this is a concept and not a final design, it contains many assumptions and approximations that would need to be resolved prior to setting up an actual pilot project. However, this study can be used as a ballpark guideline for assessing the overall feasibility of Polydome.

Perhaps most importantly, the method that we created for the ecosystem design process can be refined and reused with relatively little effort.[1] The most significant hurdle to establishing an effective Polydome greenhouse is very likely the process of designing it such that all the elements within it work to their maximum potential. We hope that having a simplified methodology for doing this, as described later in this book, will lower the threshold for initiating such a project.

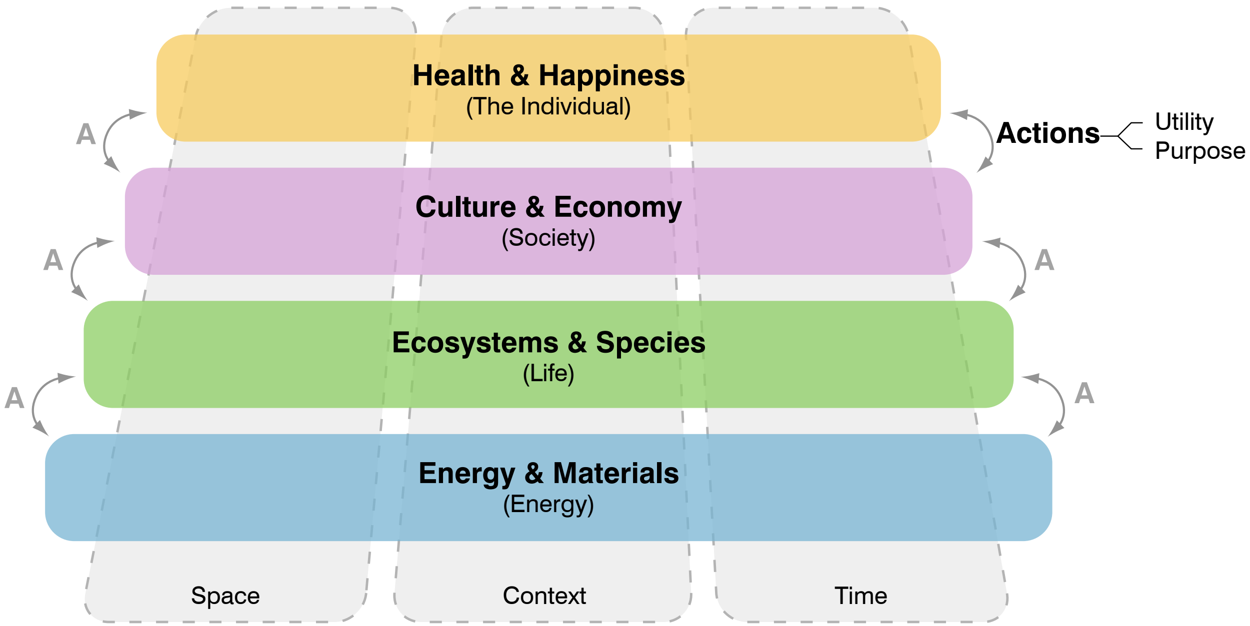
1 *See the process document for a description of the method.*

Performance Criteria

The Polydome Test case was developed using the integrated sustainability development model Symbiosis in Design (SiD). As part of the design process, we also relied on several Industrial Ecology tools and on the principles of Permaculture design.

The first step of any SiD process is the determination of goals. While Polydome was designed to be profitable, the goal of the system is not to maximize profits at the cost of everything else. It is primarily a food production system rather than a money production system.

The SiD categorization method represented in the graphic below, is a convenient means for developing a comprehensive set of performance targets across various areas of concern. We have developed goals for the Polydome system that address each category. These were used as guidelines throughout the design process.



The SiD categorization system, ELSIA, stands for: **E**nergy (Energy & Materials), **L**ife (Ecosystems & Species), **S**ociety (Culture & Economy), the **I**ndividual (Health & Happiness), and **A**ctions.

ENERGY & MATERIALS: GOALS

- The Polydome greenhouse is energetically self-sustaining. All lighting, heating, cooling, filtration, and other operations should be powered by renewable energy sources and managed through structurally-integrated energy technologies.
- It requires low or zero material inputs from outside the system boundaries. Material inputs should be from renewable sources.
- Rainwater collection systems should be installed and water should be conserved to the greatest extent possible.
- Material and energy cycles are closed to the greatest extent possible. The system is designed to recover all local materials of value, approaching or achieving "zero waste" status.
- By satisfying the targets named above, Polydome also supports both climate mitigation and adaptation strategies.

ECOSYSTEMS & SPECIES: GOALS

- The Polydome greenhouse is a polyculture. It has a diversity of plant and animal species coexisting and benefiting from one another.
- It maximizes beneficial plant-plant and plant-animal interactions; relies on natural feedback loops to manage diseases and pests; and uses natural pollination services.
- It derives maximal benefit from natural variations in thermal, lighting, and moisture conditions through crop placement.
- It maximizes productivity per square meter through the stacking of species in both space and time.
- It provides benefits to ecosystems outside of its own; it actively builds soil communities where applicable.
- It considers animal welfare a top priority. Within the system, animals are not treated as “products,” but rather as part of an ecosystem. Their natural behaviors are encouraged rather than restricted.

CULTURE & ECONOMY: GOALS

- The Polydome greenhouse is economically viable within a short- to mid-range time horizon.
- It produces significant quantities of high-quality, marketable products year-round.
- It minimizes difficult and undesirable labor.
- Polydome production is more flexible than normal greenhouse production, making the sector more resilient to economic fluctuation and improving both food security and access.
- It beneficially supports and responds to local food culture.
- It provides opportunities for functions in addition to food production, such as education, social uses, retail, processing, and others.
- It can reduce the demand for food transportation by offering a single point of sale for a wide range of locally produced goods.
- It can be used for longer than a conventional greenhouse, it integrates better into the landscape, and provides a more inspiring environment for workers and visitors alike.

HEALTH AND HAPPINESS : GOALS

- The Polydome greenhouse is a healthy, safe, and enjoyable environment to work in.
- It does not rely on the use of any toxic chemicals or materials that may pose a threat to human or ecosystem health.
- It produces healthy and nutritious food for the local community, long-term food security and improving food access.
- It is a source of enjoyment to both owners and local residents through its role in the community and relevance to the local population.
- It is aesthetically pleasing in its outside appearance, enriching rather than detracting from landscape quality.

Greenhouse Modules
There are two categories of functions in the Polydome greenhouse: production and support.

The primary role of production modules is the output of marketable products, though each one also plays a unique supporting role in the system.

The support modules provide key functions to the greenhouse, such as pollination, pest control, or logistics management.

Hydroponic Crops:
- High profit, quick turnover crops consisting of greens, herbs, and strawberries.
- Produces year-round.
- Runs partially above the soil crops, providing additional vertical stacking.
- Uses recirculated waste water effluent from the fish aquaculture system, which is monitored and supplemented with liquid nutrients from the compost module.

Temperate Crops in Soil:
- Consists of two sub-components: perennials and annuals.
- The annual crop zone is operated year-round and provided with supplementary heat and lighting in winter months.
- The perennial zone is chilled and allowed to go dormant in winter.
- The perennial zone, which primarily consists of crops such as tree fruit, berries, and vegetables such as asparagus and artichoke, takes several years to reach full maturity. In that time, it is intercropped with annual crops to provide additional yields.

Chickens:
- Eggs and meat are sold as products.
- Chickens provide extra CO_2 and heat through vents connected to the main plant zone.
- Chicken manure is collected to enrich compost.
- For several months of the year, the chickens are given free access to the greenhouse to till soil and control pests.

Mushrooms:
- Cultivated in heavily shaded areas of the greenhouse (under rows of hydroponic beds and underneath trellised vines), mushrooms utilize an otherwise unusable space.
- Year-round production of a high value crop.
- Provide a large part of the supplemental CO_2 needed to raise crop yields.

Fish Aquaculture:
- Very high production per m^2 allows for a high output of product.
- Wastewater is used as a primary nutrient input for the hydroponic crops.

Bees:
- Twenty hives are included in a special zone that can be opened either to the outside or inside of the greenhouse for pollination.
- Honey can also be harvested from the hives once a year as a supplemental product.

Vermiculture Compost:
- Processes excess plant and animal wastes into usable compost.
- Liquid extracts from this compost supplement the hydroponic production system.
- Worms cultivated in the compost aerate the soil zones in the main greenhouse.
- Provides extra CO_2 and heat into the main plant zone.

Support Crops:
- Pest repelling crops and dynamic accumulators are interplanted with commercial crops.
- The dynamic accumulators (comfrey, borage) enrich and activate compost.
- The pest repelling crops reduce the need for other pest control measures.

Plant Nursery:
- Contains a germination zone with higher degrees of environmental control as well as an early-stage growth zone.

Logistics Center:
- A central area in the core of the greenhouse is used for crop collection, washing, and preparation for retail.
- The hydroponics channels are uniquely designed to bring crops to a central work station as they mature, creating a central, social work environment.

During the development of the Polydome concept we continuously evaluated what repercussions our decisions might have on the practical aspects of a functioning greenhouse. Polydome is an entirely different way of thinking about agricultural production and we have explored how this approach could translate into a more exciting and better performing food production facility.

While not the focus of this project, which is on the development of the bio-ecological arrangement of the polyculture system itself, we have played a bit with the possible physical designs for the greenhouse, some of which are shown throughout this report.

A Polydome greenhouse could potentially look something like the image to the left, where different ecological elements come together in a spatially efficient and exciting environment. This building could possibly house a variety of functions in addition to agricultural production.

In this image, the hydroponic system is shown suspended above the temperate zone, oriented in a radial pattern so to have minimal impact on crops with high light demand. The underside of the channels can also be affixed with reflective mirrors or supplemental lighting. The plants in the hydro system float on platforms that can be rerouted much like in a postal system, each one using an RFID chip to 'find its way.' A central station sees the plants coming by for regular check-ups and whenever harvesting is required.

On the ground level, the aquaponic fish system winds through the temperate section, collecting filtered drainage water from the watering of the soil.

In the rear of the image, the central processing and logistics section sits on the north side. Beyond that is the tree-zone, which can be sectioned off easily for seasonal chilling.

Why it Works

Self-Supporting System
The basic principle behind the success of a Polydome system is that it is largely self-supporting. Most elements provide a variety of beneficial functions in addition to just producing marketable products: pollination, CO_2, shading, heat, and nutrient exchange, among others. This internal exchange of materials and services reduces the need for many technological inputs as well as certain kinds of labor.

This same principle also structurally avoids the wastage of resources, space, and time. For example, CO_2, which would normally be a waste product in mushroom production alone, becomes a valuable resource in the context of a greenhouse. For these self-supporting functions to operate properly, all available spatial “niches” within the greenhouse must be adequately occupied. This also results in greater production density.

Low-Tech When Possible
A second principle within Polydome is that low-tech solutions are used whenever possible. For example, if shading can be achieved using co-located plants, then that is considered preferable to installing a more precise mechanical shading mechanism. These low-tech solutions are supplemented with high-tech options only when technology truly provides added value, justifying its additional complexity and cost.

Economic Advantages
From an economic perspective, the key advantage of a Polydome system is that rather than focusing on the large-scale production of a single, relatively valuable crop (tomatoes, peppers), it produces many high value crops that usually have a limited local market (herbs, mushrooms, berries). This effectively translates into the large-scale production of a single valuable crop.

The economic surpluses of this strategy allow for additional, slightly lower-value local markets to also be captured.

The production of many crops in one location is potentially well-suited to local, direct sales. A small Polydome greenhouse could be located in or near a residential neighborhood, in which case it could easily have a shop for direct sales, reducing the costs associated with packaging and transport. Shrinking the distance between producer and consumer also translates into higher profits.

Such high crop diversity provides additional benefits to the local community and reduces dependence on products shipped from distant parts of the globe. This can often translate into environmental benefits as well.

Finally, there is an economy of scale in greenhouse production, even when there is a large variety of crops being produced. For example, pruning, weeding, and mulching can all be done simultaneously for a variety of crops.

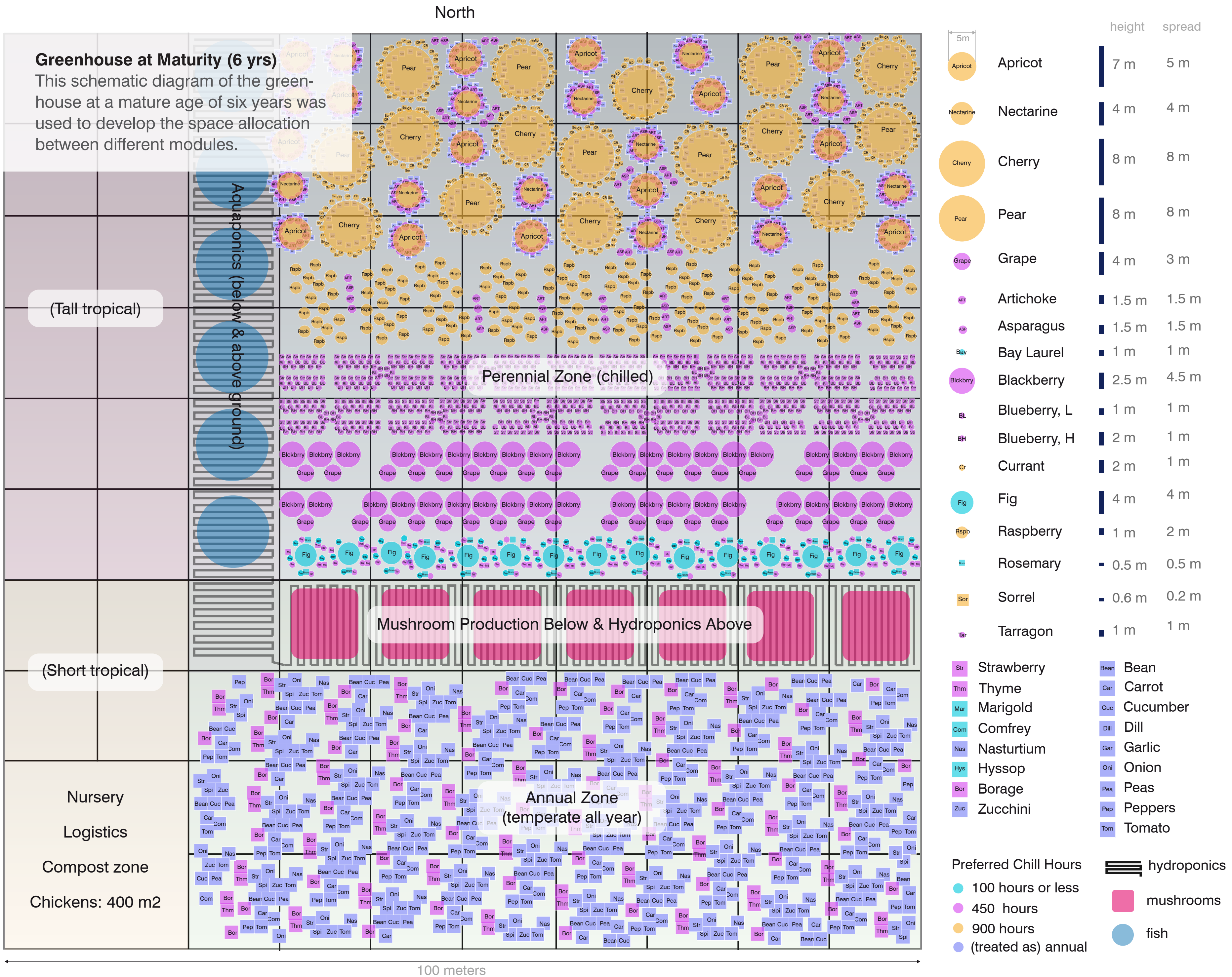
Flexible Performance
One of the benefits of the Polydome greenhouse is that it is designed to be fairly flexible in terms of its crop output.

The greenhouse can respond to changes in market conditions from year to year (particularly in the annual and hydroponic crop modules), and adjust better to local demands than a traditional greenhouse. This is much easier in a polyculture system than in a monoculture, where switching production to a significantly different crop requires readjusting the entire production facility.

Ideally, the Polydome system’s productivity would be able to adjust responsively to the exact demands of the local market.

Diverse, Social Labor
Several papers have been published on the topic of agricultural labor. There are some activities, such as many kinds of fruit picking, for which mechanized labor does not yet exist. One of the biggest problems with this category of work is the psychological drudgery and physical strain of performing the same action repeatedly, which is often required with large scale farming. If there are five hectares of tomatoes to pick, the activity is necessarily repetitive and tiring.

With a polyculture system, the problem of repetitive labor is largely alleviated. Any single crop occurs in a much smaller patches. Even visually, the greenhouse much more closely resembles a natural ecosystem, which alleviates some psycho-



North
Greenhouse at Maturity (6 yrs)
This schematic diagram of the greenhouse at a mature age of six years was used to develop the space allocation between different modules.
(Tall tropical)
Aquaponics (below & above ground)
Perennial Zone (chilled)
Mushroom Production Below & Hydroponics Above
(Short tropical)
Annual Zone (temperate all year)
Nursery
Logistics
Compost zone
Chickens: 400 m2
100 meters
5m
height
spread
Apricot 7 m 5 m
Nectarine 4 m 4 m
Cherry 8 m 8 m
Pear 8 m 8 m
Grape 4 m 3 m
Artichoke 1.5 m 1.5 m
Asparagus 1.5 m 1.5 m
Bay Laurel 1 m 1 m
Blackberry 2.5 m 4.5 m
Blueberry, L 1 m 1 m
Blueberry, H 2 m 1 m
Currant 2 m 1 m
Fig 4 m 4 m
Raspberry 1 m 2 m
Rosemary 0.5 m 0.5 m
Sorrel 0.6 m 0.2 m
Tarragon 1 m 1 m
Str Strawberry
Thm Thyme
Mar Marigold
Com Comfrey
Nas Nasturtium
Hys Hyssop
Bor Borage
Zuc Zucchini
Bean Bean
Car Carrot
Cuc Cucumber
Dill Dill
Gar Garlic
Oni Onion
Pea Peas
Pep Peppers
Tom Tomato
Preferred Chill Hours
100 hours or less
450 hours
900 hours
(treated as) annual
hydroponics
mushrooms
fish

V.3

logical stress. Work requirements are also quite likely to vary from day to day, depending on the particular needs of the season.

In the sketch of a physical layout for the Polydome model, we have also considered increasing the opportunities for workers to socialize by creating a central logistics bay, where most time is spent by groups of people. Other such features can be incorporated to improve the quality of the greenhouse as a work environment.

Greenhouse Production
Though many of the principles applied in Polydome would also provide benefits in outdoor cultivation, they can be applied to even greater effect in the controlled environment of a greenhouse.

Of course, there are the usual benefits of having an environment where ambient conditions can be controlled. Pests can be kept out, waste heat and CO_2 can be captured in the structure, and a number of other benefits can be realized. Additionally, as we propose here, different parts of the greenhouse can be kept at different climatic conditions.

There are also unique benefits in using the greenhouse structure itself as a platform for the vertical stacking of crop modules. In a natural system, vertical stacking opportunities are limited by the height and structure of natural features. In a greenhouse, the building itself can be used as a physical platform for additional crop modules. The possibilities of using robotic logistics systems can also make stacked crops more accessible.

Key Features

A Polydome greenhouse requires innovative ways of reconceptualizing the biological and structural aspects of a greenhouse system. The system is designed to enhance beneficial interactions between species within the greenhouse as well as between the greenhouse and its community surroundings.

The result is a food production system that is designed to be both more dynamic and longer-lasting, with a decreased footprint and increased benefits relative to traditional greenhouse. Our concept includes several key biological, architectural, and organizational features that are central to achieving these outcomes:

Biological Features
- Perennial Crops
- Functional Crop Clusters
- Pest and Weed Management
- Substrates

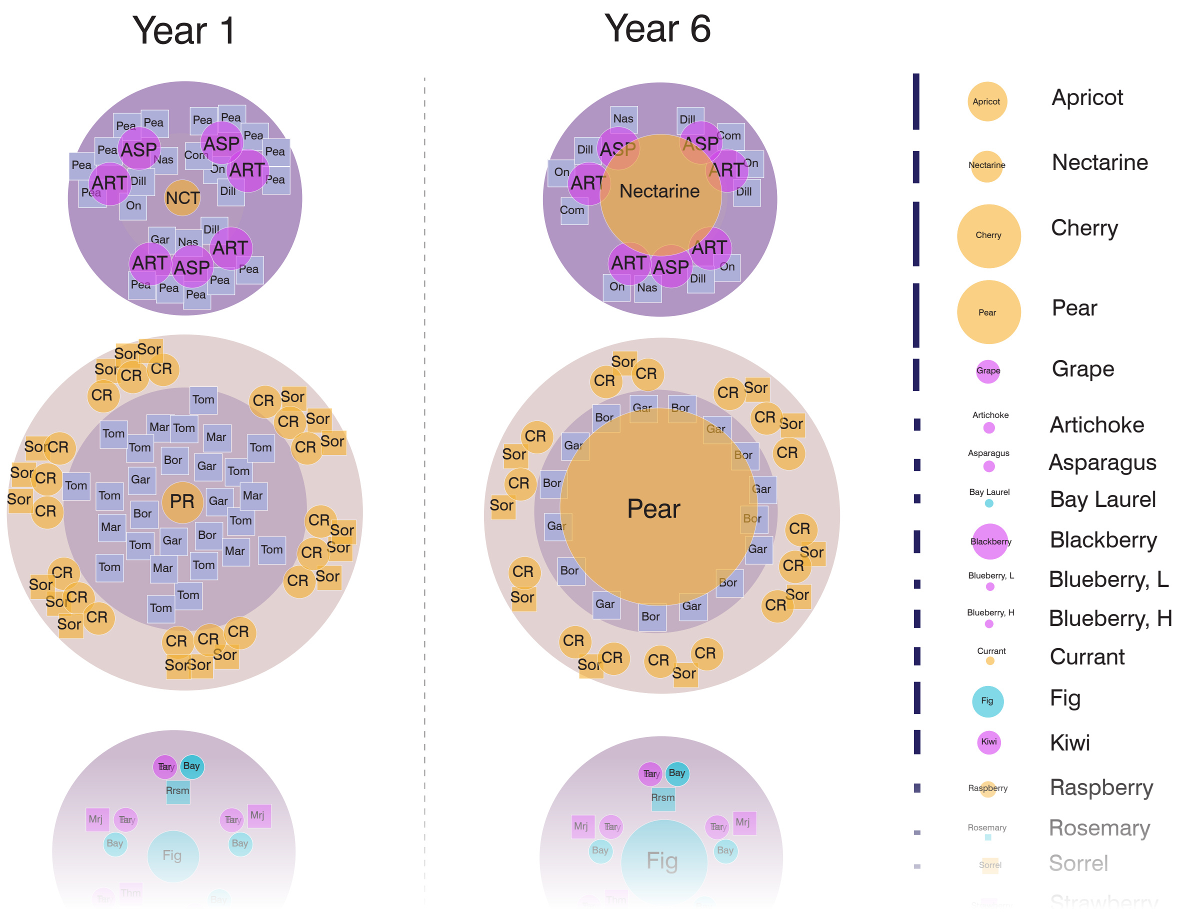
Structural Features
- Spatial and Temporal Stacking
- Microclimates and Microzones
- Advanced Logistics
- Additional Modules

Biological Features

Perennial Crops
The Polydome greenhouse is designed for a minimum lifespan of 30 years and potentially as long as 100 years. One of the main reasons that it is designed for a relatively long time span compared to traditional glasshouses is that a large number of the crops (roughly half) are perennial. These crops do not need to be replanted on an annual basis, and will continue to produce for as long as 80 years.

After the perennial crops are established, they form the basis of a semi-permanent ecosystem within the greenhouse, which does not need to be restarted from scratch at the beginning of each growing season. This allows for the longer-term development of soil communities, and also allows for chickens to be given free range within the greenhouse for certain months of the year, allowing them to turn soil and remove pests. Perennials are not sensitive to damage from the birds, whereas young annuals would be.

Buying mature perennials (cane fruit, trees, etc.) can be quite expensive. In this system, we recommend that these crops be purchased at very early stages of maturity to reduce the initial investment price. In the earlier years of their growth, they can be intercropped with temporary annual crops so that this area of the greenhouse can be used productively in the meantime. The annual crops grown in the area can also be used to prepare the soil for the perennial crops as they mature. For example, legumes planted in the area will fix nitrogen in the soil, french marigolds will fumigate the soil



Functional crop clusters evolving through time
This diagram shows the development of two crop clusters in the modeled Polydome greenhouse. Both of these are centered around trees: a nectarine and a pear. In the first few years after planting, the trees are at an immature stage, and don't occupy much space or cause much shading. In this period, most of the usable soil area around them can be cropped with annual plants. As the trees mature, they can be intercropped with smaller amounts of annual plants that continue to provide support functions to the tree. (See full diagram in the Process section).

Final Crop Selection:

- apricot
- artichoke
- arugula
- asparagus
- basil
- bay laurel
- green bean
- blackberry
- blueberry
- bok choy
- carrot
- cherry
- chive
- cilantro
- cucumber
- currant
- dill
- fig
- garlic
- grape
- lettuce
- marjoram
- nectarine
- onion
- oregano
- parsley
- pear
- peas, snap
- peppers, bell
- raspberry
- rosemary
- sorrel
- spearmint
- spinach
- strawberry
- tarragon
- thyme
- tomato
- zucchini

Additional products:
- chicken meat
- chicken eggs
- tilapia
- oyster mushrooms
- shiitake mushrooms
- honey

Support crops:
- borage
- comfrey
- french marigold
- hyssop
- nasturtium

against nematodes, and garlic can be planted to protect against certain fruit tree pests.

In winter, most of the perennials need between 150 and 1000 “chill hours,” which are hours spent below 7,5 degrees Celsius. This means that a large part of the greenhouse is scheduled to go into dormancy for this part of the year, and will not need supplemental heating or lighting. The dormancy can also be lifted in two different phases for the chilled crops in order to stagger the fruit production of these crops, creating a longer harvesting period.

Additional uses can be devised for the chilled section of the greenhouse while it is in dormancy. For example, a top section of the chill zone could be separated off and minimally heated to provide an extra hydroponics zone, or a temporary area for the cultivation of potted plants. Alternatively, it could be used as a protected “cold room” for the refrigeration of the year-round hydroponic harvest.

Functional Crop Clusters

A central feature of the Polydome greenhouse is the appropriate use of high-density planting.

The main concept revolves around the creation of successful “crop clusters,” groups of interacting plants that use space and nutrients to maximum effect, allowing multiple products to come from a much smaller single area than would normally be possible in a traditional greenhouse.

These crop clusters are like interchangeable Lego blocks. There are many functional combinations that can be mixed and matched depending on the desired output of the greenhouse.

We began by clustering crops based on their soil pH, water requirements, light requirements, and nutrient demand. We also looked at a variety of sources of companion planting data, which we used to determine beneficial plant-plant relationships. Companion plants provide each other with a range of benefits including:

- enhanced flavor
- greater yield
- trellising or groundcover
- shading
- pest suppression
- pollinator and predator recruitment
- hosting beneficial insects
- trapping pests
- disease resistance
- pattern disruption (preventing pests from easily jumping from one food plant to the next)

We also strategically sited a variety of support crops within the system. Some of them, known as dynamic accumulators (e.g., borage and comfrey), concentrate high levels of important trace minerals in their leaves, and provide a very helpful addition to compost.

Our process for developing these crop clusters is further explained in the Process Document.

Coccinelle (

Ladybug), used in natural pest management strategies.

Pest and Weed Management
There has never been an agricultural production facility safe from the scourges of pests, diseases, and weeds. However, despite academic research from the last three decades, most agricultural facilities do not take full advantage of Integrated Pest Management techniques or the latest knowledge on beneficial crop interactions.

As mentioned above, the strategic use of companion plants and support plants can have a significant impact in reducing pest attacks and diseases. In addition to these measures, the purchase of beneficial insects for release inside the greenhouse will probably still be necessary on an annual basis.

It is also possible that additional pest control measures will be required beyond these efforts. In this case, it would be ideal to experiment with sprays made of plant extracts, that have been shown in some trials to be successful against pests. The goal is to avoid chemical pest control at all costs, since it would violate the original objectives of such a facility.

Weed suppression in the greenhouse can be accomplished primarily through careful mulching practices (between 10 and 20 cm of much material is a good amount for covering bare soil). Some controlled livestock interaction (giving the chickens access to the greenhouse) can also serve as a form of weed control.

Substrates
Soil is not a common substrate of choice in Dutch greenhouses. Most growers these days opt for a hydroponic setup with Rockwool or another type of fiber as a root stabilizing base; only biological greenhouses are required to grow in soil for certification reasons.

Soil is considered problematic for several reasons:

- pest infestations, particularly soil nematodes
- the need for additional washing of crops if they have come in contact with the soil
- much greater water consumption than hydroponic production

Despite these issues, we have recommended the use of soil for a large part of the Polydome greenhouse because it offers several common sense benefits.

In following the “low-tech where possible” principle, soil is an obvious choice since it is already present. It doesn’t need to be manufactured elsewhere or shipped in. It requires very little effort to choose to grow crops underneath a hanging hydroponic installation as an added value measure if the required growth medium is already present, which in the case of soil, it is.

Soil is also a unique growth medium that has specifically co-evolved with plants. The role of bacteria, fungi, and other soil microorganisms in supporting plant growth and health is difficult to overestimate. It is clear that there is more to the

relationship between plants and soil than we currently give it credit for in our simplified understanding of agricultural nutrient demand, which we often reduce to NPK values. Ideally, our agricultural production systems can be designed to take advantage of the inherent complexity of soil communities and their interactions with plants.

Another benefit of using soil as a primary substrate is that there is no synthetic waste stream associated with soil-based crop production. Rockwool, the most common substrate for Dutch hydroponic production, needs to be regularly disposed of and re-purchased, presenting both an unusable waste stream and an additional cost. It also poses safety hazards in handling, which are avoided with soil or the use of other kinds of hydroponic substrates.

There is a great deal of evidence that the pest infestation problems in current biological soil greenhouses may be largely the result of monoculture cultivation and lack of appropriate rotation schedules. Several studies have investigated the impact of appropriate crop rotations on pest control, to impressive effect. Other studies on the impact of using certain aromatic plants to fumigate soil and repel aerial pests have shown that these approaches are remarkably effective. Up to an 85% reduction in pest-related crop damage was found in some studies that intercropped selected herbs with target crops.

On a more philosophical level, there is the idea that whenever possible, we have an obligation to enrich and build soil. Worldwide, high-quality soil is a resource that is quickly being depleted through erosion, salinification, and contamination. Soil can be replenished and improved through careful, productive management. This is something the Polydome system can contribute to, on however small a scale.

In addition to the primary soil zone, substrate is also required for the germination and hydroponic production zones. We have chosen to supplement the greenhouse with a hydroponic module in order to increase its overall productivity, beneficially re-use the wastewater effluent from the fish aquaponic module as a source of nutrients, and take advantage of unique vertical stacking opportunities.

For the germination zone, we recommend using coir (coconut fiber) as a medium, topped with expanded clay pellets and perlite. Coir is also suitable for the NFT (nutrient film technique) hydroponic channels, though it will likely need to be fixed in some kind of solid, floating framework for the channel system to work. This will also be necessary to prevent the plants from tipping once they get large.

An advantage of coir over Rockwool is that it can be reused as mulch or composted, and that it is a renewable material.

Structural Features

The longer lifespan of a Polydome greenhouse means that more effort should be invested in the quality and materials of the structure itself than is traditionally invested in a greenhouse. This life span also justifies investment in innovative structural features. Additionally, the structure should be easy to renovate, upgrade, and adapt to changing functions and technologies over time.

The structural features we have envisioned should be designed to facilitate the key ecological features of the system, which maximize beneficial plant interactions and increase crop density.

Spatial and Temporal Stacking
In the Polydome system, each crop occupies a different "niche" in space and time, allowing for crop stacking and extremely high density production.

Stacking in Space:

- **Companion planting** allows for the dense planting of mutually beneficial crops that don't compete for the same nutrients. The added benefits of companion plants are described elsewhere.
- **Vertical Stacking**: Plants have different light requirements and root space requirements. We can take advantage of this fact by placing crops on top of one another; either planting tall and short crops together, or physically locating hanging plants above ground plants.
- **Trellising**: By encouraging plants to grow vertically rather than horizontally, we can increase the amount of ground space available for other crops. This is already common practice, but can also be combined with natural trellising (on trees or other crops) for added crop density.

Stacking in Time:

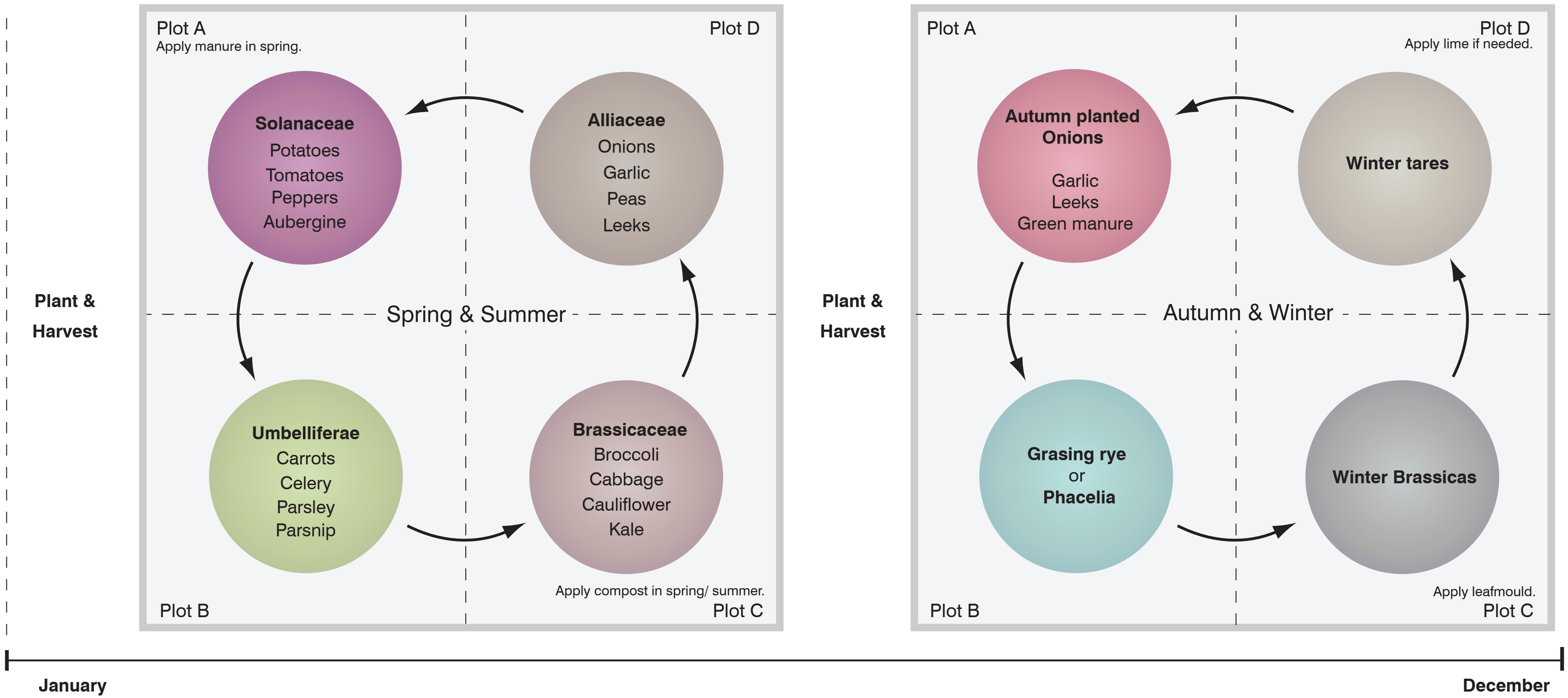
- **Succession Planting**: Plant configurations change as certain key crops reach maturity. For example, trees begin as small plants with relatively low light and root space requirements. In these early stages they can be surrounded with other plants. Once a tree matures, it can be interplanted with a shade-loving cover crop, or left bare under its canopy. In the Polydome greenhouse, it is also possible to continue integrating new perennial crops over time to extend the productive lifespan of the greenhouse. For example, several years into production, new berry bushes or trees can be planted to reach maturity later than the first batch.
- **Continuous Cropping** is the practice of planting small supplies of short-time yield crops in quick succession to extend the duration of the harvest. For example, quick-yielding beans can be planted repeatedly in short cycles. Rather than having a single large harvest, this results in continuous yields. This is particularly relevant in the hydroponics module, but can also be practiced in the annual soil modules.
- **Space Sharing**: Early season crops are intercropped with late season crops, allowing a single space to be used to its maximum potential by several rounds of yielding plants.
- **Crop rotation** refers to the alternation of crops planted in a single location. This rotation is typically done once a season. It is a practice that must be followed for the sake of soil health (pest accumulation), and to avoid selective nutrient depletion. There are well-known guidelines for which families are best for following each other with.

Microclimates and Microzones
The conditions inside most greenhouses are specifically catered to the particular plant under cultivation – lighting, humidity, fertigation schedules, and all other aspects of production are designed around that particular crop.

In the Polydome system, the general conditions are catered to an "average" plant preference. To get more specific conditions per plant, microclimates and microzones are created through crop placement, in a way that echoes how plants in a natural environment find more optimal conditions by selectively placing themselves in specific niches. This approach reduces the need for many energy-intensive climate and atmospheric controls.

However, because of the greenhouse's unique design, it will be especially important to monitor key parameters such as temperature, humidity, root-level oxygen, light penetration, and atmospheric CO_2 in different parts of the greenhouse.

Four Year Crop Rotation



This feedback will provide essential information for how to most effectively distribute annual crops so that they continue to produce effectively.

In terms of light demand, the layout of the greenhouse has been carefully conceived to ensure that shading does not interfere with the growth of most crops. The tallest crops are placed on the north side of the greenhouse, and they are interplanted primarily with shade-tolerant varieties. Moreover, these fruit trees do not fully shade the ground below them.

In some areas, however, it may be desirable to add supplemental light sources, particularly as technologies improve and high-powered LEDs become available and affordable.

Advanced Logistics
Some of the logistics features that we have included in our model of the Polydome greenhouse include:

- A central processing bay where all harvested crops are delivered either automatically or semi-automatically. This space allows several workers to sit together in a social environment while processing crops rather than working individually in distant parts of the greenhouse.

- A series of Nutrient Film Technique (NFT) hydroponic channels organized in a fan-shaped pattern over the annual crop zone, causing minimal shading. This section of the NFT system also feeds into a more concentrated section of hydroponic channels (with a mushroom production zone located below them). All of the channels are installed such that plants float through them arriving at the central processing bay just as they reach harvestable age. RFID tags associated with each plant track when it was transplanted into the hydroponic zone, controlling its timed arrival in the processing bay.

- Movable, narrow platforms that travel on rails and can be strategically lowered allow for the harvesting of some of the taller and larger crops. This increases the ease of harvesting, reduces the need for ground access, and prevents unnecessary soil compaction.

- A system of steel cables attached to the central processing bay allows for easy and low-tech delivery of harvested products. Containers hung from these steel cables can be filled with harvested crops and sent directly for processing, using a combination of gravity and electric pulleys.

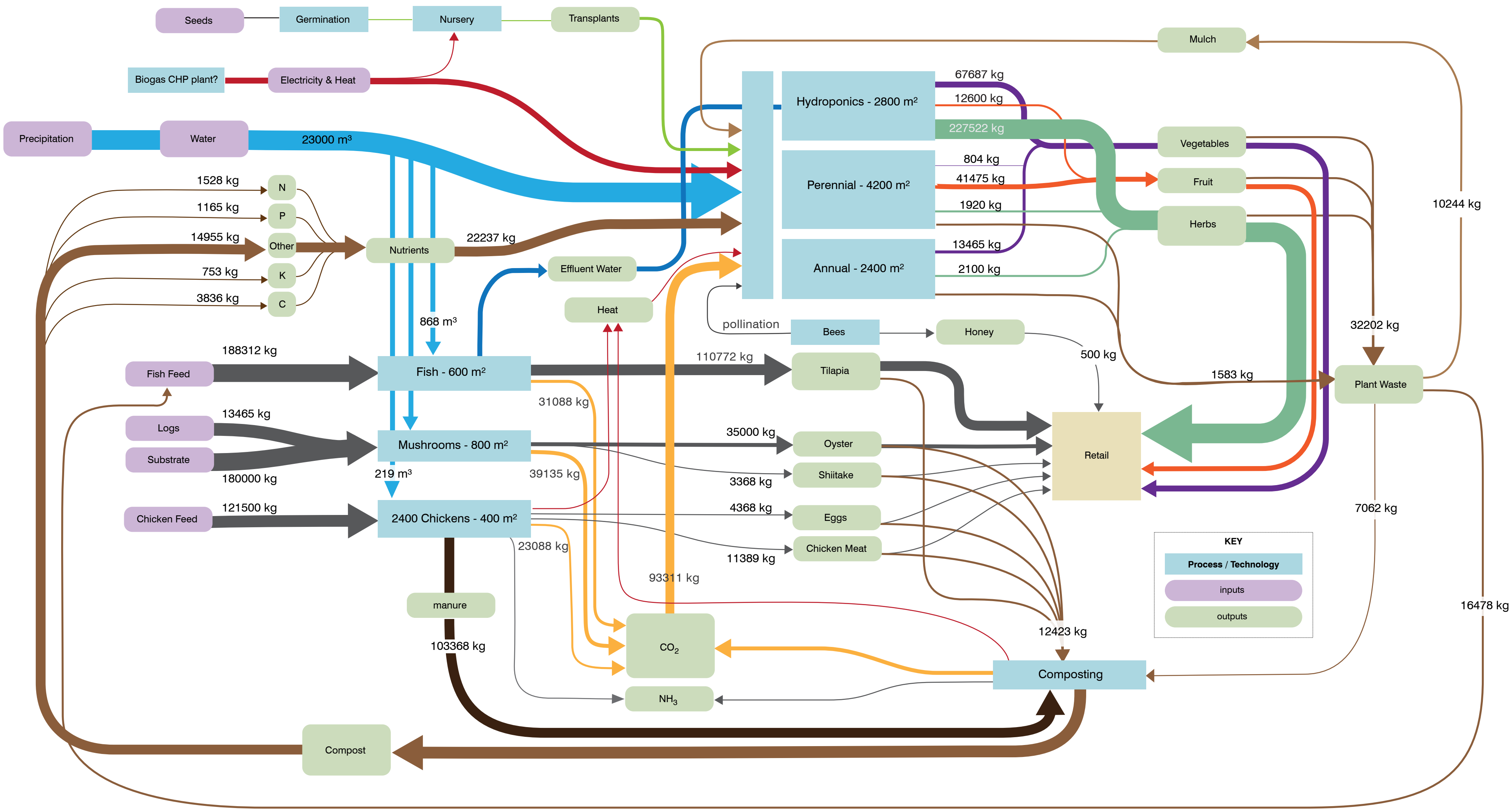
These are just examples of some of the logistical arrangements that could be used within a Polydome greenhouse. Working out all of the technical possibilities is a separate task from this concept development.

Regardless of how they ultimately function, these logistical features must facilitate harvesting, simplify transport of crops from across the greenhouse to the logistics center, and reduce need for ground-level access. They must do this without shading crops below, and, ideally, using a minimum of electric power. Flowing water or gravity-based systems are a good option to investigate.

The Possibility for Additional Modules
Because the Polydome system is modular, composed of a number of interacting pieces that can be exchanged like lego blocks, it is possible to replace modules that are not functioning well or to develop entirely different modules.

A particularly promising module that was explored during the research phase was the possibility of a tropical zone. For market reasons, it was an especially attractive option, since many tropical crops are high value and in demand. Moreover, their production in distant locations automatically makes them more expensive due to import tariffs and transport costs. Local production could potentially be quite cost competitive. However, due to lack of sufficiently detailed data on growing tropical crops in greenhouses, we did not include it in the current model. A tropical module could be particularly interesting if a greenhouse can be located near a free source of heat (such as a data center or a number of industrial facilities).

Polydome Concept Overview



Material and Energy Flows

A polyculture system creates many opportunities for cycling materials and nutrients within the system. The map to the left shows the calculations we have made for the material flow within our model greenhouse.

As stated in the original performance targets, the ultimate goal for a Polydome greenhouse is to have fully closed material and energy flows. Achieving this would mean that the production facility would not represent a source of pollution, nor would it drain non-renewable resources.

Nutrients
Though we have managed to close several "waste" cycles - for example, all vegetable, plant, and animal waste is beneficially reused within the system - there still remain some gaps.

Fully closed nutrient loops are inherently difficult to achieve in agricultural production because the major nutrient flows are exported out of the system in the form of consumable products.

The only way to close this loop is to receive a source of nutrients from the outside (green waste from parks, manure from animal production facilities, food waste from restaurants, or sewage from residential areas would all be potential examples). In this case, we have solved the nutrient deficit through the cultivation of chickens, however the chicken feed will still be coming from an outside source. The fish and chicken feed are the major sources of "nutrient import" that the current model still requires. However, these flows could be supplied internally by adding additional modules (algae production for the fish and a source of wild grain for the chickens).

Water Use
The modeled Polydome greenhouse has a fairly high water demand due to the predominant use of soil as a substrate. However, it is possible to reuse some of the water after it has passed through a drainage system, which we have not added into our calculations here.

Additionally, a large part of the crop zone does not require much water during the winter dormancy phase, resulting in relatively lower water use than for a year-round soil greenhouse of comparable size.

Energy Use
Greenhouse production is typically energy intensive because of the requirements for ventilation, climate control, supplemental lighting, and the use of other electronic equipment.

The goal of the Polydome greenhouse is to reduce the system's overall energy demand by eliminating the need for many, though not all, of these system controls. The remainder of the required energy should then be from a renewable source.

Whatever the exact design, the Polydome system should ideally take advantage of an appropriate combination of relevant energy technologies, such as those described in the earlier section on greenhouse technology, to achieve carbon-neutrality.

Closing the Loops
There are several competing priorities in the design of a Polydome system, which include yields, potential earnings, and material flows.

In this case, we have optimized the system for economic returns and plant compatibility. One of our primary objectives was to examine the financial viability of the model.

It would not be particularly difficult to recalibrate the system design so that all material loops are closed. This is best done with a specific location and local consumer market in mind.

Potential Applications

There are a number of unique applications to which the Polydome concept can be applied - some of them more obvious and straightforward than others.

One of the basic operating assumptions of this initial Polydome test model is that it is a food production system. However, the Polydome model can also be used to produce non-food crops, such as fiber, medicinal products, or chemical feedstocks. It can also be combined with other industrial processes, such as restaurants, shops, or food processing facilities. Combining multiple functions with a Polydome greenhouse could create more opportunities for material cycling as well as provide added economic value.

Community Integration
One of the most obvious functions for a Polydome greenhouse, which has already been mentioned, is to integrate it directly into a residential community. The community and the greenhouse could derive mutual benefit from one another: a direct market on one hand, and a source of fresh, local food on the other. Furthermore, the residential community could provide the necessary nutrient sources for the closing of the greenhouse's nutrient cycle.

The increasing demand for productive urban agriculture makes this an interesting possibility. Assuming that one hectare of Polydome production can provide 80% of the dietary variety of a population of 2000 people (which it can if the product ratios are recalibrated), then a city of half a million residents would only require 250 hectares of Polydome facilities to provide 80% of its nourishment. These could be distributed throughout the city at regular intervals.

Processing Facility
The cultivation of a large variety of crops leads to the risk that not all of them will be sold before they spoil. In this situation, it makes sense to co-locate the greenhouse with a small processing facility where crops can be processed into value-added products such as essential oils, jams, chutneys, or dried products. This will prevent spoilage from occurring, while increasing the economic yield from the greenhouse products.

Industrial Feedstock Production
A potentially unique opportunity for a Polydome greenhouse is to use it for the production of biological feedstock for industrial facilities. Fine chemical manufacturers often require a variety of bio-based products, from mushrooms to herbal and flower extracts. These biological products are often difficult to track in terms of their "eco" credentials, such as in the case of certain oils and flowers. Having more control over their production and easier access to these feedstocks could be a major benefit for such industrial players, particularly as demand for biological feedstock grows.

Beer Garden
Food production facilities also often require a range of agricultural products. In particular, breweries need a certain mix of crops (hops, barley, other grains and flavoring agents) in order to produce their final product. These could all be grown in a specially-designed polyculture greenhouse, which could also serve as a visitor's center and tasting hall for the brewery.

Restaurant or Shop
Siting a Polydome greenhouse together with a restaurant or shop is another logical step because it provides access to a direct sales outlet. This is the most likely means of connecting a Polydome facility to a local community. A second benefit of co-siting with a retail facility is that facility's wastes can be recovered and reused within the greenhouse.

Co-siting with Industry or Agriculture
An option that has already been mentioned elsewhere is the opportunity for locating the Polydome facility near existing agriculture or industry for the purpose of symbiotic material sharing (recycling of waste heat, green wastes, manure, or other materials). This is a great alternative from the perspective of material reuse.

Management and Marketing

Because the Polydome system is quite unusual in the number of distinct operations it contains, there are some opportunities to experiment with management and marketing structures.

Management Structures

One option is that each “module” in the Polydome system could be owned by a different individual, similarly to co-sited operations in an eco-industrial park. However, because this would raise overhead costs, such a solution would only make sense if the Polydome facility was scaled to be of a very large size.

It is also possible for such Polydome greenhouses to be owned by residential cooperatives, with the labor subcontracted out to suitable and knowledgeable parties. In this scenario, the greenhouse would be operated partly as a community service.

However, it is likely that a typical ownership structure would still offer the most reasonable and cost-effective management alternative for a Polydome greenhouse.

Product Marketing

Developing a unique eco-brand, or gaining some form of recognition for the ecological benefits represented by the Polydome greenhouse, could be a key factor in boosting sales and attracting customers.

The waste, water, and CO_2 footprint of each product could be listed alongside it. Particularly when compared to conventional alternatives, Polydome products should have strikingly better performance. As consumers become increasingly aware and concerned with environmental impact, this will continue to be a strong marketing position.

With a growing focus on small and regional production among certain groups, new initiatives like Food Hub[1] are also springing up, which may help coordinate the distribution of diverse products from smaller growers.

Another marketing model which may make sense for Polydome is a modified CSA (Community Supported Agriculture) model. CSA gained popularity in the late 1990s and has continued to be quite popular to this day. Customers buy “shares” of produce from a local producer, and receive a mix of each week’s harvestable yield.

Because of the relative flexibility of the Polydome greenhouse, it also may be possible to “produce on demand,” based on customer pre-orders from the previous season. This could be used as a kind of CSA approach, with the added benefit of allowing consumers to select the kinds and quantity of different produce they will receive.

1 *http://www.food-hub.org/*

Economic Analysis

We constructed a simple budget to assess the economic viability of our proposed model. These calculations are meant to represent a ballpark assessment and do not take into account more complex issues such as taxes, insurance, depreciation of equipment, and similar topics.

Market Value of Products
Since the greenhouse is meant to be productive for at least 30 years, it is difficult to estimate what the value of crops and other products will be over this time period, particularly since market prices already tend to fluctuate from year to year. We have used several data sources for farm gate crop prices: the FAO's annual global data set, the Rodale Institute's crop values, Dutch auction data, and in a few rare cases where nothing else was available, modified prices from Dutch supermarkets.

Because the discrepancy between price data sets was so significant, we constructed two economic scenarios: a "high" scenario, which uses the highest market values, and a "low" scenario, which uses modest pre-retail prices (auction values). These were meant to roughly correspond to a scenario where many of the products will be sold directly to customers, versus a scenario where most products will be auctioned.

Greenhouse Structure
A typical greenhouse structure costs around 35 euros per square meter to erect. For vegetable production systems, the cost of the structure represents only 40 - 50% of the total cost of the system. Additional costs include robots, track systems, cooling, screening elements, ventilation, and lighting.

Because this system is meant to be longer-lasting and more complex than a typical Dutch greenhouse, we have taken these basic figures as a foundation and multiplied them by a factor of four to generate an estimate of the initial investment required. We did not specify the exact technical elements of the system, which makes it impossible to come up with a precise estimate.

Using this factor of four increase, the initial structural costs of a one-hectare Polydome greenhouse are estimated at 2,8 million euros. This is a very high cost for a small size, with the goal being that production values should be adequately high to justify the cost, and that the structure will be designed for a long operational life span.

Operational Costs
Major costs of traditional greenhouse operation include: energy costs, labor, inputs (chemicals, beneficial insects, substrate, seed, etc.), as well as the packaging and transport of goods.

In the Polydome greenhouse model, some of these costs are theoretically reduced - such as the cost of many inputs, some of the continuing energy costs, and ideally the cost of packaging and transporting goods. In the best scenario, the greenhouse would be attached to some kind of shop, and would therefore avoid the cost of most packaging and shipping.

On the other hand, the cost of labor is estimated to be a fair amount higher than in a traditional greenhouse, since the various modules require additional oversight. We added a fairly large safety margin to our labor estimates to ensure that they were at least somewhat reflective of the complexity of the system.

However, because the technological systems in the greenhouse are not fully designed, we could not estimate the up-front costs of these systems nor what their annual expenses might be. Based on our calculations of costs associated with the other modules, we estimated that the system would require an operating budget of around 400.000 euros per year.

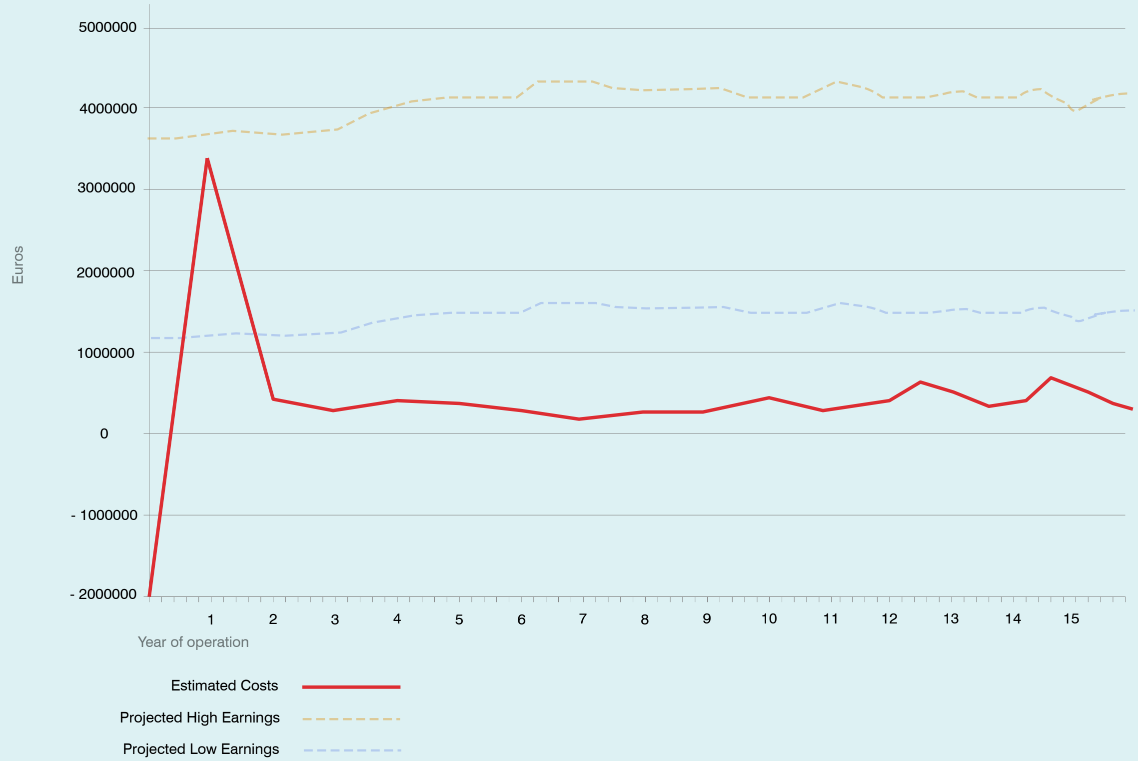
Yields
A summary of the annual yields produced in the Polydome model system at maturity is displayed in the column to the right. This estimate represents the yields from year six of production and beyond. It was calculated by analyzing the productivity of each functional crop cluster, and extrapolating from the final crop layout.

Something which is immediately clear is that the crops are not scaled relative to one another to consistently supply a population with a diverse range of food. This relative scaling is something that could easily be modified to optimize either food production for a community (for example, size all primary outputs to the demands of 10000 people). Based on our calculations, we estimate that a single hectare Polydome system can supply

Summary of Annual Yields

Category	kg / year	people supplied
Fruits	*27455*	*458*
Vegetables	*110471*	*1841*
Mushrooms	*69800*	*6980*
Herbs	*190543*	*38109*
Fish	*105233*	*7016*
Chicken meat	*10479*	*233*
Eggs (not in kg)	*1404000*	*5200*
Honey	*500*	*1250*

Estimated Costs & Earnings of the Polydome Greenhouse



most annual food demand for 2.000 - 5.000 people, depending on the particular crop / livestock arrangement and local dietary preferences.

Alternatively, rather than scaling productivity to local consumption, the modules could be relatively scaled to one another in order to optimize material cycling. Currently they have been scaled based largely on economic productivity and optimal crop interactions.

The highest earnings are generated by the hydroponic system, which has the greatest individual yields per m^2. The sales from this module can be significantly lowered, however, while still maintaining a high level of earnings.

Return on Investment
A typical return on investment for a modern Dutch greenhouse is 7 - 10 years, which in most business sectors is considered quite a long period for achieving returns .

In the case of the Polydome greenhouse, we were unable to estimate an exact return on investment schedule since a large degree of uncertainty remains in the exact technological outfitting of the system and the associated costs. However, we believe that it should fall at least within this range. What we were able to estimate with relative accuracy are the greenhouse yields, from which we generated a range of annual earnings. The graph above represents both the high and low (pre-cost) earnings scenarios, which diverge significantly. The actual performance of the system is likely to fall somewhere in between the two extremes.

The high annual earnings, which assume a direct sales model, result in an estimated earnings of around 4 million euros per year. The low annual earnings scenario, which uses more modest, pre-retail prices, generates around 1,5 million euros per year.

Notably, even though costs are not subtracted in these calculations, these earnings compare favorably with the production of more traditional crops, such as tomatoes. A hectare of tomatoes producing at 60 kg per square meter and selling at an auction price of 0,72 cents yields 734.400 euros.

It is important to note that the hydroponic plants module is still by far the most profitable in this system. Eliminating that module results in an earnings of around 600.000 per year for the remainder of the greenhouse, though then of course, extra space would be freed up for additional productivity.

Our final conclusion is that, though there is quite a bit of uncertainty in these calculations, a reasonable case is presented for the profitability of a Polydome greenhouse. The central ideas behind the Polydome economic strategy: temporal and spatial stacking and the capture of multiple high value markets, do seem to produce an economic advantage in the model.

Ascertaining the exact costs is something that needs to be done with greater precision once an actual design is made.


V.3

Key Benefits

Economic:

- Diversification of crops offers protection from sudden market volatility in commodity prices.
- Product diversity reduces the chances of total crop failure as a result of disease or pests; some crops will always be more susceptible than others.
- Diversification allows capture of all the small “high-value” markets in a local area.
- The opportunity for direct sales creates a possibility for greater earnings.
- Crop output is relatively easily adjustable on an annual basis to the demands of the local market.
- Initial investment continues to produce returns for several decades.

Economic & Environmental:

- Stacking of crops in space and time allows for very high density production.
- Integrated Pest Management (IPM) and nutrient cycling strategies result in avoided costs: no need for pesticides, chemical fertilizers, pollination services, and many other inputs that are typically associated with a greenhouse system.
- Internal reuse of material flows can make the greenhouse into a zero-waste facility, and reduces the need for outside resource purchases.
- Diverse, local production can reduce the local community’s dependence on food products shipped from distant locations.
- As a result of all the planned material cycling, the footprint of Polydome-produced products should also be lower than most alternative products.
- Polydome production can replace other forms of environmentally damaging farming.

Socio-Cultural:

- The Polydome greenhouse creates opportunities for creative, diverse labor in comparison to traditional agriculture.
- It creates the possibility for direct interaction with local community and allows for direct market response to local demands.
- Can potentially improve the health of nearby residents by providing access to fresh, local produce.
- Can contribute aesthetically to the local environment.
- Can reduce transportation in its food network, improve food security and food access, thereby aiding climate adaptation strategies.

Challenges

Though comprehensive in its underlying vision, the Polydome concept is in need of significant practical and technical experimentation to evaluate the ideas presented here.

There are several questions that may naturally arise about how such a system would function in practice. Some key concerns might include:

- High up-front investment in system design and construction
- Potential difficulty in marketing a diverse product range
- Risk that products may be of suboptimal quality, since the system is calibrated to produce many crops rather than one
- Less control over the exact timing of crop production
- The knowledge required to operate such a system is much larger than that required for a monocultural production facility; knowledge barriers may be considered too high
- The basic technical ideas, such as the impacts of some crop arrangements and the proposed hydroponic system structure, require further testing

From interviews with various parties involved in the Dutch greenhouse sector, it is clear that the level of technical expertise within the industry is very high. An appropriate design for Polydome would need to be worked out to the high standard of industry specifications, which would require an additional research effort.

The crop arrangement we have selected is certainly not guaranteed to perform exactly in the way we have modeled. However, the goal was never to create a model that was perfectly accurate; rather, it was to illustrate a highly plausible arrangement for how such a polyculture system might work.

Regardless of the uncertainties involved, the need for innovation in a sustainable direction and the potential benefits of a Polydome system as have been outlined in this report are very high.

We must begin thinking in entirely new ways if we are to solve the challenge of sustainable food production. The Polydome greenhouse represents just such a possibility. It shows us where we can afford to reduce our reliance on technological inputs, and instead gain additional performance through “ecosystem design.”

We believe the potential benefits of the Polydome approach are great enough to justify working to resolve the challenges laid out here.

Future Development

To make the Polydome concept a reality, an ideal next step would be to design and run one or more pilot projects to test specific elements of the proposed model. These experimental greenhouses could examine basic assumptions about crop interactions, actual yield, and the optimization of material flows.

Another interesting possibility for a pilot project would be to build a Polydome system with the goal of producing food for a specific community. This would be particularly useful in exploring the direct retailing option and evaluating the true economic performance of the greenhouse.

Eventually, new logistical and technological features can be specifically designed to cater to the Polydome system. However, initial pilots can be run in existing greenhouses, particularly those that have been recently decommissioned or that are too old for normal production.

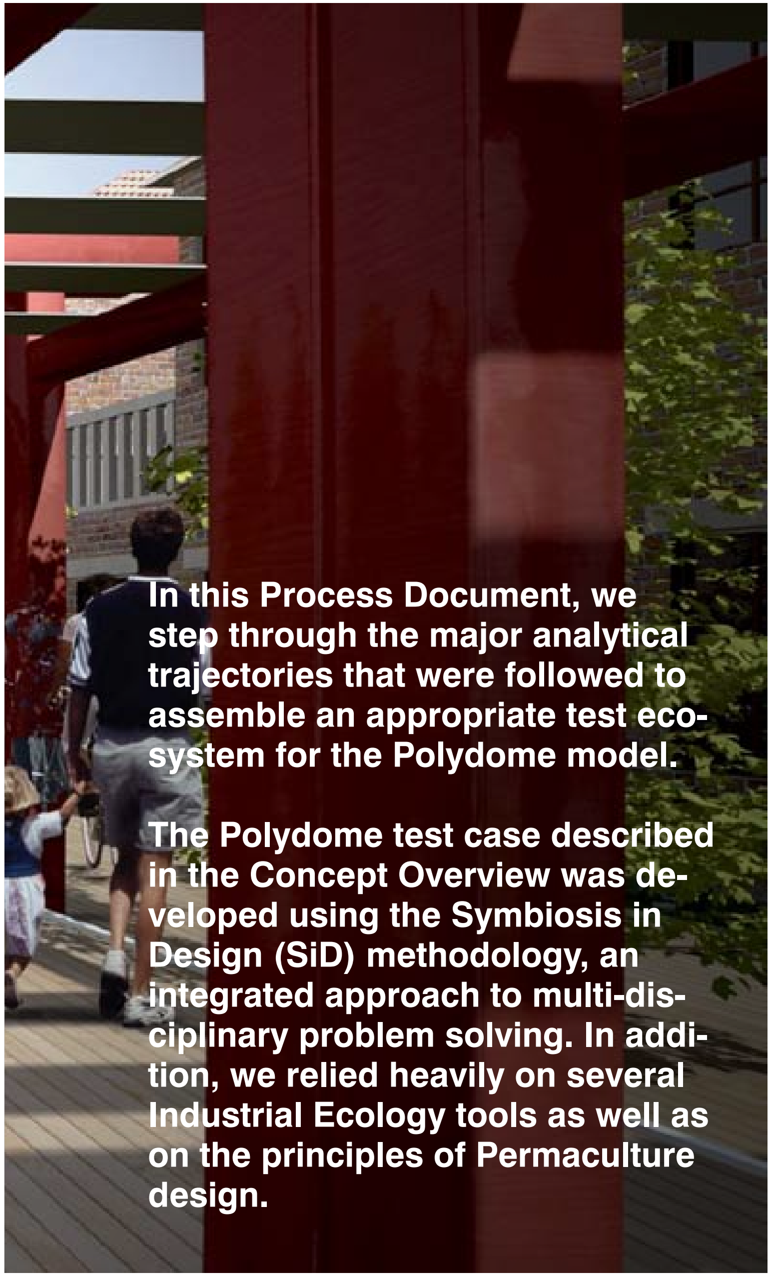
Once experimental pilots have been run, a formal business case and design can be developed for a specific Polydome system.

In this Process Document, we walk through the various steps we took in developing the Polydome test case model.

Polydome Process Document

Study Approach

Designing an Ecosystem



In this Process Document, we step through the major analytical trajectories that were followed to assemble an appropriate test ecosystem for the Polydome model.

The Polydome test case described in the Concept Overview was developed using the Symbiosis in Design (SiD) methodology, an integrated approach to multi-disciplinary problem solving. In addition, we relied heavily on several Industrial Ecology tools as well as on the principles of Permaculture design.

Industrial Ecology (IE) is a field of research that uses tools for strategically mapping the material inputs and outputs of a system across its entire life cycle. We used an IE approach in quantifying the changes in the approximate material profiles of the model systems in terms of energy, material, water, waste, crop yield, labor, and other flows.

The world "permaculture" is a contraction of the words "permanent" and "agriculture." It is a design philosophy developed in Australia in the 1970s, which has since gained popularity worldwide, but has generally been limited in its influence to rural contexts and field farming. The goal of permaculture is to establish long-term, self-regulating human systems that are largely modeled after natural ecosystems. The primary focus of permaculture is on agricultural design.

There are several loose "design principles" contained in the permaculture approach, which include: relying on diversity, ensuring that each element within a system provides multiple beneficial functions, and several others. These principles were incorporated in our goal-setting process. We used SiD as a framework for combining these two sets of tools.

Prior to conducting the SiD analysis, we interviewed various parties in the greenhouse sector in order to better understand the latest technological advances, real costs, and on-the-ground issues in greenhouse production.

In this phase we also began assembling the required data for the subsequent analysis: a large data library on crop, livestock, mushroom, and aquaculture production. We then used this data library as a foundation for the SiD analysis.

The basic steps in any SiD analysis involve:

1. **Goal setting.** Establishing the performance criteria of the final design - in this case the performance goals of the Polydome greenhouse.[1]

2. **Mapping the system.** Identifying the key elements that make up the system of interest and defining their interconnections. In this process, system mapping consisted of two key parts: defining system boundaries (what crop and livestock elements are we going to include, and why?) and then examining their key interrelationships.

3. **Synthesizing knowledge.** Combining all the data from the various system mapping exercises, gaining an overview of key leverage points.

4. **Optimizing the system.** Positioning key elements in the most beneficial way relative to one another and scaling them appropriately. Considering effects in time, space, and context.

5. **Evaluating and iterating.** In this phase we check our results against the goals we set out in the beginning, and ideally would return to earlier steps as necessary. In this case, we only completed one round of iteration because this is a preliminary study without a specific application in mind.

Our primary concern in this design was to create a functional ecosystem through the careful selection of crops and livestock.

The Polydome Ecosystem Design Method

In a natural ecosystem, plants and animals arrange themselves through a continuous process of trial and error. A seed may fall in a certain location, only to die a few weeks after sprouting because the spot was too wet, dark, or exposed to predators. Microbes also form colonies based on their preferred conditions, creating diverse, invisible communities of around one billion individuals per gram of soil. Likewise, animals travel from habitat to habitat as they search for areas with adequate food, shelter, and potential mates.

Because living creatures are constantly traveling, reproducing, and dying out, their patterns of distribution can adjust to changing conditions. Natural ecosystems are constantly in flux, facing climactic fluctuations, physical habitat changes, and varying concentrations of food availability.

During periods of relative stability, species settle in patterns that take maximum advantage of the current conditions. Anyone who has explored a natural environment has probably encountered such patterns.

For example, along any rocky coastline, plants and animals arrange themselves in bands dependent on distance from the water. Areas that remain under water even at the lowest tides harbor the most water-dependent species, such as fish and anemones. As we move towards the shore, to areas that may dry out towards the end of the low tide period, we start finding species that are slightly less water-dependent and more mobile, such as sea stars, crabs, and snails. Even further towards the shore, we start to see areas densely packed with creatures that can seal themselves off from the dry air, giving themselves several safe hours of life without water, such as mussels and barnacles. This kind of stratification is based on the needs and survival capacities of each individual species.

Our task in designing the Polydome ecosystem was to artificially imitate the phenomenon seen in such a rocky shoreline: create an optimized spatial distribution for each species in the system. This assignment was complicated even further by our

1 These criteria are listed on pages 20 -21 of this document

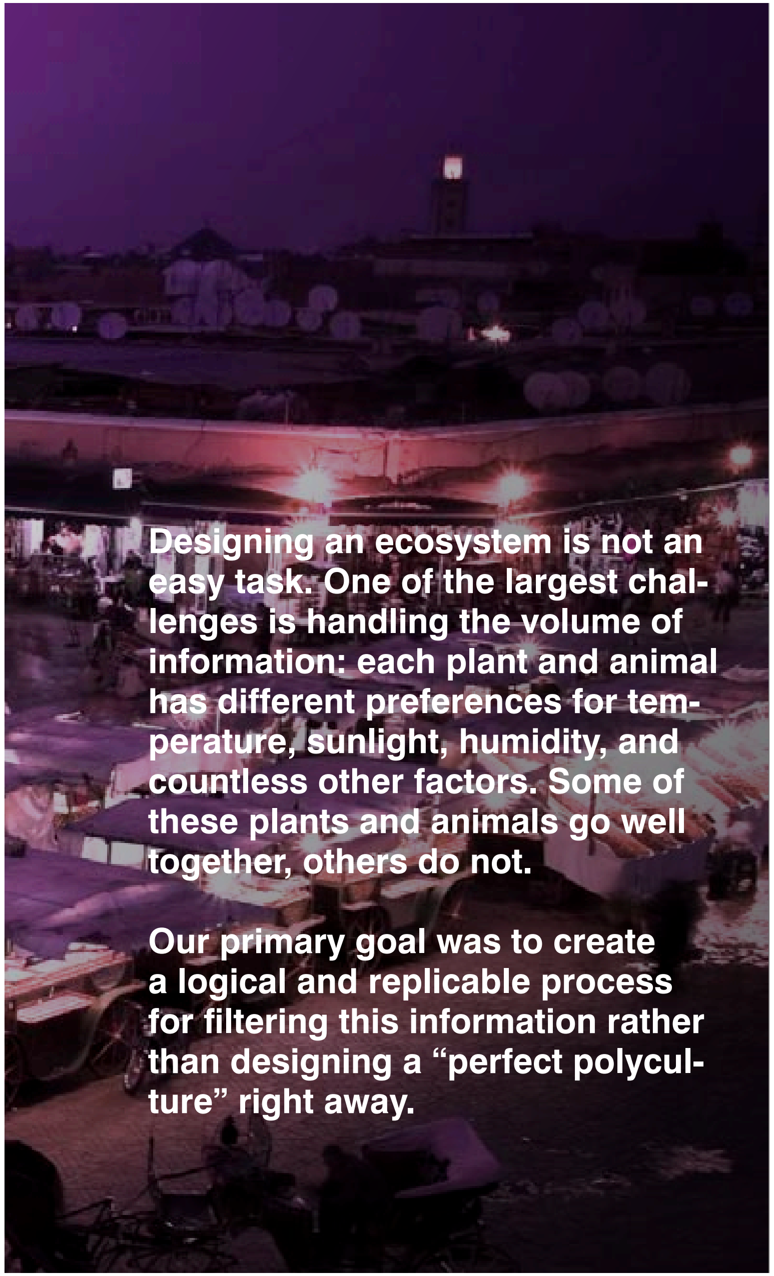
need to go beyond biological factors. We also wanted to arrange species based on their maintenance frequency, economic productivity, and, in the case of animals, strong ethical considerations for their health and natural behavior.

In order to conduct such an optimization on paper, without an experimental space where plants and animals could be placed next to one another, we had to collect enormous quantities of data. First we had to determine which exact data points are critical for each species. In the case of plants, which are non-mobile, there are many: light, soil pH, soil oxygen, moisture, nutrient levels, temperature hardiness, chilling requirements, and many others. The largest challenge in this process was gathering all of the appropriate data required for decision-making.

After having determined the full range of data points that were necessary, we created a filtering and analysis process for this data. The process we have developed here allows us to systematically filter a very large amount of information about crops and livestock, and optimize it for several key parameters at once. Ultimately, one of the main outcomes of this study was the design of a functional, repeatable process for assembling a polyculture system rather than perfecting a single design.

Defining System Boundaries

Selecting crops and livestock



Designing an ecosystem is not an easy task. One of the largest challenges is handling the volume of information: each plant and animal has different preferences for temperature, sunlight, humidity, and countless other factors. Some of these plants and animals go well together, others do not.

Our primary goal was to create a logical and replicable process for filtering this information rather than designing a "perfect polyculture" right away.

The first phase of our ecosystem design process was to assemble a library of crops and livestock that could potentially be included as part of the system. We wanted to cast our net as broadly as possible, so we did not initially exclude elements that might seem unintuitive as greenhouse crops (for example, trees or grains), nor did we focus on one particular climatic zone.

We considered three different climatic options for our system: temperate, Mediterranean, and subtropical / tropical. Within these climatic zones, we assembled a broad list of food-producing plant types ranging from vines to trees to herbs.

Beyond plants, we assembled lists of fungi, livestock (chickens, rabbits), aquaculture (fish, shellfish, aquatic plants), and mircro-livestock (bees, worms, and other beneficial insects) that could all play a beneficial role in the system.

In a final category, we considered non-food crops, such as wood, oil, fiber, crops for medicinal use, and plants that are not primary crops in themselves, but rather are useful as companions for primary crops. For practical considerations, rather than assembling a comprehensive list of these secondary crops, we focused mostly on selecting a few that seemed qualitatively interesting.

Creating the Library

As a first step prior to assembling a list of crops and livestock, we conducted a quick analysis of conditions in the Dutch food market. This gave us a better idea of which products are valuable and in relatively short supply in the Netherlands. Some extremely profitable crops have limited or saturated markets, which is something we wanted to be aware of.

However, we did not take the results of the market scan very strictly, since the Polydome greenhouse is meant to perform in a very different context than that of most growers who mass-produce for the global export market. With local food production as a primary goal, the market constraints are somewhat different; in many regards, it is more appropriate to focus on local dietary preferences.

The Dutch Market

Fruits and Vegetables
The Dutch horticulture sector is extremely developed and one of the largest in the world. Even so, we found that the majority of fruits consumed within the Netherlands, 80%, are imported.[1] This indicates an opportunity for the expansion of the local fruit production market. Decreasing the length of supply chains and removing the cost of import tariffs can provide an opportunity for extra earnings in this sector.

The most popular fruits consumed within the Netherlands are apples, oranges, and bananas, accounting for 2/3rds of total fruit consumption. The sales of strawberries, kiwi fruit, pears, and pineapples are increasing strongly.[2]

In terms of domestic production, apples and pears are the most commonly cultivated fruits in the country, followed by strawberries and soft summer fruit. A majority of the output is exported to Germany.

In the vegetable sector, the situation is reversed relative to the fruit sector, with 85% of domestic vegetable consumption coming from homegrown sources. However, most domestic vegetable production is concentrated on a few key products. The greenhouse sector is dominated by tomatoes, cucumbers, peppers, radishes, and eggplants while the field crop sector is focused on onions, carrots, leeks, and brussels sprouts.

Approximately two-thirds of fruits and vegetables are exported. Current vegetable production is three times higher than local demand because of this export-oriented production focus.[3] Many export statistics are complicated by the Netherlands' status as a major shipping hub; re-exports are often combined with domestically produced exports.

Mushrooms
The Netherlands is one of the three largest mushroom producers in the world.

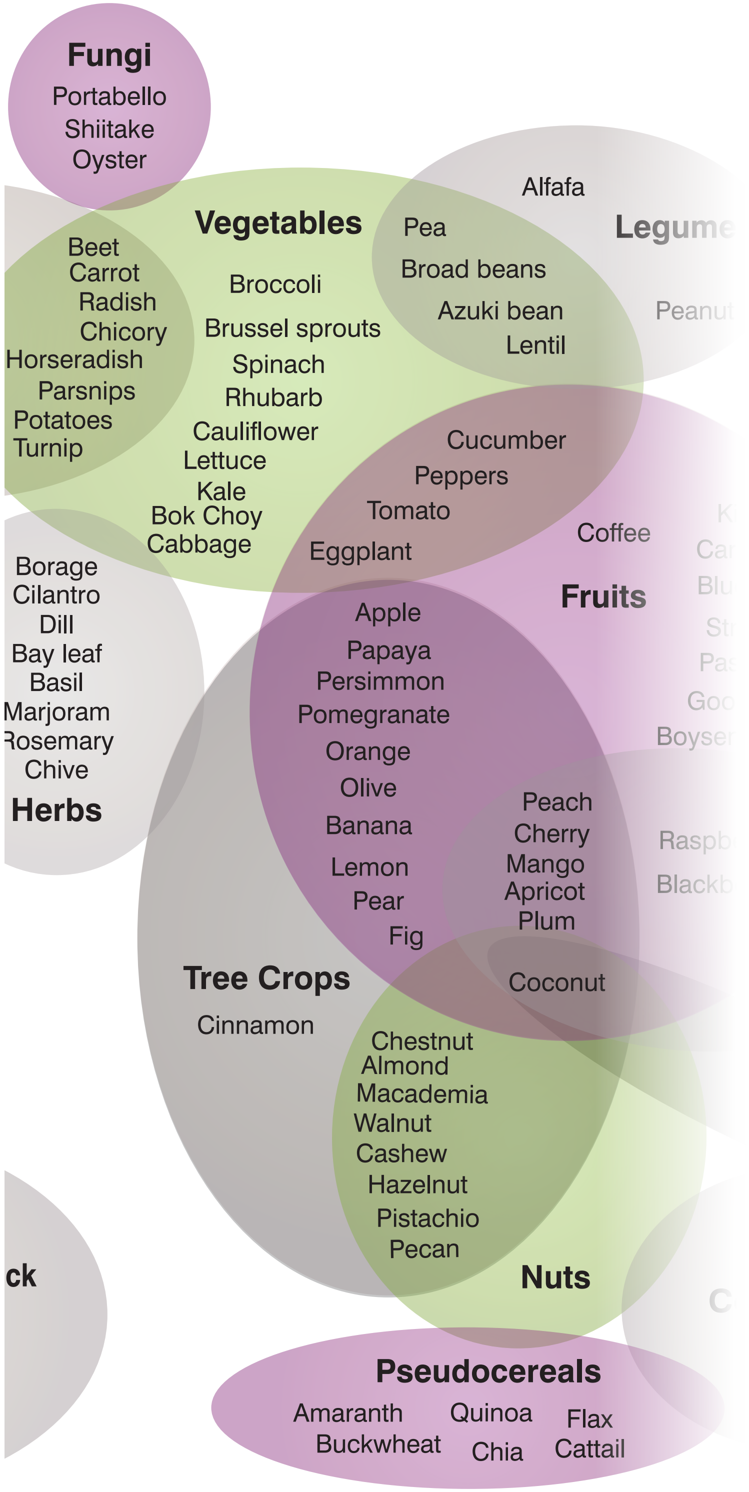
Over 75% of mushrooms consumed in the Netherlands are fresh, which means that imports are unlikely to affect the domestic market due to rapid spoilage. In 2005, the Netherlands produced 250.000 tons of mushrooms a year, with roughly 2/3rds destined for industrial uses.

Herbs and Spices
Production of spices and herbs is limited in the Netherlands. Developing countries supplied 75% of the import volume in 2008.

The Netherlands imports an estimated average of 1.500 tons of dried herbs per year. Over 77% of the herb imports consist of sage, oregano, marjoram, mint, thyme, and rosemary. Domestic production

1 *Mattas, K., Baourakis G. Supply chain analysis of the fruit and vegetable market in The EU (Case studies for The Netherlands and Germany) p. 33*
2 *Facts and figures of the Dutch Agri-sector, 2008*

3 *CBI Market info, "The Fresh Fruit and Vegetables Market in the Netherlands." 2008.*



consists of parsley, sage, mint, thyme, dill, savory, and tarragon, which satisfies local fresh market needs and part of the dried herb market. Market demand is continuing to grow, in particular for marjoram, oregano, sage, thyme, and bay leaves. Herbs are also increasingly used as natural preservatives and anti-oxidants, particularly in meat products, which indicates a direction for continued market expansion.

The main herbs consumed domestically include thyme and oregano. There has been an increase in ethnic food consumption,which has driven a demand for certain fresh herbs such as coriander leaves.

Ecological and Organic Produce
Though Dutch interest in “ecological” and organic food products has been among the lowest in Europe, it is a steadily growing market. As an example, sales of biological foods rose by 20% in last three quarters of 2010, while total supermarket sales rose only 1,8%.[4]

There is growing political and personal interest in more sustainable practices, both on a national as well as European level.

Conclusions
Based on this initial market scan, we concluded that one of the primary opportunities in our proposed design is to simply increase the diversity of local production. Though the volume of vegetables produced is very large, the diversity is small, with the majority concentrated among a few common products. Transport, shipping, packaging, and tariffs contribute a very significant percentage of the final costs of products. Saving on these secondary costs by producing a larger variety of foods locally could translate directly into added profits.

Opportunities probably also lie in improving the quality of produce in terms of taste, and catering to the growing population of people interested in sustainably produced food.

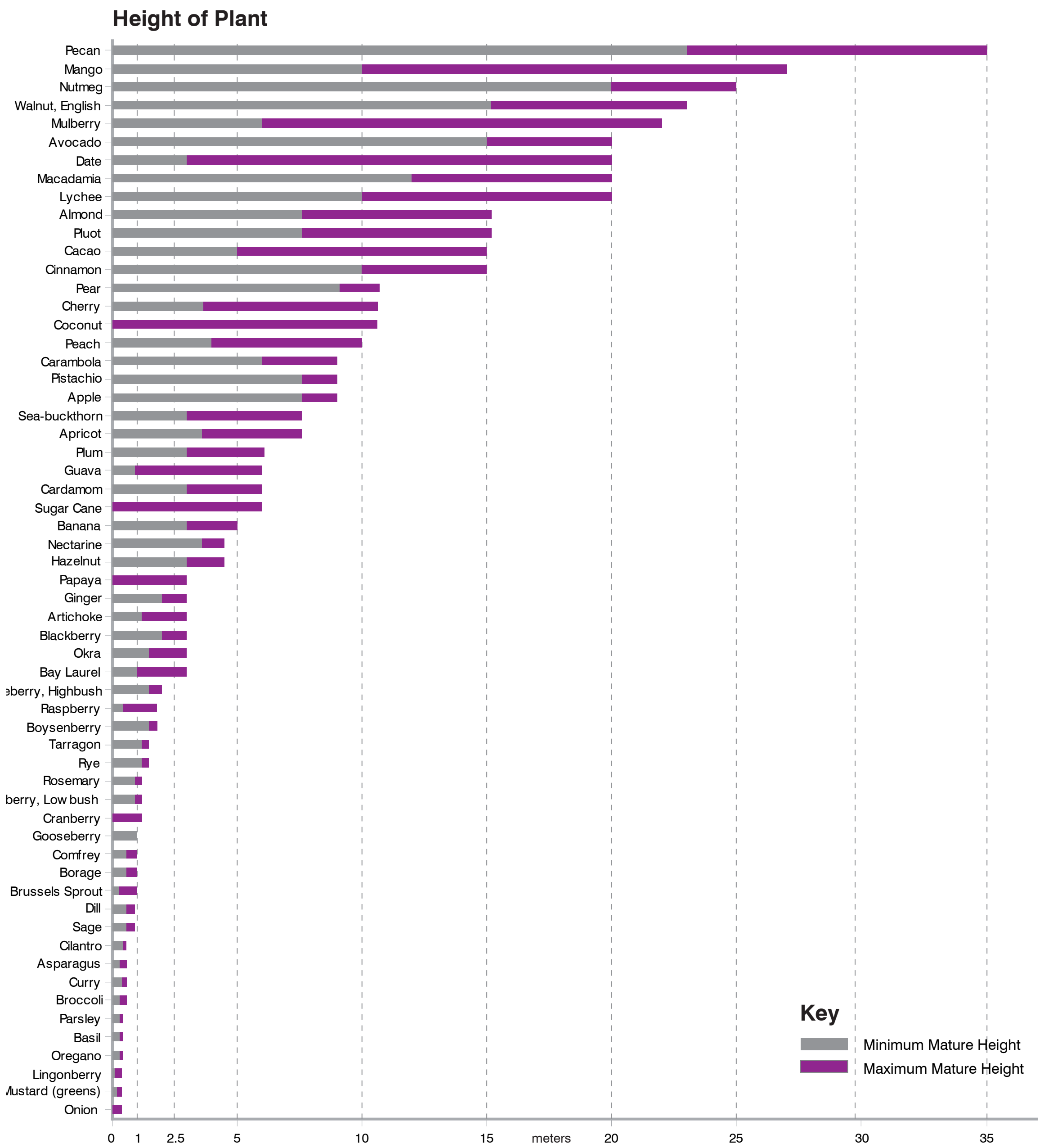
4 *http://www.biologisch-voedsel.nl/*

Selecting Desirables

Once an initial list of crops, livestock, and secondary elements was assembled, our primary task was to narrow down the pool of potential species to a number that was manageable for inclusion in the test case.

It was unfeasible to collect a full range of key data for each entry in the initial library, however, to even complete the first round of elimination, we needed to collect some key figures for all entries. We wanted to leave the pool sufficiently broad to make changes in selection as we progressed iteratively through the analysis later on, but didn't want it to be so large as to be overwhelming for data collection purposes.

Because the number of potential crops is so great, we focused primarily on developing a systematic and quantitative elimination strategy for crops rather than livestock and other supporting elements. Decisions about livestock were made based on more qualitative aspects. The two sets of methods are described separately.



Crop Selection

Our over-arching goals for crop selection were to pick crops that would be marketable and profitable, relatively easy to grow, and contribute to a functioning, diverse ecosystem.

We devised a three step process for crop selection, which used a combination of quantitative and qualitative analyses. The three steps are outlined briefly here, and then described in greater detail in the analysis:

1. **System incompatibility**
   - Excessive height
   - Long maturation period
   - Allelopathy
2. **Economics**
   - Basic crop value and yield potential
   - General labor requirements
   - Prioritizing for perennial plants
3. **Supporting Elements**
   - Selecting beneficial companion plants
   - Selecting elements that provide required functions or material flows

Each of these steps is described in greater detail in the upcoming analysis.

The data we used for this process were as complete and up to date as we could find within our time constraints. However, we would recommend improving the completeness and quality of some of the data sets before using this process to generate an actual Polydome design.

One of our primary limitations was the fact that we didn't have complete yield and price figures for all crops of interest, which necessarily pushed them out of our working pool even though they may have been valuable additions.

Analysis

1. System incompatibility

We began by eliminating plants with problematic physical features. This was not a comprehensive elimination process. In an actual Polydome design, we would recommend developing these first elimination criteria in a much more systematic manner.

- **Excessive height**

For all tree species, we chose to eliminate those tending to grow over 10 meters tall. Dwarf cultivars were considered an option in certain cases. Exceptions were also made for varieties of trees that perform well when pruned for smaller size, or that can be espaliered.

- **Allelopathy**

For all species, we chose to eliminate crops that are strongly allelopathic or poorly performing when planted in polyculture. For example, walnut secretes a chemical in its root zone that prevents any other crops from settling nearby. Fennel and wormwood have similar properties in that they generally interfere with the growth of surrounding crops.

2. Economics

- **Basic crop value and yield potential**

Because one of the primary goals of the Polydome greenhouse is for it to be economically sustainable, our first round of elimination was geared at filtering the crops by economic productivity. As a

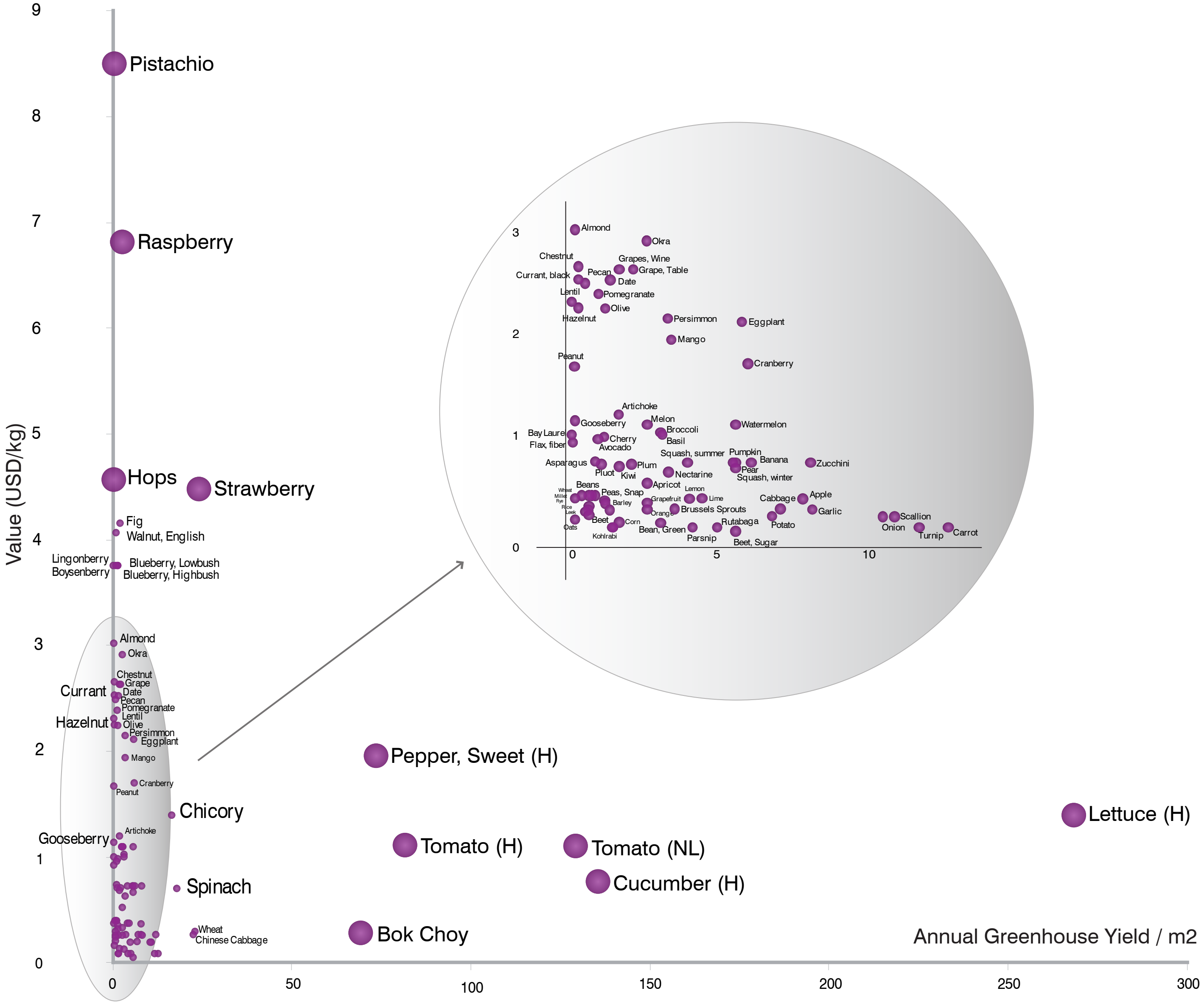
Yields and Prices
These scatter plots show annual greenhouse yield per square meter as related to farm gate prices from two different sources: the United Nations Food and Agriculture Administration (FAO), and a combination of market prices from other sources. The FAO values appeared to be very low for the most part, which is why we searched for secondary data.

The prices have been normalized to U.S. Dollars; however, in most cases they actually represent Dutch or European prices.

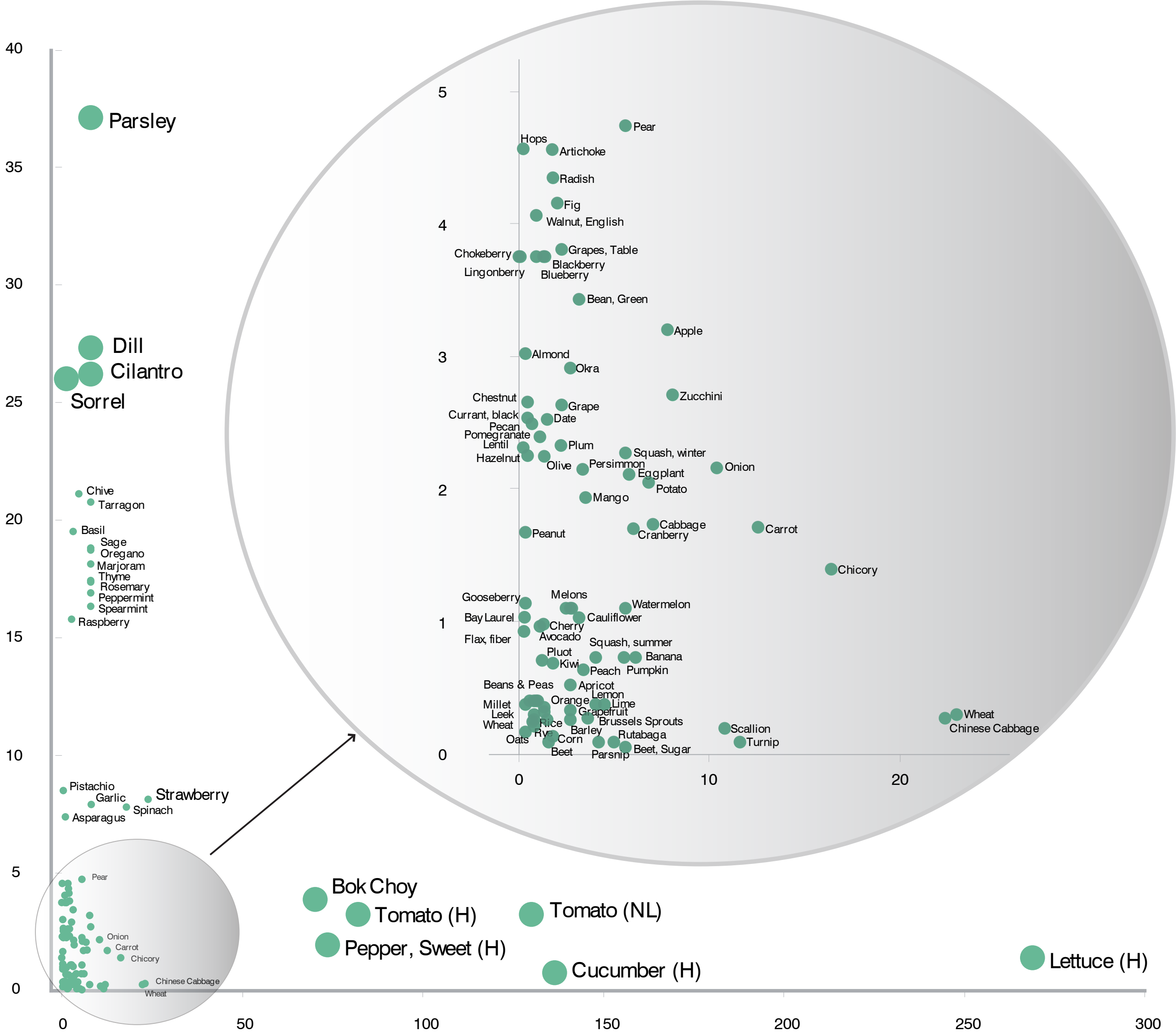
The data quickly reveals that standard Dutch greenhouse choices: tomato, pepper, and cucumber, perform very well in such an analysis. However, one of the main reasons for this is that the productivity of these crops has been greatly increased over the years since their adoption in Dutch greenhouses. These facilities now produce them so efficiently, that other crops have a difficult time competing in terms of yield.

Two other evident points include the very significant discrepancy in data between the two different sets of sources, and the fact that the majority of crops fall into a cluster of fairly “low yield, low value” elements.

2007 FAO Farm Gate Prices vs. Annual Greenhouse Yield / m2



Max Farm Gate Prices vs. Annual Greenhouse Yield / m2



first elimination step in this regard, we constructed the scatter-plot diagrams showing yield vs. farm-gate price (shown on the previous two pages).

This is a crude mechanism for several reasons. For example, production costs are not taken into account, thus the economic values do not represent net profit. Furthermore, a great deal of the production values we have are for field-based production, which does not accurately reflect greenhouse yields. However, we considered this to be suitable as a first measure of elimination, since many of the later analysis steps took these factors into account.

- **Prioritizing for perennial plants**

We also chose to prioritize for perennial crops, such as berries, fruit trees, and certain perennial vegetables. Even though these are not always the most profitable crops, they create interesting opportunities for temporal stacking, and establish a more permanent ecosystem foundation.

- **For all perennials, we eliminated crops that require over five years to reach bearing age.**

Also for economic reasons, we ensured that all crops within the system would have productive yields within a reasonable amount of time. Some crops take a very long time to reach productivity, which can be fine on cheap land in an outdoor field, but is difficult to justify in a greenhouse. Prior to reaching maturity, all crops in the Polydome system can still be intercropped with short-lived plants for added value use of the space.

- **Labor requirements**

It is difficult to estimate how much labor a polyculture system will require per hectare when compared to a traditional monocultural system, since a number of activities will be shared between crops.

However, some crops require additional care, such as pruning and training, which can alter the cost associated with cultivating that crop.

We used labor statistics found in pre-assembled crop budgets to make a basic categorization of “high,” “medium,” or “low” labor. However, we ultimately determined that this was perhaps an unreasonable criterion for elimination, since it would get rid of many crops of particular interest.

Instead we chose to consider the labor requirements when making the actual spatial arrangements of crops - for example, ensuring that “high labor” crops would be clustered together in areas of easy access. We also relied on these labor estimates in making our final cost calculations.

3. Supporting Elements

We defined a number of secondary elements that we considered necessary for system functioning. These include a vermiculture compost system, honeybees for pollination, and certain plant types that provide key ecosystem support functions. These were organisms that we included in the design regardless of their specific profitability, which in some cases was zero - though in all cases they represented at least some avoided cost.

Beyond these support modules, we also wanted to intercrop with companion plants. There are various functions that companion plants can perform, all of which we wanted to include strategically in our final system. These functions include, among others:

- enhanced flavor
- greater yield
- trellising or groundcover
- shading
- retaining moisture
- pest suppression
- pollinator and predator recruitment
- hosting beneficial insects
- trapping pests
- disease resistance
- pattern disruption (preventing pests from easily jumping from one food plant to the next)

We finally settled on a limited number of very versatile “helper plants”:

- **Comfrey**

Comfrey is a dynamic accumulator that extracts a wide range of nutrients from the soil, collecting them in its fast-growing leaves. Each plant contains up to 2 kg of leafy material when harvested, and breaks down easily when added into compost. Sterile cultivars exist, which can keep the spread of the plant confined to desired areas. These sterile cultivars can be propagated vegetatively.

- **Borage**

Borage is a versatile "nurse crop," known to assist a variety of plants in their growth, as well as repel a number of pests.

- **Nasturtium**

Nasturtium, which is also an edible plant, is known to repel woolly aphids, whiteflies, and an number of other pests. Studies have also shown that it attracts predatory insects.

- **French Marigold**

French Marigold is perhaps best known for its ability to fumigate the soil of harmful nematodes, with the effect persisting for several years afterwards.

- **Hyssop**

Hyssop is a purple flowering herb said to increase the yields of certain target crops.

Livestock and Mushroom Selection

We used a combined qualitative and quantitative methodology to select the appropriate mix and scale of livestock and mushroom integration into the Polydome system.

Qualitative (Primary) Factors

1. **Material and energy cycling:** maximize endogenously sourced materials and energy and minimize non-productive outputs.

2. **Beneficial interactions:** design and manage for biodiversity that increases productivity while improving resilience. In the case of livestock and mushrooms, this may need to be more passive than it is for crops and includes aspects like passive heating, CO_2 enrichment, and macro nutrients flows managed in compost.

- Pest control
- Nutrient cycling
- CO_2 enrichment
- Passive heating
- Biological diversity/resiliency
- Nutritional diversity
- Economic diversity
- Habitat

3. **Economic diversification:** adopt a portfolio approach to species selection and spatial orientation that reduces the amplitude of seasonal revenue fluctuations and minimizes exposure to market volatility.

Qualitative and Quantitative Factors

Based on the primary selection, we modeled the financial implications and market size to determine the appropriate scale for each component (within an order of magnitude).

4. Annual economic productivity per square meter

5. Established market demand (sometimes this is quantitative, sometimes qualitative).

Aquaponics

Aquaponics is a form of aquaculture that combines the cultivation of aquatic animals (typically fish) with aquatic and/or terrestrial plants.

Aquaponics improves the efficiency of both aspects of the system because the biological wastes from the fish cultivation provide the organic nutrients and irrigation for the vegetables while in turn the outflow water from the vegetable component is clean enough to recirculate to the fish component.

Essentially, aquaponics uses water as the medium for cascading nutrients within a relatively closed loop system. A properly staged aquaponic system can provide harvests throughout the year while reducing nutrient spikes and troughs.

The proposed aquaponic system focuses on the beneficial relationships between a key fish species: nile or red tilapia (*Oreochromis niloticus or Oreochromis spp*) and a number of hydroponically growing herbs and greens. While the choice between Nile and red tilapia produces different mass yields per square meter, they each produce virtually identical economic yields per square meter.

The tilapia family are the most commonly cultured fish in the world. They are stress tolerant and are a commercially desirable food. Nile tilapia are well adapted to feeding primarily on plant-based feeds such as grain and soybeans and can also consume algae and zooplankton. Research performed at the University of the Virgin Islands has worked to refine and optimize a tilapia-basil system and according to the model presented in this publication, it has a potential average annual gross economic productivity of $268.48 per square meter of installed capacity.[5]

Other options for aquaculture include a fish polyculture modeled after a Chinese system. It cultivates four species of carp that each occupy a different ecological niche: "the grass carp eats large plant material and grass clippings, the silver carp eats algae, the bighead carp eats zooplankton, and the black carp eats snails and other detritus."[6]

5 *Rakocy, J., R.C. Shultz, D.S. Bailey, E.S. and Thoman. 2004. Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. Acta Horticulturae. Vol. 648. p. 63–69.*

6 *Van Gorder, Steven D. 2000. Small Scale Aquaculture: A hobbyist's guide to growing fish in greenhouses, recirculating systems, cages, and flowing water. Breinigsville, PA: Alternative Aquaculture Association, Inc.*

The overall productivity may be lower than a high-intensity system with commercial feeds, but it has the potential for high net economic productivity and environmental impact minimization due to the elimination of feeding, operations, and maintenance costs. Tilapia and carp can productively co-exist with each other within a fish polyculture and have nearly identical temperature requirements.[7]

Tilapia and carp can both consume dried leafy vegetables as supplemental feed including comfrey, spinach, and vegetable amaranth. The fish in the aquaponics system can therefore serve an additional purpose of converting unmarketable or spoiled vegetables into usable and high quality calories. Adding animal manure to the aquaponics system increases primary productivity of phytoplankton and zooplankton—which in turn serve as additional supplemental feed. Therefore, the system can also accept a limited amount of the manure produced from the livestock portion of the operation.[8]

We also investigated the possibility of including European Eels (*Anguilla anguilla*) or American Eels (*Anguilla rostrata*) in the system.

Globally, eel is in high demand and a combination of factors have led the International Union for the Conservation of Nature (IUCN) to list European Eels as critically endangered and American Eels as threatened. Under these circumstances, closed-loop cultivation becomes desirable.

Until recently, it was not possible to grow young eel fingerlings, or glass eels, in captivity. This meant that all eel farming was necessarily dependent on wild-caught fish, which did nothing to reduce the worrisome pressure on the wild population. In the last year, new developments in specialized feed for baby eels have made it possible to cultivate these fish in captivity for the first time.

When more information becomes available regarding the costs and productivity eels bred fully in captivity, this could prove to be a profitable and desirable alternative for the Polydome system.

7 *Ibid.*

8 *Ibid*

Final Crop and Livestock Selection:

- apricot
- artichoke
- arugula
- asparagus
- basil
- bay laurel
- green bean
- blackberry
- blueberry
- bok choy
- carrot
- cherry
- chive
- cilantro
- cucumber
- currant
- dill
- fig
- garlic
- grape
- lettuce
- marjoram
- nectarine
- onion
- oregano
- parsley
- pear
- peas, snap
- peppers, bell
- raspberry
- rosemary
- sorrel
- spearmint
- spinach
- strawberry
- tarragon
- thyme
- tomato
- zucchini

Additional Products:

- chicken meat
- chicken eggs
- tilapia
- oyster mushrooms
- shiitake mushrooms
- honey

Support Crops:

- borage
- comfrey
- french marigold
- hyssop
- nasturtium

Mapping the System

Time, Space, and Context

After making a preliminary crop selection, we began to map the different interactions between the various elements in our target ecosystem.

In particular, as part of the SiD process, we look at the ecosystem through the lens of three key variables: space, time, and context.

The mapping exercises within the SiD process serve as a prelude to the design phase. In constructing the maps, we come to understand how all the different elements behave relative to one another, and how they respond to key environmental conditions and flows.

Constructing appropriate maps required that we gather additional data on the subset of elements that we went forward with after the previous phase.

To create an ecosystem containing both plants and animals, which uses space as densely as possible and cycles materials as completely as possible, we had to consider a number of distinct analyses: from time lines to spatial plots.

Time

Time is a critical factor in designing an agricultural ecosystem. Most elements within the system operate on both a diurnal and an annual cycle. Other elements, such as perennial crops and animals with longer life spans, also have a longer time scale to take into account.

Long-lived perennials (such as trees, bushes, etc.) often have an initial phase in which they are still reaching maturity and not yet at peak productivity. In these periods, it is possible to plant around them with other crops that have shorter growth and production cycles.

In order to understand the relevant activities in the Polydome system, we constructed two sets of time lines. One long-term time line was used to understand the longer-scale patterns of perennial crop development.

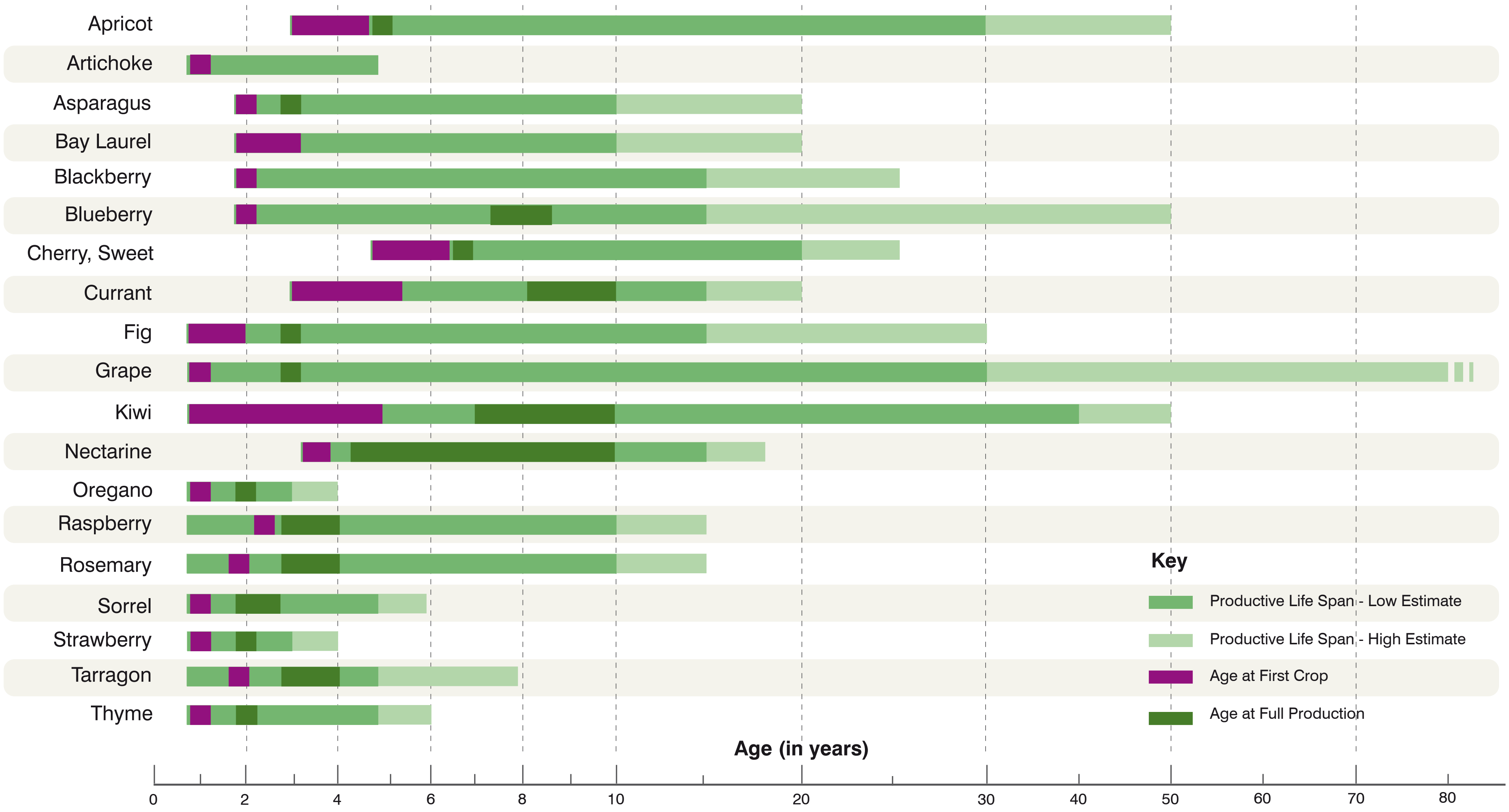
A second time line, showing an annual resolution of activity, was used to show times of year when each crop and livestock element needs different kinds of care: pruning, mulching, harvesting, etc.

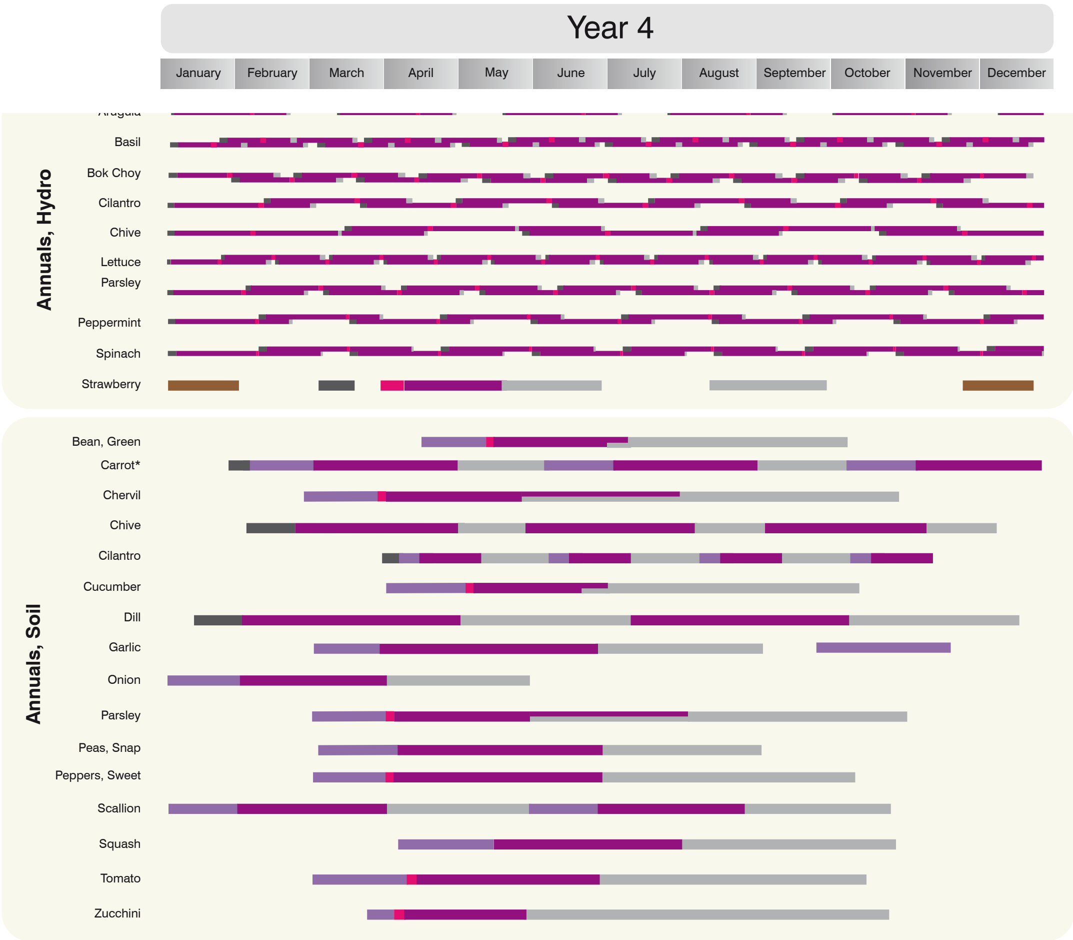
Within the time scale, we also had to consider crop rotation requirements. Several of our chosen annual species cannot be grown in the same location for more than one season.

Productive Life Cycles
The time line graphic to the right is used to understand the longer-term Cycles within the greenhouse, and to keep track of the changes in yields as the greenhouse reaches different stages of maturity.

It is clear from time line to the right that by the 30 year mark, most of the primary perennial crops will have exhausted their productive life spans. This kind of graphic can also provide guidance for longer-term planning - for example,by indicating when perennial crops need to be replanted.

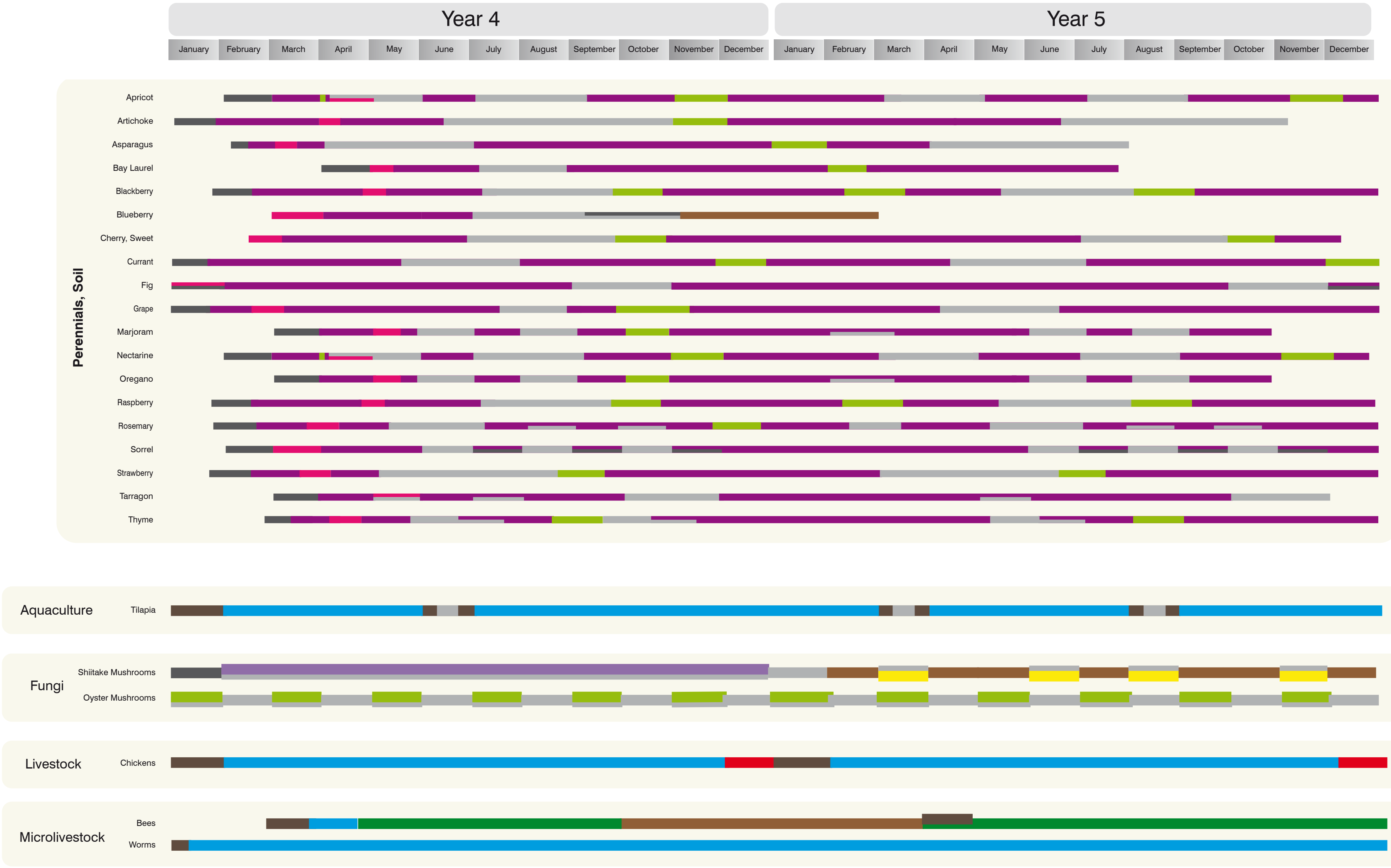
Productive Life Span of Perennial Crops

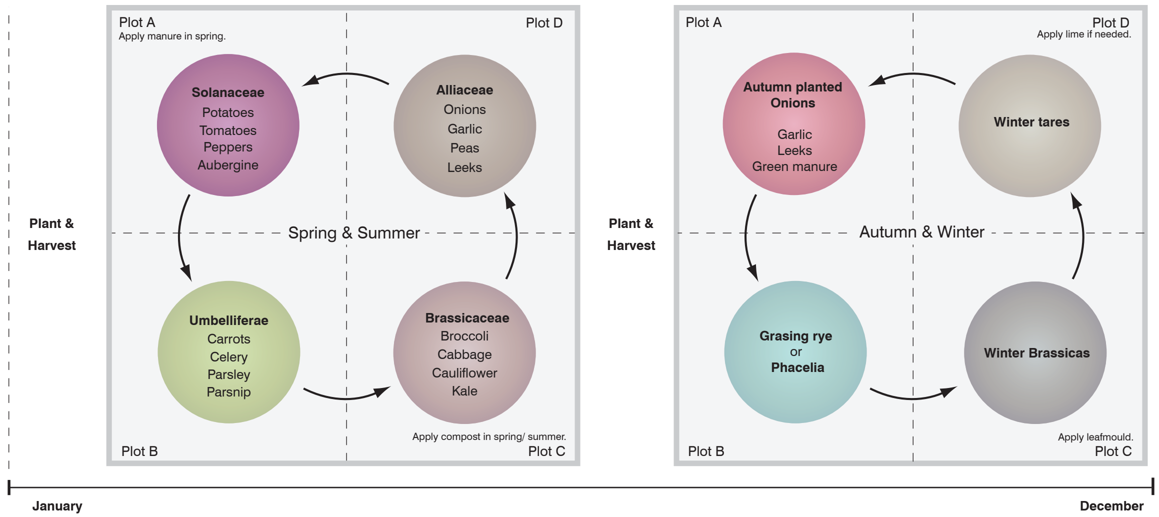




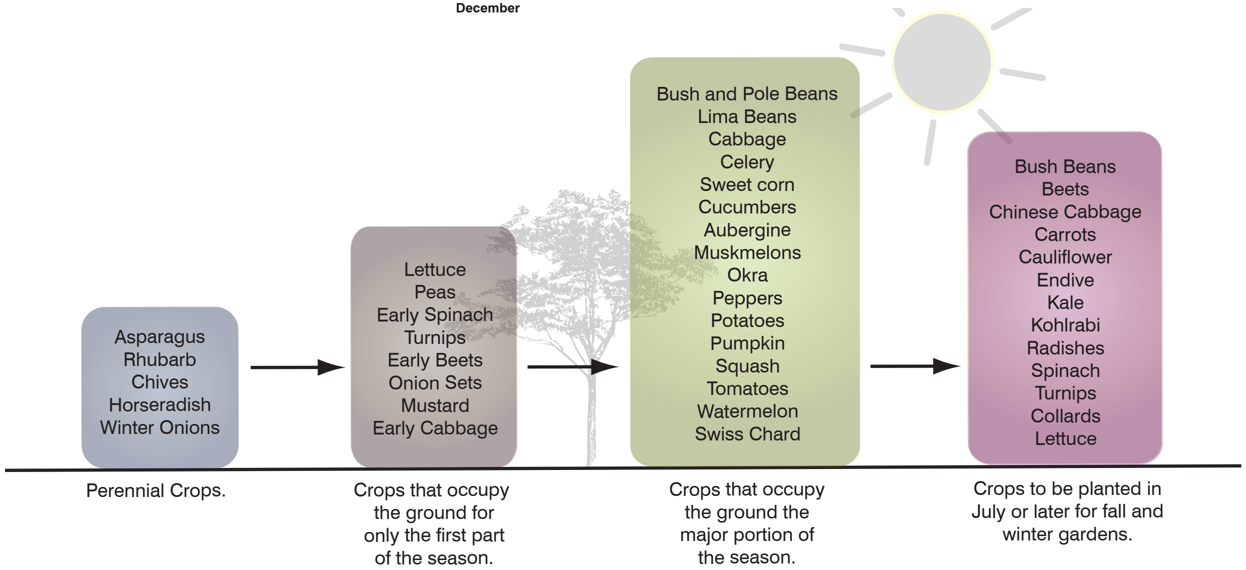
Annual Activity Cycles
These time lines illustrate the annual cycle of activity associated with each particular element in the system. From these snapshots, it is easy to see where periods of greater activity take place within the year. We also used the information in these graphics in constructing additional labor estimates for the entire system, and quickly determining periods of high labor requirement.

For ease of reading, The time lines have been split up by functional modules (hydroponics, annuals in soil, perennials, in soil, etc.) . The elements in each of these groups share a number of treatment patterns, which makes the system more manageable in terms of organizing and planning activities.


Year 4
Year 5
January
February
March
April
May
June
July
August
September
October
November
December
Perennials, Soil
Apricot
Artichoke
Asparagus
Bay Laurel
Blackberry
Blueberry
Cherry, Sweet
Currant
Fig
Grape
Marjoram
Nectarine
Oregano
Raspberry
Rosemary
Sorrel
Strawberry
Tarragon
Thyme
Aquaculture
Tilapia
Fungi
Shiitake Mushrooms
Oyster Mushrooms
Livestock
Chickens
Microlivestock
Bees
Worms



Four year crop rotation



Succession Planting

Space

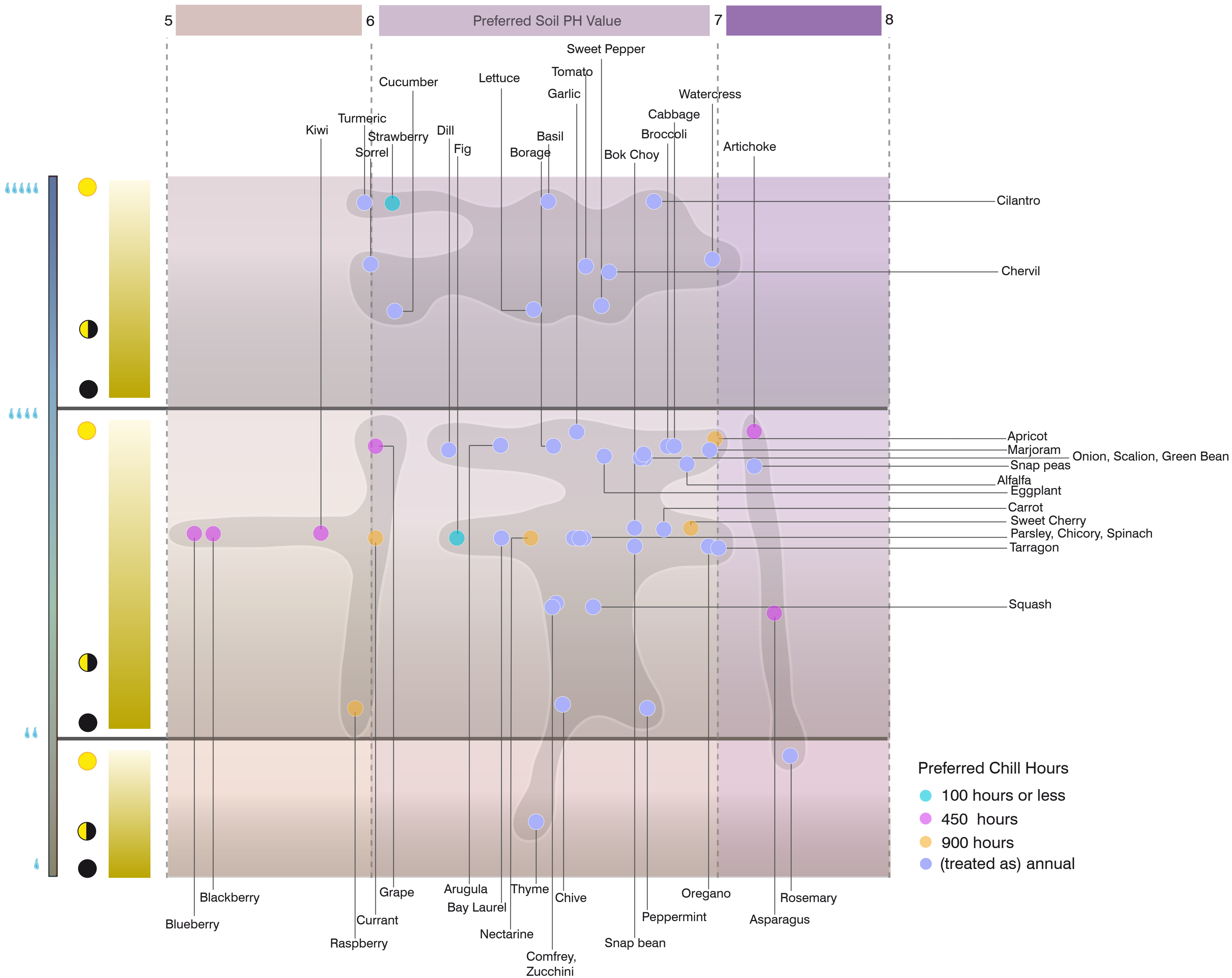
Several major factors affect the spatial layout of the crops and different modules in the Polydome system.

For crops alone, the primary considerations include:

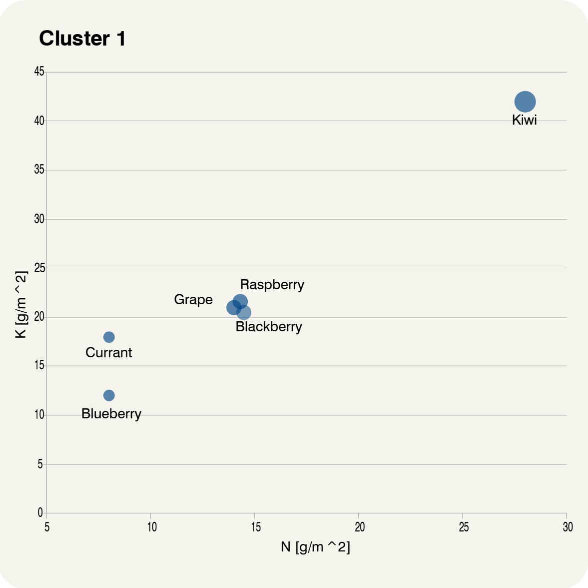
- Soil pH
- Soil type
- Water requirements
- Light requirements
- Plant Height and Spread
- Root Depth
- Nutrient requirements
- Labor requirements
- Crop Rotational Requirments
- Necessary Chill Hours
- Cold Hardiness

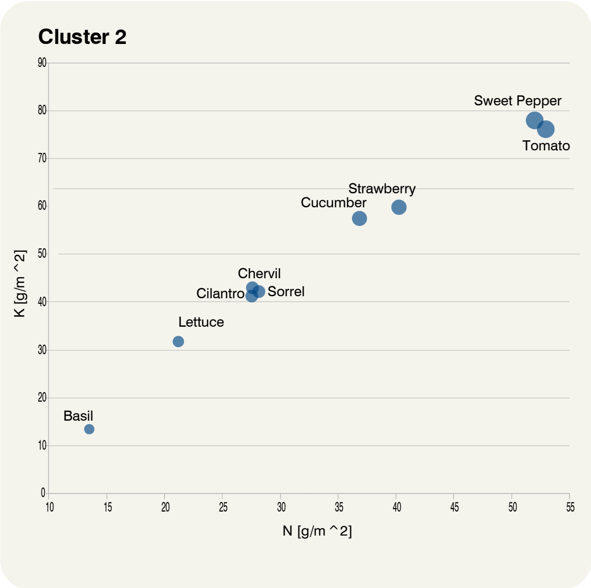
To understand the impact of each of these factors on physical crop placement, we created maps that combined a number of the factors, arriving at progressively higher-level understandings of the interrelationships between the crops.

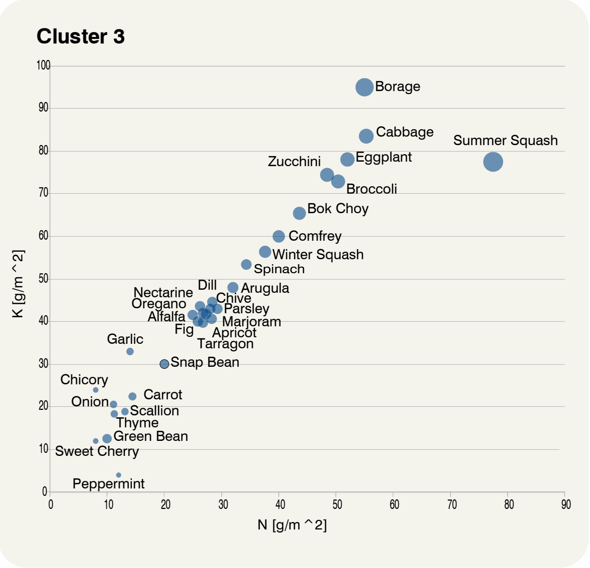
Spatial considerations for fish, livestock, and mushrooms were made later on in the analysis - in the system optimization phase, and in considering the final layout of the greenhouse structure.

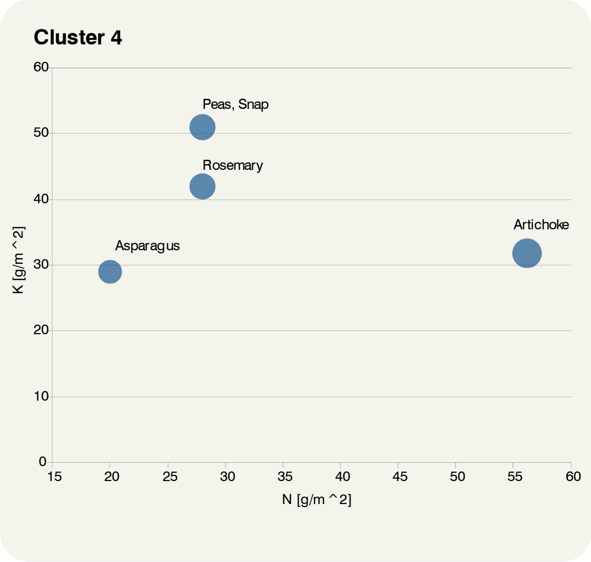


5
6
Preferred Soil PH Value
7
8
Sweet Pepper
Tomato
Garlic
Cucumber
Lettuce
Watercress
Cabbage
Broccoli
Turmeric
Kiwi
Strawberry
Dill
Sorrel
Fig
Basil
Borage
Bok Choy
Artichoke
Cilantro
Chervil
Apricot
Marjoram
Onion, Scalion, Green Bean
Snap peas
Alfalfa
Eggplant
Carrot
Sweet Cherry
Parsley, Chicory, Spinach
Tarragon
Squash
Blackberry
Blueberry
Grape
Currant
Raspberry
Arugula
Bay Laurel
Thyme
Nectarine
Chive
Comfrey, Zucchini
Oregano
Peppermint
Snap bean
Rosemary
Asparagus
Preferred Chill Hours
100 hours or less
450 hours
900 hours
(treated as) annual







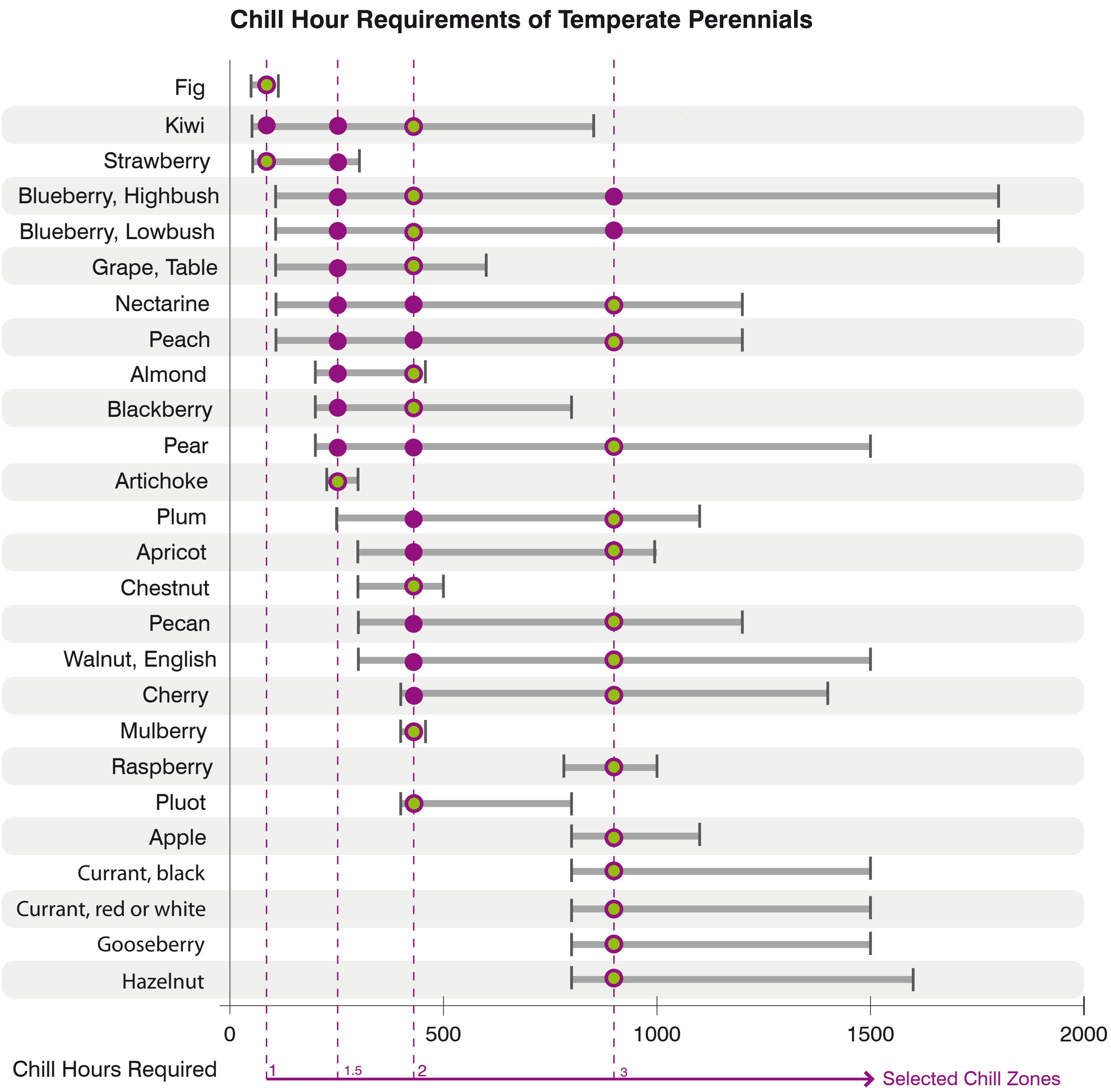


These two graphics represent a large part of the analysis we did to understand spatial grouping requirements for the crops within our system.

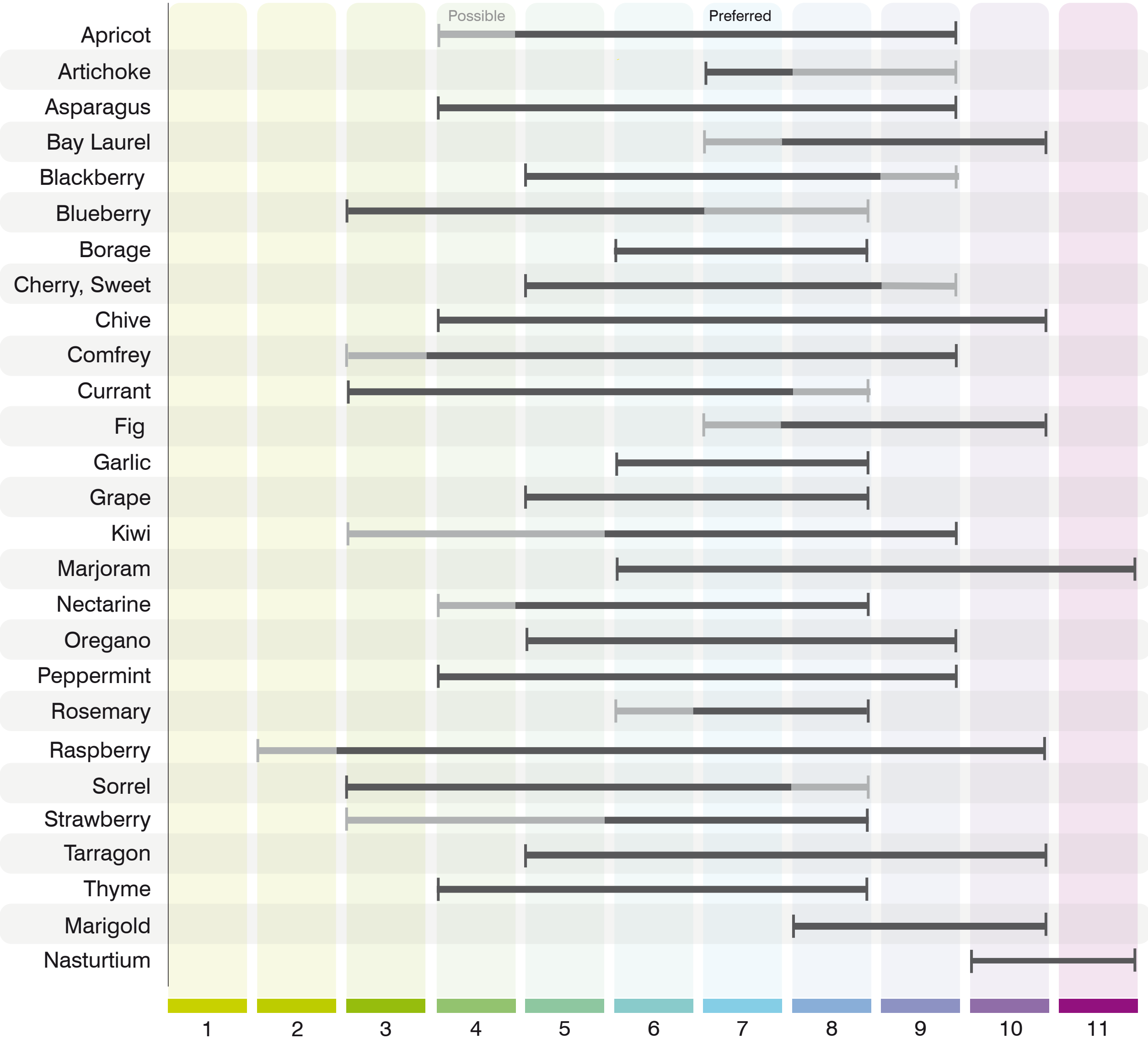
On the far left is a plot which has three scales corresponding to key plant preferences: light demand, water demand, and soil pH. An additional level of information regarding chill hour requirements is added into the graphic using the colored rings around the dots representing each crop.

By plotting each crop on this grid, we were able to visually resolve which of the plants have similar preferences in terms of their basic siting needs. We used this map to identify four main "clusters," which would be used in all further spatial analysis.

We then took each of these clusters, and represented the plants within them as a function of their nutrient demand (shown in the adjacent graphic). This allowed us to make further refinements for plant grouping.


Chill Hour Requirements of Temperate Perennials
Fig
Kiwi
Strawberry
Blueberry, Highbush
Blueberry, Lowbush
Grape, Table
Nectarine
Peach
Almond
Blackberry
Pear
Artichoke
Plum
Apricot
Chestnut
Pecan
Walnut, English
Cherry
Mulberry
Raspberry
Pluot
Apple
Currant, black
Currant, red or white
Gooseberry
Hazelnut
0
500
1000
1500
2000
Chill Hours Required
1
1.5
2
3
Selected Chill Zones

Cold Hardiness of Temperate Perennials



The temperature sensitivity of perennials is a very important factor in determining their spatial placement in the Polydome greenhouse arrangement.

In particular, we needed to know which of the perennial crops we wanted to cultivate could survive in the "chill zone," which is designated to remain unheated for most of the winter.

The two graphics on the left were instrumental for identifying and illustrating which perennials could be located in the chill zone, and which needed to be kept relatively warm throughout the year.

Context

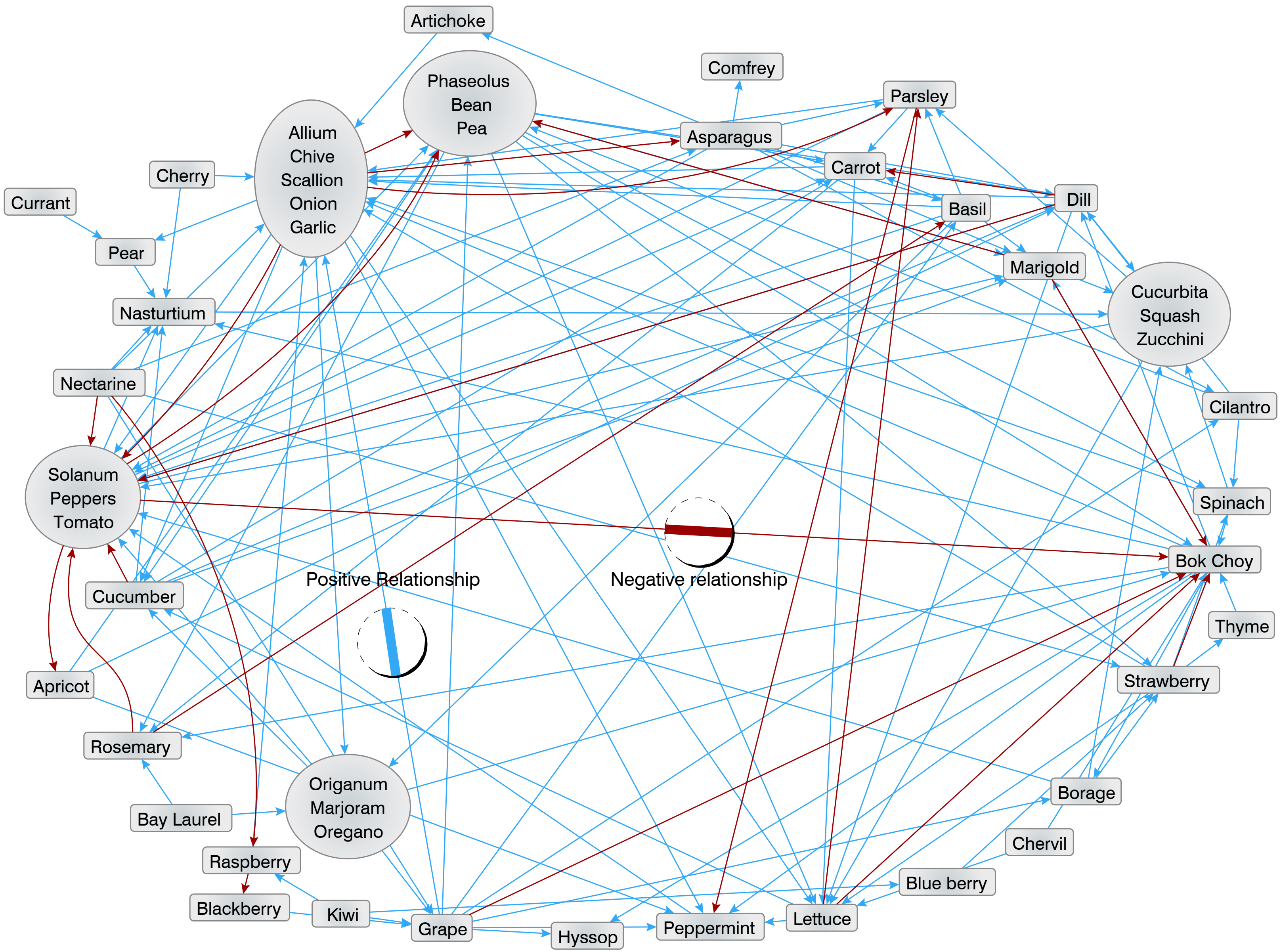
The primary analyses we did regarding the "context mapping" of the system involved analyzing known companion plant relationships as well as constructing material flow balances.

Companion plant information is not always entirely reliable, since much of the available data is somewhat anecdotal. However, several agricultural extension services and Universities have also published lists of companion plant groups, which can be considered more reliable.

In the limited research studies available on companion planting, there have been some impressive findings on the successful impact of such interactions. One source cited a yield increase as high as four-fold as the result of interplanting a Brassica crop with Elm oyster mushrooms.

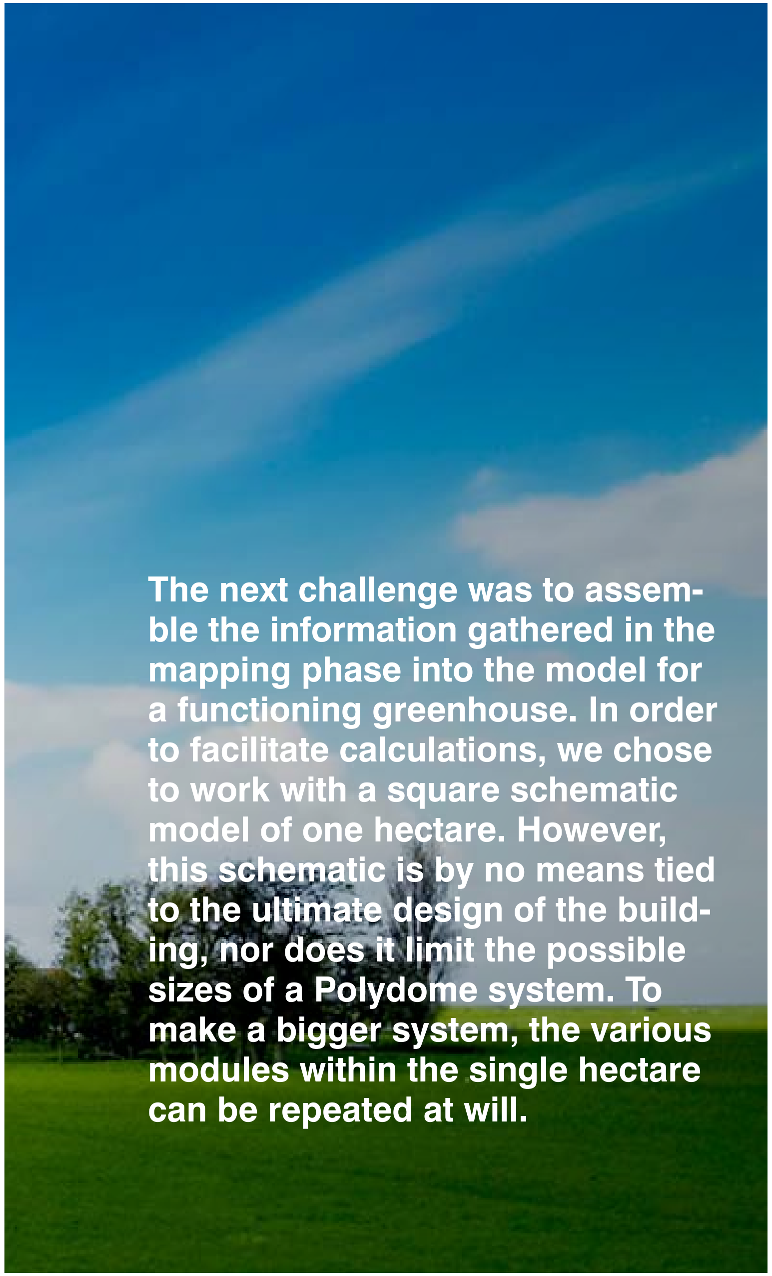
Companion Planting Network
The network diagram on the right shows the available companion planting data on our final crop selection. This map was used in constructing the final crop groupings and layouts.

The diagram shows the relationship between individual plants, reduced to positive or negative values. A positive value means the plants thrive well in each other's vicinity, performing better than when alone or in a group of similar plants. A negative relationship means that the plants are detrimental to each other when grown in close proximity.


Artichoke
Comfrey
Phaseolus
Bean
Pea
Allium
Chive
Scallion
Onion
Garlic
Parsley
Asparagus
Carrot
Cherry
Currant
Pear
Dill
Basil
Marigold
Nasturtium
Cucurbita
Squash
Zucchini
Nectarine
Cilantro
Solanum
Peppers
Tomato
Spinach
Bok Choy
Positive Relationship
Negative relationship
Cucumber
Thyme
Apricot
Strawberry
Rosemary
Origanum
Marjoram
Oregano
Borage
Bay Laurel
Chervil
Raspberry
Blue berry
Blackberry
Kiwi
Grape
Hyssop
Peppermint
Lettuce

Optimizing the System

Combining the Elements



The next challenge was to assemble the information gathered in the mapping phase into the model for a functioning greenhouse. In order to facilitate calculations, we chose to work with a square schematic model of one hectare. However, this schematic is by no means tied to the ultimate design of the building, nor does it limit the possible sizes of a Polydome system. To make a bigger system, the various modules within the single hectare can be repeated at will.

The relative ratios of the various modules have significant implications for material cycling, economic returns, and the suitability of the greenhouse to service local populations. Crop selections can be made to optimize for any one of these key factors, or a balance of all at once.

As stated previously, our current design optimizes primarily for economic productivity and beneficial plant interactions. This does not result in the closure of all material loops, but the design could be relatively easily adjusted to do so.

Crop Cluster Development

The assembly of functional crop clusters involved the use of the various maps and graphics shown on the previous pages as continuous data references. Every time we created a plant grouping, we tested it on various parameters to ensure it wasn't violating any non-compatibility issues.

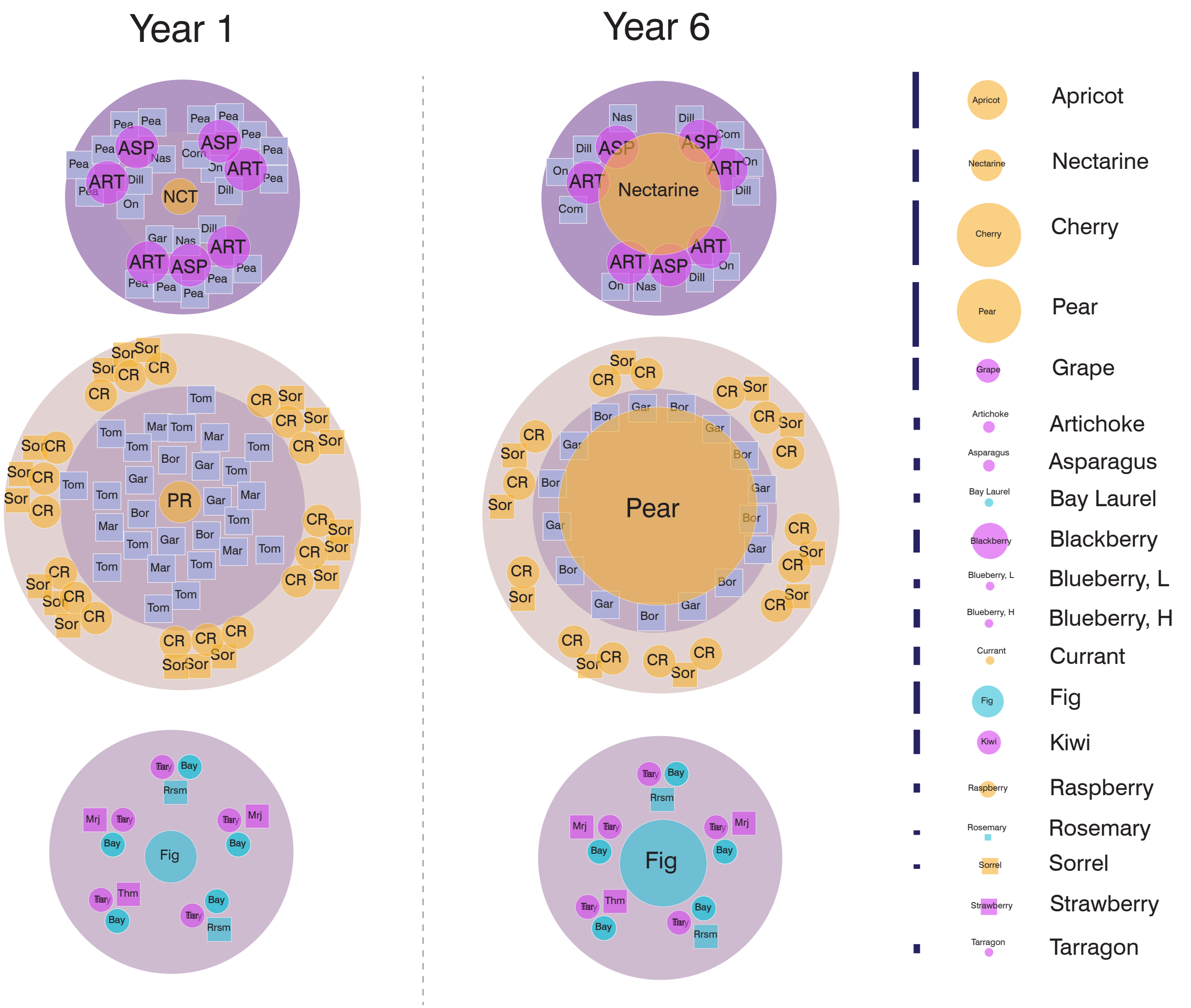
Key crops were selected as starting points. In most cases, we chose a high value perennial or a prominent annual to form the center of the cluster.

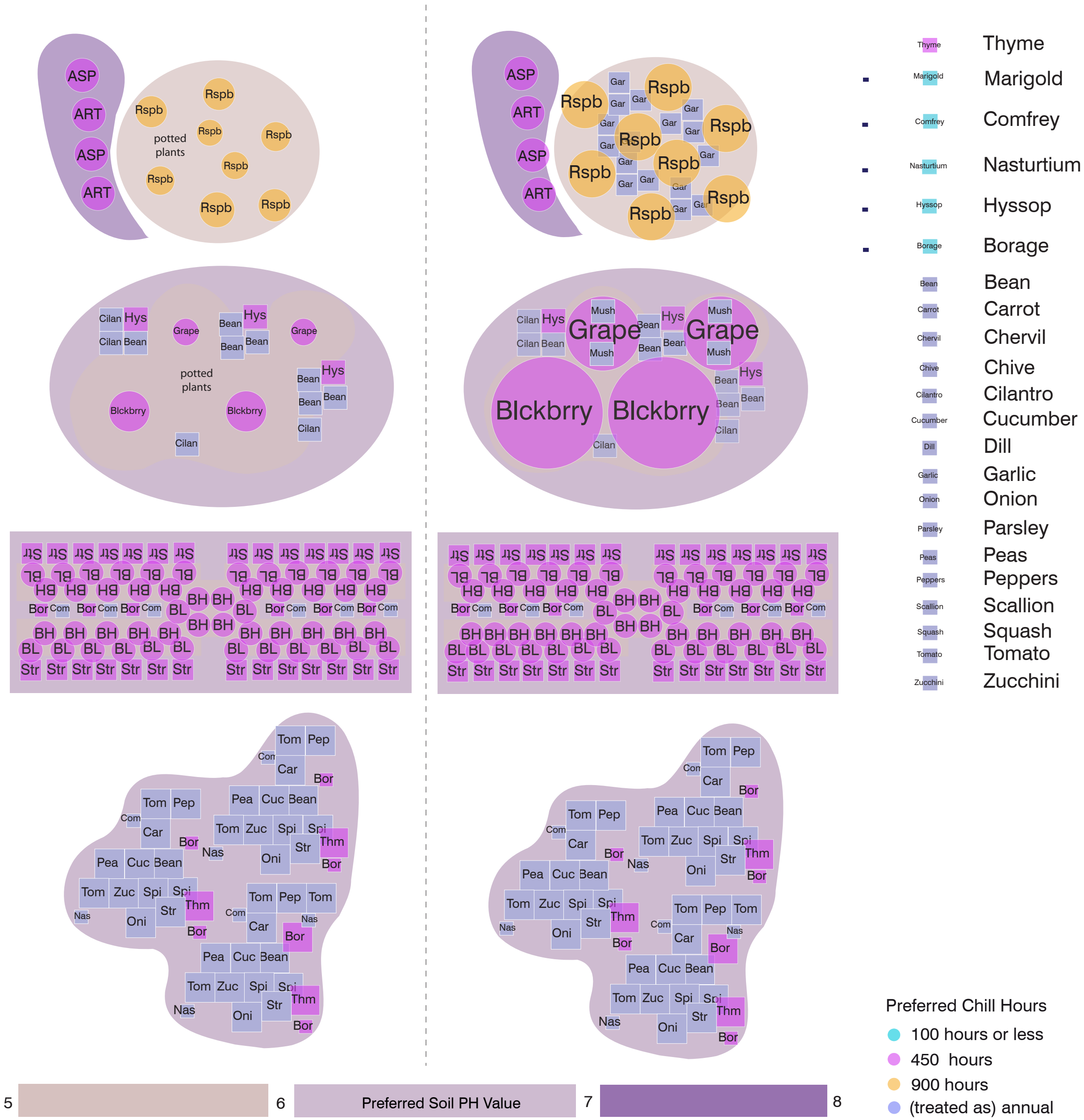
We defined soil, pH, and water requirements for that key plant, and then began to assemble useful companion groupings taking into account all the spacial factors listed previously (light, water, and other requirements).

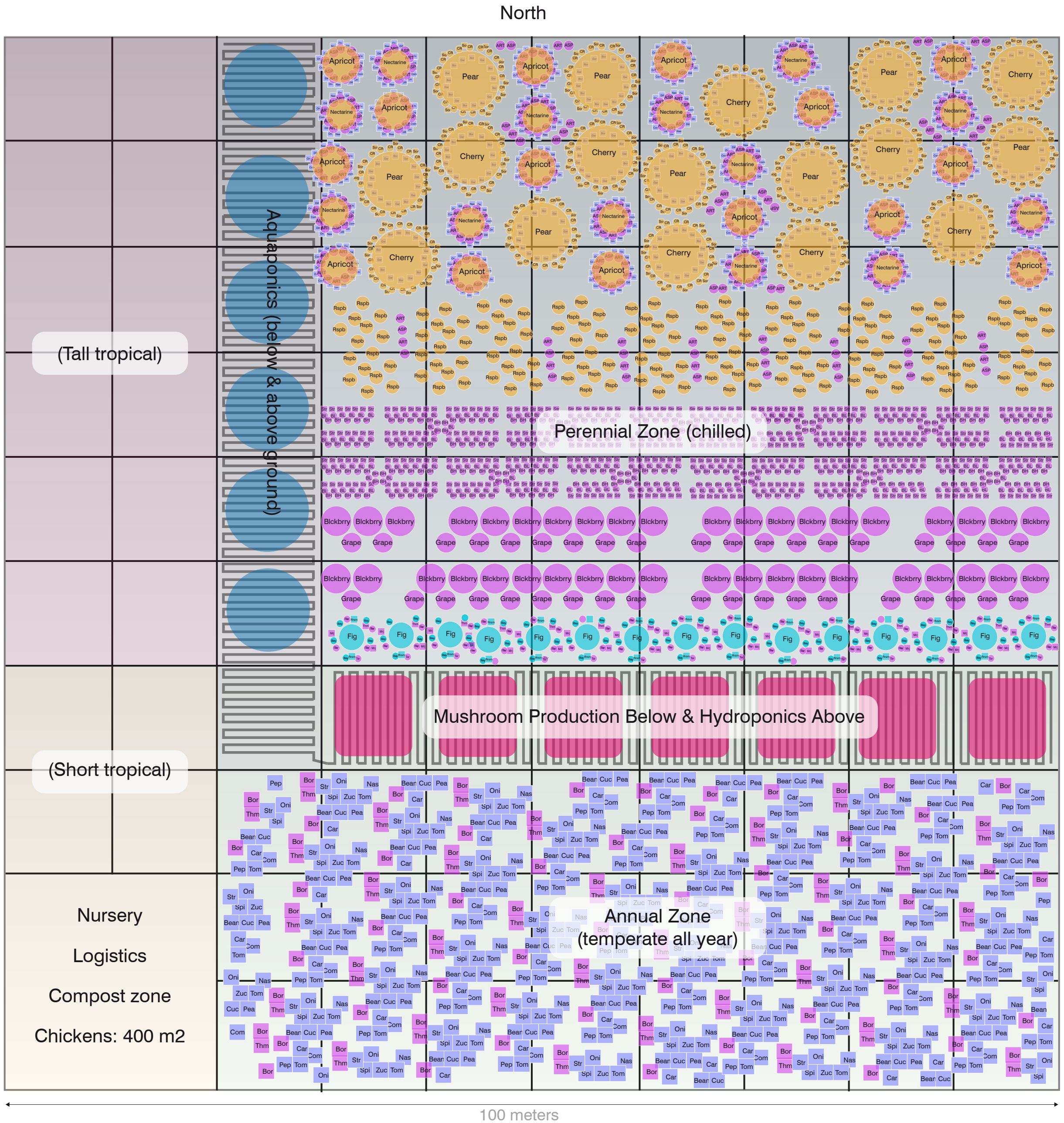
The result was a series of crop clusters consisting of 3 - 8 crops each. These clusters are the building blocks of the Polydome system, and can be matched and interchanged depending on the final requirements of the system.

Wherever relevant, we also modeled how these crop clusters might change over time. This was significant in the case of trees and large bushes.

In the graphical representations here, all trees and crop elements are "scaled" accurately to one another, taking into account their mature height and spread.




potted plants
Thyme
Marigold
Comfrey
Nasturtium
Hyssop
Borage
Bean
Carrot
Chervil
Chive
Cilantro
Cucumber
Dill
Garlic
Onion
Parsley
Peas
Peppers
Scallion
Squash
Tomato
Zucchini
Preferred Chill Hours
100 hours or less
450 hours
900 hours
(treated as) annual
5
6
Preferred Soil PH Value
7
8



Final Greenhouse Layout

Once we developed all of our final crop clusters, we arranged them on a schematic one-hectare greenhouse plot.

Just as with the development of the functional crop clusters, the large-scale placement of these groupings was also carefully considered in terms of heat and light requirements, seasonal chilling, and soil pH gradients.

The north-facing side of the greenhouse was assigned to the tree crops (none of which are taller than 8 meters at maturity), and intercropped with a variety of perennials and annuals, as determined by the crop clusters.

This tree-zone gives way to a series of lower perennials: cane fruit bushes, blueberries, asparagus, artichoke, and grapes. The grapes mark the end of the “chill zone,” which needs to be cooled during the cold months of the year.

Next comes a thin band of perennials that does not require chilling: figs and Mediterranean herbs such as tarragon, rosemary, and bay leaf.

In between the perennial zone and the annual zone is where the greenhouse logistics center will be located. A strip of aquaculture and intensive hydroponics is placed near this central zone.

Finally, the hydroponic zone is located in suspension over the centrally located mushroom modules, and also extends in a fan shape (at much lower density) over the temperate annual zone, which faces the south side of the greenhouse.

In this greenhouse model schematic, we have left a strip empty at the left, which indicates where the tropical zone could have gone. It would also have had a gradient from high to low plants, following the north-south line.

In this case, the space is assumed to be assigned for nursery functions, additional logistics, chicken zone, compost, supplementary equipment for the hydroponics facility, and any other functions that have not been placed elsewhere. It would also have been possible to stretch the temperate zone horizontally to fully fill the width of the graph, and locate these other service zones elsewhere.

All of these elements have been sketched in a more realistic fashion in the visualizations, giving a sense of what the interior space might actually feel like.

Summary of Annual Yields

Category	kg / year	people supplied
Fruits	*27455*	*458*
Vegetables	*110471*	*1841*
Mushrooms	*69800*	*6980*
Herbs	*190543*	*38109*
Fish	*105233*	*7016*
Chicken meat	*10479*	*233*
Eggs (not in kg)	*1404000*	*5200*
Honey	*500*	*1250*

Modeling Economic Productivity

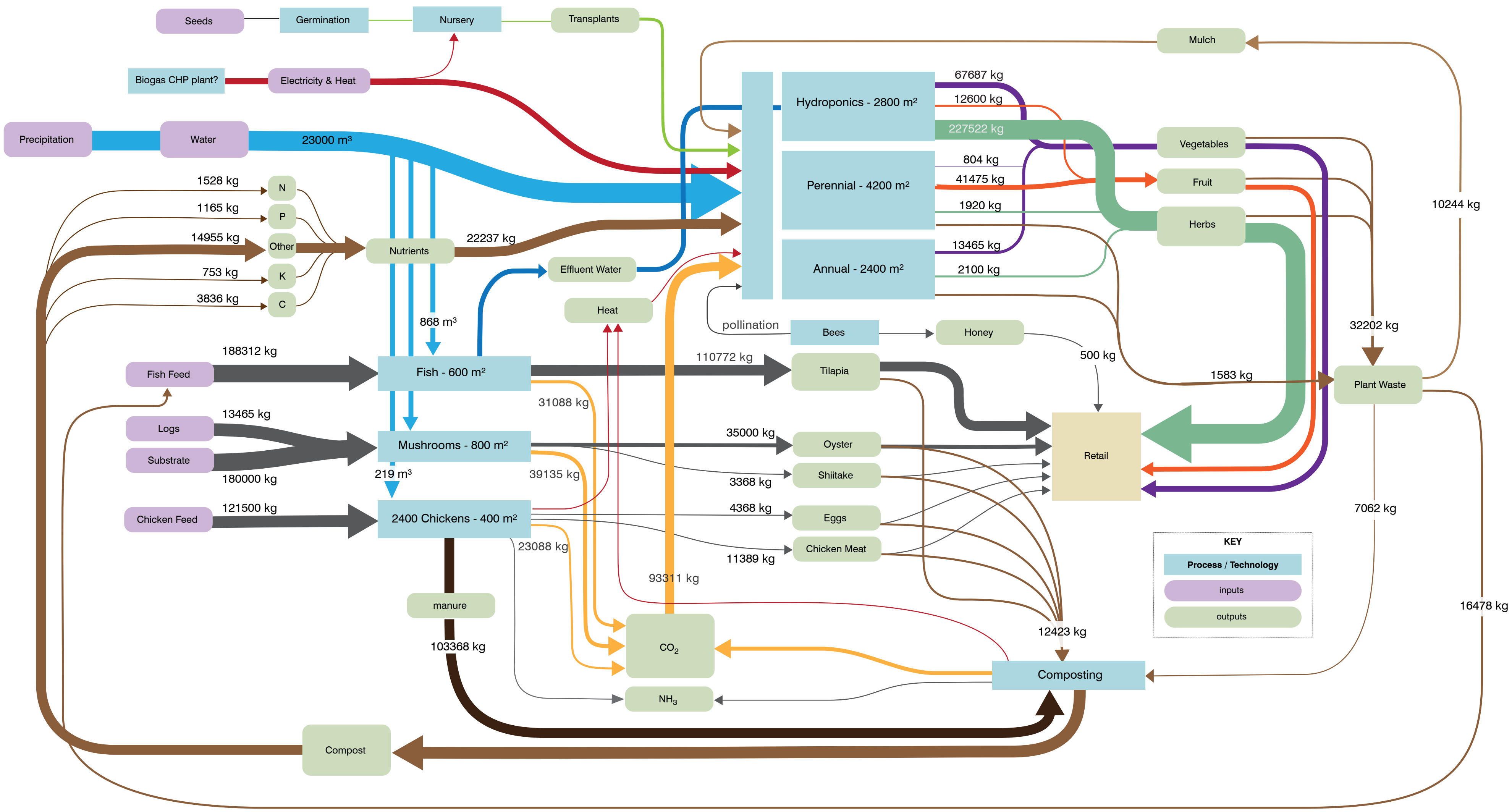
The economic productivity of the greenhouse was modeled by taking the one-hectare schematic, and extrapolating yields per plant cluster per year. We modeled years one, three, and six in order to get a range of productivity values as the greenhouse reached maturity.

The yields displayed in the chart on the left represent what can be expected from the greenhouse model in the sixth year of its operations, once all of the perennial crops have reached maturity.

In year six, the average productivity per square meter is estimated at 78 kg of marketable product (having built in an estimate that 10 - 15% of each harvest will not be marketable). This is comparable to high-yielding Dutch tomato greenhouses, and represents a much larger variety of crops.

The vast majority of the economic output comes from the hydroponic herbs, and is followed by the mushroom and the fish modules. The remaining modules are still profitable in combination, but not to an equally large extent.

Optimizing the System



Material Flow Analysis

The Material Flow Analysis for this test case greenhouse is as complete as we could make it, considering a number of uncertainties remaining in the system design.

We made particular efforts to track not just the overall quantity of green waste traveling out of the system and then returning as compost, but to actually make estimates as to its elemental composition. We modeled estimates for N, P, K, and C breakdowns whenever available.

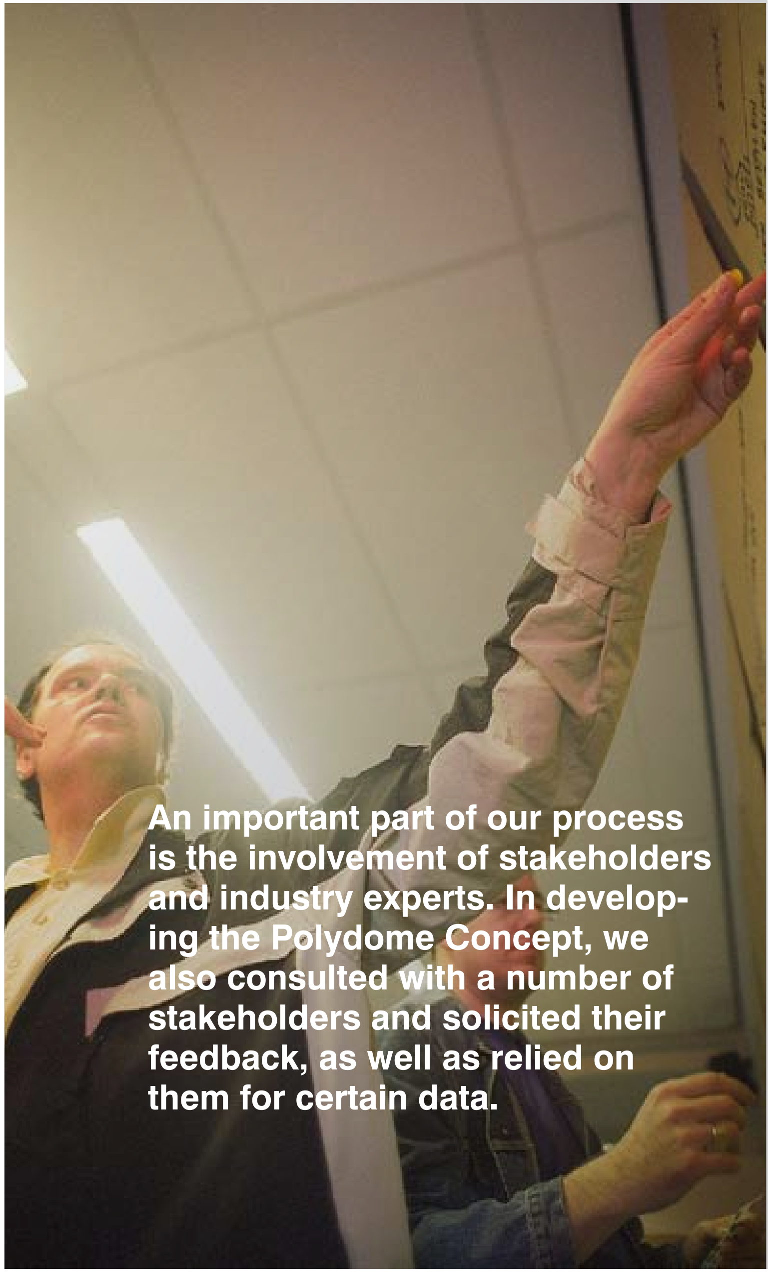
In addition, we were able to model the generation of heat and CO_2 from the animal, mushroom, and compost modules. The CO_2 production from mushrooms and chickens alone is only around 2,4% of the level of output achieved by a commercial CO_2 generator. However, the additional source provided by compost is very large and easily scalable, which means that it could be adjusted to provide the necessary supplemental CO_2.

Our conclusions are that the system can easily supply its own nutrients if it contains a livestock module. We have calculated that the nutrients contained in the compost stream relative to the demands of all the crops are more than fully satisfied, largely as a result of the chicken manure. In fact, the number of chickens in the model is quite a bit too high from a nutrient cycling perspective; they are largely included for their value as secondary products. In the next iteration of the design the number should probably be reduced quite significantly.

To fully close the nutrient loop, we would ideally find a means of producing all fish and chicken feed on site. Both the fish and the chicken can consume some of the vegetable waste generated in the system to provide some of their nutrients. Vegetable waste is lower quality than commercially available feed, so it cannot be considered a complete source. Because tilapia are vegetarian, fish feed for their consumption can easily be generated by growing algae or other suitable plant matter. Chicken manure can be readily used as a fertilizer for algae. This is something that could be added into a subsequent model of the system.

We have made rough estimates on electricity inputs, assuming that we have a moderate amount of supplemental lighting into the facility. We have assumed that the greenhouse will also be equipped with a FiWiHex system, reducing or eliminating its heat requirements. However, the energy aspects of this model are the least accurate.

Interviews & Feedback Sessions



An important part of our process is the involvement of stakeholders and industry experts. In developing the Polydome Concept, we also consulted with a number of stakeholders and solicited their feedback, as well as relied on them for certain data.

In particular, we spent time visiting the facilities of:

Koppert Biological Systems, where we spoke with entomologist and consultant, Tim Bossinga. Koppert is an international firm, which specializes in providing biological control services and natural pollination to both greenhouse and outdoor growers. Our conversation with Tim gave us many new insights into the practice of managing insect populations within greenhouses. In particular, we learned how broadly used beneficial insects already are for pest control in the Dutch greenhouse sector. We also discovered certain restrictions on keeping insect populations in greenhouses, such as how many of them are unable to handle prolonged exposure to high levels of CO_2.

Technokas and Bode Projecten, where we spoke with director Peter Zwinkels and engineer Bart Wolters. These sister companies are experienced in handling the design and establishment of greenhouses from concept through construction. As such, we were able to gain many insights into the general costs and requirements of establishing and operating a greenhouse. Additionally, Technokas is the originator of the Fresnel Daylight System, which we were very interested in exploring as a potential energy-producing option for the Polydome greenhouse.

Fytagoras, where we spoke with Arie Draaijer, Wessel Holtman, and Henrie Korthout. Fytagoras is a spin-off company from Dutch research institute TNO. They conduct a variety of studies on the growth and development of plants, particularly as relates to greenhouse management. Among many other things, we learned about the importance of gas sensors in greenhouses, the impact of oxygen levels on root systems, and the commercial need for synchronizing plant germination. These ideas influenced our thinking about which basic technological systems must still be included in a Polydome model.

PlantLab, where we spoke with Gertjan Meeuws. PlantLab is an innovative company exploring the possibilities of efficiently growing plants under fully artificial conditions in order to achieve maximum turnover and efficiency. We learned a great deal about the artificial environments in which plants can flourish, including that when all other conditions are right, they can continue to grow just as quickly, if not faster than usual, with only 7% of their normal light exposure.

Bouwen met Groen en Glas, where we spoke with Emile Quanjel. BGG is a campaign, which helps stimulate the integration of glass and plant elements into the built environment. We wanted to explore the possibilities for the use of a system like Polydome, and discover which stakeholders might be interested.

Kainga Farm, where Bianca Verrijdt gave us an inspiring tour of her small polycultural farm. Though we visited only after most of our research had been completed, we were gratified to find real-life confirmation that many of the concepts we were working with do bear out in practice. We were charmed by the delicious food and happy animals.

Conclusion

Though much of the knowledge used in the development of the Polydome concept is not new, it is the way in which this knowledge has been combined that is unique.

The Polydome concept shows how we can move away from monocultures while maintaining a modern, highly-efficient approach to food production. By combining the unique benefits of greenhouses with the many untapped opportunities of polycultures, we create a system that creates a multitude of positive impacts: on individuals, on economic health, and on the environment.

The primary innovation of Polydome ultimately lies in its absolute maximization of production density and diversity. To our knowledge, no other commercial food production facility is capable of outputting comparable diversity and yield. This aspect alone makes it a promising direction for sustainable agriculture. The more concentrated our food production, the more land can be spared from going under the plow.

Even more exciting is the realization, that by following through on the design principles of Polydome to their fullest extent, we can achieve something previously unheard of in human history: net zero-impact food production.

By using the latest greenhouse technologies, we can ensure that all energy and water used within the system come from renewable sources. By applying intelligent design, we can eliminate drudgerous labor and allow the animals within the system to retain their natural behaviors. Relying on carefully designed plant interactions and soil care to manage pests and diseases will eliminate the need for chemicals. Locating the greenhouse near points of direct consumption will cut out the entire impact chain associated with the packaging and transport of food.

If they work as modeled, Polydome systems could revolutionize food production. For the first time in history, we could have cities that are net food producers, capable of supporting themselves from within rather than relying on vast tracts of hinterland. A city the size of Rotterdam (600.000 residents, a total of 20.600 hectares of land), would require between 120 and 600 hectares to provide 80% of its food needs, or less than 3% of its total land area. This means that Polydome is a potentially vital building block of a resilient, sustainable society.

We estimate that the entire population of the Netherlands could be largely fed using between 3.200 - 8.000 hectares of Polydome greenhouses, which is considerably less than the 10.000+ hectares currently under greenhouse cultivation.

Even though the Polydome concept needs to be further developed and tested, the potential it holds cannot be ignored. We must start on the path towards truly sustainable food production: Polydome can be one of the routes.

Colofon

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Acknowledgements

Our sincere thanks go out to everyone who assisted us in the course of the Polydome study. Without you our project would not have developed into what it is today.

Our thanks go out to our interviewees at:

Koppert Biological Systems:
Tim Bossinga

Technokas & Bode Projecten:
Peter Zwinkels and Bart Wolters

Fytagoras:
Arie Draaijer, Wessel Holtman and Henrie Korthout

Plantlab:
Gertjan Meeuws

Bouwen met Groen en Glas:
Emile Quanjel

Kainga Farm:
Bianca Verrijdt

InnovatieNetwerk:
Peter Oei

“Agriculture is the noblest of all alchemy; for it turns earth, and even manure, into gold, conferring upon its cultivator the additional reward of health.” - Paul Chatfield