Association for Vertical Farming

CONTROLLED AGRICULTURE & ECOSYSTEM ECONOMIES

A Thought Leadership Piece on Using Vertical Farming Systems to Feed Each Other and Create Greener Urban Spaces

ASSOCIATION FOR VERTICAL FARMING 2017

IMAGE: METRO GROUP

"We see the future as a place where circular systems are researched as readily as linear systems are researched today.

Association for Vertical Farming

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Association for Vertical Farming

AUTHORS

Initiated by the Association for Vertical Farming - AVF - a project group, named AVFami (aquaponics, mushrooms, insects), was formed consisting of members of the AVF. International scientists gathered together in order to illuminate the potential to overlap several systems of indoor food production, leading to a theoretical biological model that encapsulates the spirit of ecosystems.The Association for Vertical Farming is an internationally active non-profit organization of individuals, companies, research institutions and universities. Authors, editors, and team members on this project include:

ZJEF **VAN ACKER** | **Mushroom Ambassador**

Zjef is an applied bio-engineer from Belgium who has been on a vertical farming quest since 2012. He combines his passion for vertical farming with his passion for international collaboration to help transform our society into a healthy ecosystem. Within the AVF he works around education and organises multiple events around the world. He is CEO of KIKVORS and is also leading an AVFami inspired mushroom project in Ghent, Belgium.

SEPPE **SALARI** | **Insects Ambassador**

Seppe has been interested in plants and nature ever since he was a boy and started helping his grandfather in his vegetable garden. To follow in his footsteps, he started a bachelor's degree in plant sciences at Wageningen UR located in the Netherlands and is now pursuing a Masters degree there. Along the way his interests expanded. His dream is to turn organic waste back into food and create a circular food-system. To accomplish that goal, he's growing black soldier flies, strawberries, Tilapia, and mushrooms in a small scale experimental system.

MEGAN **MUNKACSY** | **Aquaculture Ambassador**

Megan is the Project Group Manager for AVFami and a marine biologist who specializes in shellfish biology and aquaculture. Currently, she works on oyster restoration full-time in the United States. With the AVF, she is building her understanding of modern, terrestrial-based for systems, so that she can begin to bridge the gap between the marine aquaculture and vertical farming worlds.

RADU **GIURGIU** | **Plants Ambassador**

Radu is a nature-geek. At the end of 2016, he obtained a PhD in Agronomy with a study on Medicinal Plants in Controlled Environment. He is a firm believer that building bridges between knowledge and technology can result in positive alternatives to food production systems on the way to achieving sustainability. He is involved in multiple international projects gravitating around plant science and food security.

This group was supplemented by Penny Mc Bride, Andreas Woell and Erik Denkhaus

PENNY **MCBRIDE**

Penny has worked for the past 15 years in sustainable food solutions and organic waste management systems. Most recently, she helped to found Vertical Harvest of Jackson Hole located in Wyoming, which is a three-story hydroponic greenhouse that not only supplies fresh produce to local grocery stores and restaurants, but also employs individuals with developmental disabilities. Through the years of project development and implementation of Vertical Harvest, Penny gained a vast amount of experience understanding greenhouses systems, regulatory requirements, financing, and community development. Penny now operates a consulting group that helps small and large scale developers with feasibility studies, development and implementation of urban agricultural solutions.

ANDREAS **WOELL**

Andreas is founder and General Manager of ANSI-Culture Consultants UG located in Germany. He gained more than 25 years of experience on international terrain in the field of renewables and energy efficiency, in particular. Animated by the "Sahara Forest Project" (http://saharaforestproject.com/) some years ago, Andreas started to focus on awareness raising, support and ideas all around the topics related to modern indoor farming concepts. This includes themes like aquaponics, ecological reasonable hydroponics, vertical farming, completed with renewable energy sources and energy efficiency measures. His consulting firm assists interested operators for an indoor farm from the first idea up to the realization of the project. Andreas has a large international network of governmental, non-governmental entities and companies in the field of Aquaponics, Hydroponics, Renewables and Energy Efficiency.

ERIK **DENKHAUS**

Erik completed his masters in plant biotechnology in 2015 in Stellenbosch, South Africa. Since then he has used his scientific training and motivation to help find solutions for innovative food production techniques. Erik has completed internships with the EDEN ISS team at the DLR, the German Aerospace Center, which is the national center for aerospace, energy and transportation research of Germany as they design systems for plant cultivation during space flight missions. He is currently working for Agrilution in Munich, Germany and is motivated as ever to be involved in the vertical farming revolution. Agrilution has developed a home hydroponic system that is scheduled to launch in the first quarter of 2018.

PURPOSE

The Association for Vertical Farming Project Group - termed AMI (Aquaponics, Mushrooms and Insects) will consider these three distinct productions systems within a vertical farm as a potential catalyst to move controlled food systems into the circular economy realm. This white paper should serve as a basis guide to understanding the featured species, as well as a theoretical basis for further research tasks, and a springboard for putting theory to practice.

IMAGE: GROW UP URBAN FARMS

INTRODUCTION

The Association for Vertical Farming (AVF) is an internationally active non-profit organization, with over 280 members from around the world, all focused on advancing Vertical Farming technologies, designs and businesses. Its mission is to facilitate the global implementation of Vertical Farming systems to ensure food security, food safety, green jobs, environmental protection and climate change resilience. Vertical Farming is an intensive, highly dense form of production agriculture within highly controlled environmental conditions.

> **“ Its mission is to facilitate the global implementation of Vertical Farming systems to ensure food security, food safety, green jobs, environmental protection and climate change resilience. Vertical Farming is an intensive, highly dense form of production agriculture within highly controlled environmental conditions.”**

The demand for ‘local food’ has grown rapidly in recent years, with sales of $1 billion in 2005 to $7 billion in 2013. It is poised for further rapid advance as consumer preferences for fresh, local produce and food safety and security gain more traction. Vertical farming can be a sustainable solution by eliminating constraints of traditional agriculture and enabling year-round production, high yields, high quality, lower footprint and a faster farm-to-table mechanism. Vertical farming is poised to be a major component in the next big revolution in the global food supply chain.

Vertical farming is considered a sustainable solution to food production because it applies the tenets of a circular economy: to keep a resource in use as long as possible, to extract its maximum value, and to redevelop what is left of those materials as a new resource. Conversely, many modern societies have diverged from this model, adopting the linear method of production: produce, consume, dispose.

One only has to look to nature to witness circular systems as old as geologic time. Natural ecosystems rely on networks where the waste, or outputs, of one system are the input products of another. Using this structure, nature has achieved a series of cycles from which there is no real waste, only opportunities for another process to capitalize on and transform one product into something new. This regenerative way of developing a diverse portfolio of products from an interwoven system of production is the model that will take modern food production into a scalable and sustainable model that is able to food system resilience.

The joining of hydroponic food production and aquaculture to form aquaponics is probably the most well known example of a model that is emblematic of nature, where the outputs of one system can be utilized by the other. As fish release waste, which is high in plant nutrients, into the water, plants take up this waste to produce edible products, and the water is then returned to the fish tanks better prepared for reuse than when it entered, with very little water lost.

Excitingly, aquaponics is not the only natural and profitable overlap in the food production world. In this report we look specifically at the integration of fish, Basil, mushrooms, and insects into a vertical farming system, in which we aim to build a framework for how to capitalize on marketable products, system health, and reduction of waste.

IMAGE: METRO GROUP

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IMAGE: APONIX

FISH

INTRODUCTION

For over 2000 years, people have been feeding their families and economies through the practice of farming aquatic organisms, commonly referred to as aquaculture. Sprouting from the settlement of Asian communities, aquaculture farmers cultivated and improved the practice over generations. High demand required limited land to produce food as efficiently as possible, leading to pond systems which hosted various species of carp, and eventually included plants. Today, this practice is referred to as polyculture in land systems, and aquaponics in indoor farming systems. Although originating with carp, aquaponics has since branched out to include various species of fish, including catfish, barramundi, trout, and Tilapia. While these species, and others, are all strong examples of food that is able able to grow in alternative systems, this report will focus on Tilapia, specifically the Nile Tilapia (Oreochromis niloticus). In this report, we will address the most successful parameters known to support the Tilapia aspects of modern-day aquaponics systems. This report is based on the available scientific research, but is in no way exhaustive of what is understood.

IMAGE: METRO GROUP

INPUT: *LIFECYCLE*

Tilapia in aquaculture go through three size classifications, based on weight, as they grow: fry, fingerling, and juveniles/adults. For the most part, all life stages require the same or similar settings, although there is some research that suggests treating systems differently based on their size class, particularly in terms of diet, density, and light exposure (photoperiod) can increase growth rates[3,9]. Tilapia should not be bred in captivity unless you are well studied in the practices, and many Tilapia farmers purchase their fish as fry.

INPUT: *WATER PARAMETERS*

Much like owning a home aquarium, there are several considerations to be aware of when establishing and maintaining an indoor Recirculating Aquaculture System (RAS) for vertical farming. These factors include, but are not limited to: dissolved oxygen (DO), pH, water temperature, lighting, density of organisms, and several aspects of diet. It should also be noted that, for a truly circular system, a tank system which filters waste through a drain in the center and which employs limited water exchange (<0.5%) is most water efficient[13].

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TABLE 1:

Basic Biological Parameters of the water for Nile Tilapia Tank Rearing[3,12,13]

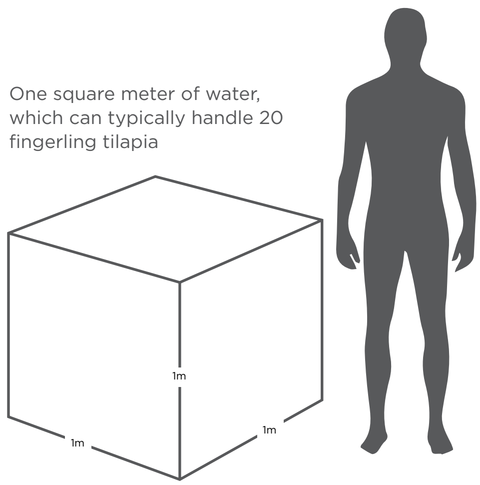
		FRY (0.02–1.0 g)	FINGERLING (1.0–10.0 g)	JUVENILES + ADULTS (10.0–200.0 g)
PHOTO PERIOD (hours light:hours dark)		24L:oD or 18L:6D	>12L:>12D	
CALCIUM HARDNESS (usually added as $NaHCO_3$)		50-100 mg/L		
ALKINITY (usually added as CO_2)		100-250 mg/L		
CARBON DIOXIDE (CO_2)		40 mg/L		
AMONIA (NH_3)		<1.0 mg/L		
NITRATE (NO_2)		<5.0 mg/L		
DISSOLVED OXYGEN (DO)	FUNCT.	<4.0 mg/L		
	IDEAL	5.0-7.5 mg/L		
pH	FUNCT.	5.0-10.0		
	IDEAL	6.8-9.0		
TEMPERATURE (°C)	FUNCT.	25.0-32.0		
	IDEAL	27.0-30.0		

*suggested nitrite levels when Chloride (Cl-) is between 150-200 mg/L

Parameters for Tilapia rearing, broken down by input and life stage

INPUT: *DENSITY*

Further inputs in the aquaculture aspects of vertical farming include a consideration of fish density and diet. It is suggested that for every 1,000 litres of water, or $1m^3$, you stock 20 Tilapia fingerlings (20 Tilapia/m^3)[12]. As your fish grow, grade them by size and continue to expand into new tanks to maintain rapid growth, water quality, and system efficiency. The Food and Agriculture Organization (FAO) suggests production to capacity ratio ranges from >3 to >4.5.



INPUT: *DIET*

Considering Tilapia are omnivores, eating both plant and meat materials, and the fact that they grow relatively fast, a lot has been looked into how to feed them most effectively. In good conditions, Tilapias have a Feed Conversion Ratio (FCR) of 1.4–1.8, meaning that to grow a 1.0 kg Tilapia, 1.4–1.8 kg of food is required[10,12,13]. Tilapias' diet must consist of high protein, depending on their age class. First feeding fingerlings require diets of up to 50% protein, while adults are optimized at a level of around 30%. Traditionally, this requirement has been met by fish meal and pre-made pellet foods. However, these methods are extremely detrimental to the environment and wild fish populations. A reasonable diet alternative is **Black Soldier Fly** meal, which provides a protein content of 40%, supplemented by herbaceous material, perhaps algae.

Dietary factors such as carbohydrates, vitamins, and amino acids are also critical to consider. Digestibility of carbohydrates is dependent on a variety of factors, but complex carbohydrates have shown to be the most easily digested by Tilapia, with the top candidates being starch and maltose [11]. It should also be noted that plant-based diets stunt the ability of Tilapia to absorb metals such as calcium, phosphorus, magnesium, manganese, zinc, and iron. To encourage the absorption of these critical elements, Tilapia farmers may consider food sources which supplement phosphorous via di-calcium phosphate or add microbial phytase into the tank[14].

OUTPUT: *MARKET AND USES*

A market size Tilapia is a 250g-600g fish depending on your system, which takes around six to eight months to reach[13]. Tilapia are a white fish often sold as food, and a report by country on market prices can be found through GLOBEFISH and the United Nations (FAO).

However, there are other markets where Tilapia are on the rise. In late 2016 it was announced that a group of researchers in Brazil found that sterilized Tilapia skin not only reduces pain in burn victims, it also helps them to recover faster[15]. Other interesting by-products include gelatine for time-released medicines.

In vertical farming, aquaponics, and hydroponics, waste from the Tilapia can be reutilized as compost and fertilizer for other systems of food production, most commonly leafy green vegetables and herbs, such as **Basil**.

OUTPUT: *WASTE AND BY PRODUCTS*

In Tilapia culture the sludge and refuse of the fish has bloomed in popularity as an applicable by-product. The most mainstream utilization of this is the development of aquaponics systems which recycle the water from Tilapia tanks through hydroponics systems to grow plants, usually leafy greens (**see Basil**). The outputs of Tilapia in a system depend highly on their diet.

There are also a variety of "waste" products and by-products from Tilapia systems, including dead fish. Dead fish can be used as a dietary component high in protein, fish oil, phosphorus, calcium, and an array of antioxidants for organisms that break down organic waste for food.

Components of fish effluent include calcium, magnesium, potassium, ammonia, nitrate, phosphate, sulfate, iron, manganese, zinc, copper, boron, and molybdenum[12]. The amount of these products present in each system varies based on diet, and research particularly cites a need for a better understanding of how these parameters change with dietary inputs.

TILAPIA

CONCLUSIONS

In order to create a food producing ecosystem utilizing Tilapia rearing, a lot of work needs to be done to understand how various components affect fish product composition. We already know that Tilapia can be grown in "-ponics" systems, and have seen some of the first modern aquaponics farms be successfully based on Tilapia culture. The challenge will be how to feed Tilapia in a way that is efficient for both their growth and nutrient content while providing waste that can benefit other systems.

IMAGE: T.ZÖLLNER

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PLANTS

INTRODUCTION

The agriculture revolution might have been the turning point of humanity. Domesticating plants and animals allowed people to achieve food security; this lead to settlements, and cultures that rapidly covered the entire globe. The rising population with an increase in urbanization is now putting intense pressure on agricultural systems. New alternative systems are being researched and developed, such as Vertical Farming (VF), an intensive, highly dense form of production agriculture within highly controlled environmental conditions.

Controlled Environment Agriculture (CEA) is the combination of technologies using the science of growing plants to improve the production and quality of crops [14]. Both the aerial and the root zone environments are controlled. Stacked layer systems are increasing cultivation areas and can be implemented at urban sites contributing to feeding cities with fresh and healthy plants.

The optimal plant environment can be controlled precisely, but each of the plant species require specific conditions; there is no single success formula. This may be the reason why there are a limited number of species cultivated to date, with a goal to increase the species spectrum in the coming years. The plants that can be cultivated in CEA or VF can be grouped in three categories, by the harvest index:

COMMON HYDROPONICS PLANTS BROKEN DOWN BY FACTORS TO CONSIDER WHEN GROWING FOR HARVEST

GROUP	SPECIES	EASE OF GROWTH	VEGETABLE PHASE	REPRODUCTIVE PHASE	PAST DISEASE	HARVEST INDEX	CEA/VF KNOW-HOW	OTHER
HIGH HARVEST INDEX (HHI)	Lettuce, spinach, basil	Very easy, fast, repetitive	Yes	No	Little	>50%	High	Low shelf life
LOW HARVES INDEX (LHI)	Tomato, cucumber, bell pepper	Medium, 2-3 cycles	Yes	Yes	Medium	<50%	High-medium	Needs pollination
VERY LOW HARVESTINDEX (VLHI)	Thyme, St. John's, Wort, Echiancea	Difficult, 1-2 cycles	Yes	Yes	High	<15%	Medium-low	Needs abiotic

INTRODUCTION: *BASIL*

Basil is a very popular crop among farmers because it has a high harvest index, it is relatively easy to grow and it is well adapted to hydroponic and CEA systems, having a high profitability margin [11]. Basil is also grown as a microgreen with a strong taste due to the high concentration of secondary metabolites in the young plants. The plant is considered an aromatic herb which means that it's high antioxidant compounds and essential oils makes it one of the best choice for food production and other industries, such as medicine or cosmetics.

The following paragraphs will describe the most successful parameters known to support Basil growth in modern-day CEA and VF systems, based on scientific research. This report is in no way exhaustive, aiming to find the common ground for linking plant cultivation with other systems discussed in the paper.

INPUTS

Light is fundamental to plant cultivation. Artificial lighting in VFs is fueling debate on energy consumption and the sustainability of food production in such systems. The most important lighting parameter is photosynthetically active radiation (PAR), which refers to the spectral range, from 400 to 700 nm, of solar (or artificial) radiation which plants use in the process of photosynthesis. Chlorophyll is most effective in capturing red and blue light which directed plant lamp fixture manufacturers to focus on these specific wavelengths for the horticulture industry. Different wavelengths have varying effects on the plant's morphology and secondary metabolism, which means that the lighting choice is very important for the yield and the quality of the plants [5]. Artificial lighting is supplied by various types of lamps such as fluorescent, High Pressure Sodium (HPS) or Light Emitting Diodes (LED). LEDs are more efficient in converting electrical power (W) to photosynthetic light (μ mol/m^2/s) than the other alternatives, so they are increasingly used in the industry [3].

Basil can be grown with a light intensity from 180 to 300 μ mol/m^2/s [1, 2]. Red spectrum (638 nm) can improve the antioxidant properties of Basil, while blue light improves the yield of other phytochemicals related to superfood products [8, 15]. Basil prefers an air temperature ranging between 20 and 27˚C with a relative humidity of 60%. These factors can slightly oscillate without significantly influencing the growth or quality of the crops [1, 13].

Basil is cultivated in VF in hydroponic, aeroponic or even aquaponic systems. One of the most popular growing methods is Nutrient Film Technique (NFT). Nutrient solution has an effect on both growth and the bioactive activity of the plants [10]. Because Basil is grown as a leafy green, it is not necessary to bring the crop to the reproduction phase, easing the selection of fertilizers, which can typically have a N-P-K (Nitrogen-Phosphorus-Potassium) ratio of 3-2-3. Electrical conductivity (EC) gives an indication of the total salts in the nutrient solution and can remain the same throughout the vegetation cycle or gradually be increased during the vegetative phase. One of the optimal parameters of the nutrient solution is the EC range of 0.5-2 mS/cm with a pH of 5.5-6.5 and a minimum of 6.5 mg/ L dissolved oxygen concentration. Oxygen concentration will depend on water temperature, which should range between 20 - 25ºC, 68 - 77ºF. This will create an optimal environment for root development and nutrient absorption.

Carbon dioxide is an important gaseous parameter in the cultivation phase due to its role in the gas exchange and photosynthesis of the plants. Plants can be grown in the standard atmospheric CO_2 conditions (400 ppm) but for an enhanced yield the CO_2 should be increased artificially to a range of 800 - 1000 ppm. Supplemental CO_2 is required for any installation that is closed, or not freely ventilated to outside ambient air, else internal CO_2 will become the limiting factor for plant growth, and diminish the effectiveness of photosynthetic lighting. PAR, CO_2, nutrient solution, and other abiotic factors all combine to influence both the yield and bioactive substances of plants, therefore the individual parameters interdependency should be taken in account.

OUTPUT

Because of the high costs of energy in VFs, plants with greater increased added market value should be considered included, such as herbs and pharmaceuticals. Therefore, Basil can be a valid option for Urban Controlled Environment Agriculture [13].

Basil is used fresh, dried or processed and can be harvested multiple times, cutting of the stem, or at once harvesting everything down to the roots. If the plants are grown for their chemical composition rather than biomass, it is important to know that the metabolites dynamic is not linear, having peaks throughout the vegetation cycle which can determine other optimal harvest peaks [7]. As said before, Basil is widely used as microgreens that are harvested at the seedling phase.

In the context of a Circular Economy, there are more outputs which are generally considered waste streams such as oxygen, inedible plant products (roots), used growth substrate, nutrient solution, heat (from lamps) etc. As these factors are not usually included in the production strategy, the information is scarce. Specifically, for Basil, there is not enough information in the scientific literature, therefore this part of the report contains a broader plant species spectrum. Most studies are coming from the interplanetary exploration and space mission projects where all inputs and outputs are equally weighted in the priorities for controlled environment agriculture [10, 12].

The roots of the Basil crops are not used and are generally wasted. This inedible plant tissues could be oxidized (incinerated or aerobically digested) to resupply CO_2, but consume an important O_2 dosage that is valuable as an important output. Therefore, the inedible plant parts should be valued as an input for different cultivation systems such as insects or mushrooms, that will help transitioning to a circular economy [16]. Even inorganic wastes, such as rockwool substrate, that is usually dispersed in landfills, can be reused. The main solutions for recycling used substrates are recycling to rockwool factories, soil amendments, mixing into other substrates, mixing into composts, brick production, landfill cover, mushroom casing etc. [4].

The nutrient solution is usually recirculated, saving water consumption up to 90%. The most common way to treat the wastewater is through UV-lighting, but it can be also be done through biological filtration with bacteria strains [8, 10]. Instead of using commercial fertilizers, the waste of the fishes is a valuable source of ammonia that is transformed by bacteria in nitrite than nitrate, valuable for the plants.

Energy consumption in intensive cultivation facilities contradicts with the goal of lowering CO_2 emissions. Therefore, an important topic in CEA plant cultivation is energy efficiency. As LEDs are getting more and more efficient, they prove to be a good candidate for lighting systems. Temperature should be maintained in the optimal parameters, therefore heating and ventilation systems should be designed in a way to have the least possible loss. In an urban setting, heat energy can be used and shuttled around to surrounding buildings and in this way the cumulative energy cost gets driven down.

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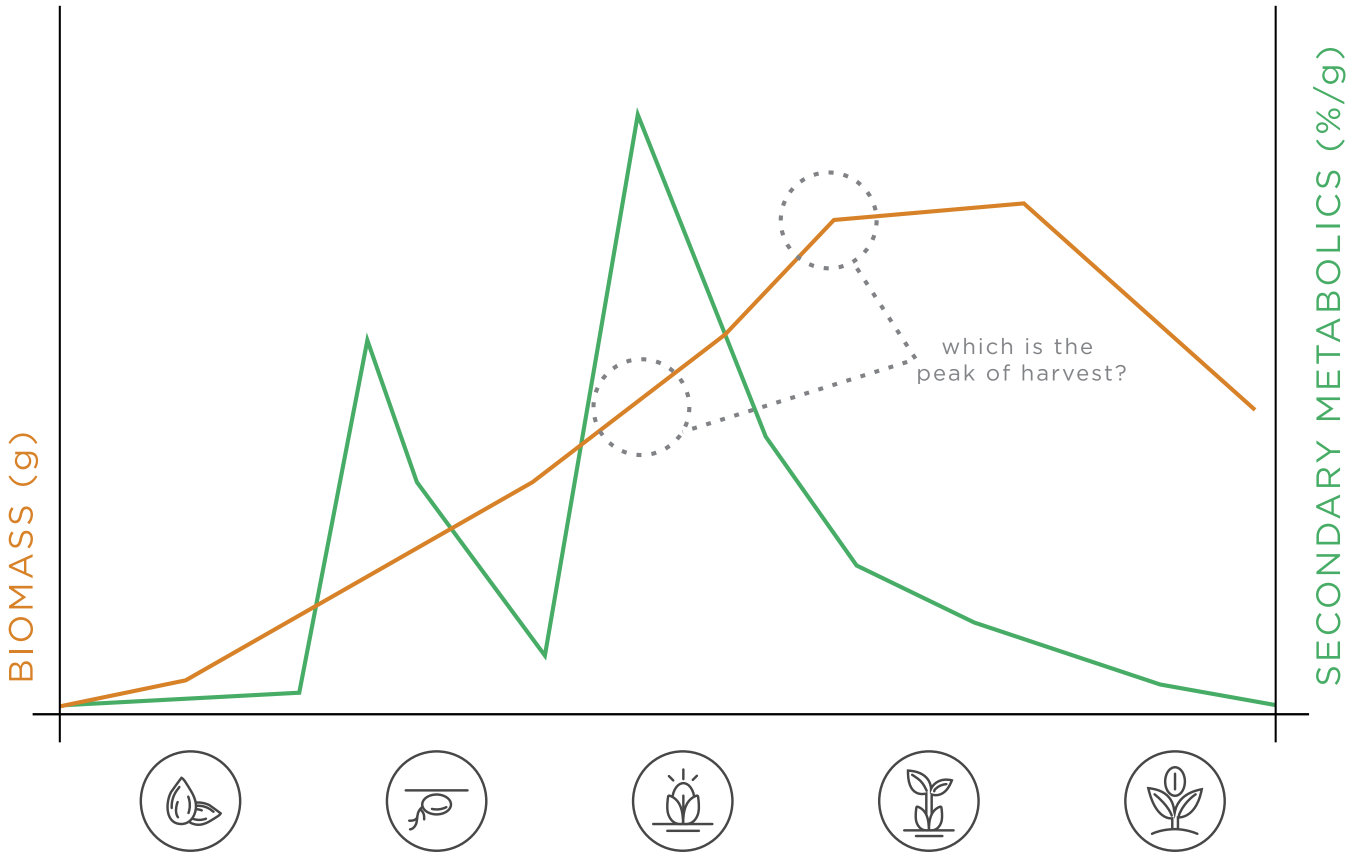
TABLE 3:

DYNAMICS OF THE YIELD AND QUALITY OF THE PLANTS RELATIVE TO THE VEGETATION CYCLE



Source : Radu Giurgiu (MELiSSA Workshop 2016, Lausanne)

PLANTS CONCLUSIONS

Currently, growers are focused on the inputs that plant cultivation systems need to achieve high yields and quality that can be valued on the market. This production paradigm can be further developed to go beyond the linear process where the so called waste streams are mere outputs that can be changed to inputs for other systems that will produce other food products. The Aquaponic system is a successful cooperation of plant and fish cultivation and the other food sources like insects and mushrooms could be integrated in this strategy.

IMAGE: METRO GROUP

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MUSHROOMS

INTRODUCTION

The ancient Egyptians believed that the mushroom was a sacred food and was therefore reserved for the pharaohs. The first cultivation of the common button mushroom (Agaricus bisporus) occurred in the 1650s, grown on compost. In Asia it is believed that mushrooms have been cultivated for longer, but no common date can be agreed upon. These days, the mushroom in all its variations is gaining ever more attention.

> " Mushrooms are one of the great decomposers of the natural world. They break organic matter down into base elements, which are then upcycled by the mushroom itself and/or made available for use by other organisms like plants."

Modern interest in mushrooms continues to bloom. The European mushroom market alone has grown into a $35 billion industry and is expected to grow to $60 billion by 2025 [3]. This market is mainly dominated by the common button mushroom, but the demand for more exotic types is ever increasing. Some examples of exotics that have been grown commercially include the Shiitake (Lentinula edodes) and Oyster mushrooms (Pleurotus ostreatus), on which this report will focus.

Mushrooms are one of the great decomposers of the natural world. They break organic matter down into base elements, which are then upcycled by the mushroom itself and/or made available for use by other organisms like plants. Mushrooms are a truly integral part of ecosystems, and their production is pivotal in such a method of food production.

This report will focus on the cultivation of the oyster mushroom as it is gaining in popularity around the world, due to its easy cultivation methods and its potential to act as a key in the flow of nutrients and energy in a food producing ecosystems. It can be tied in with black soldier fly cultivation, aquaculture and hydroponic production of plants.

OVERVIEW OF OYSTER MUSHROOM CULTIVATION:

Oyster mushrooms can be grown with relative ease, yet In commercial growing operations, sophisticated controlled environment growth chambers or rooms are used to obtain optimal yields. These rooms allow the grower to control all the environmental aspects (eg: CO_2 concentration, air temperature, humidity and lighting conditions)[1,2,7].

Mushrooms' natural growth cycles are replicated in these controlled growth rooms to optimise production. Mushrooms follow a three stage life cycle, and each stage requires slightly different environmental conditions. Briefly, stage 1 starts the process with mushroom spores being inoculated into a starter medium container. Once mycelium growth is sufficient in the starter medium container, these starter culture mediums are transferred to the main growth medium. Stage two is the period where this mycelium starter culture grows throughout the main growth room media. Finally, stage three produces the fruiting bodies which are then harvested and sold as edible mushrooms [1,7].

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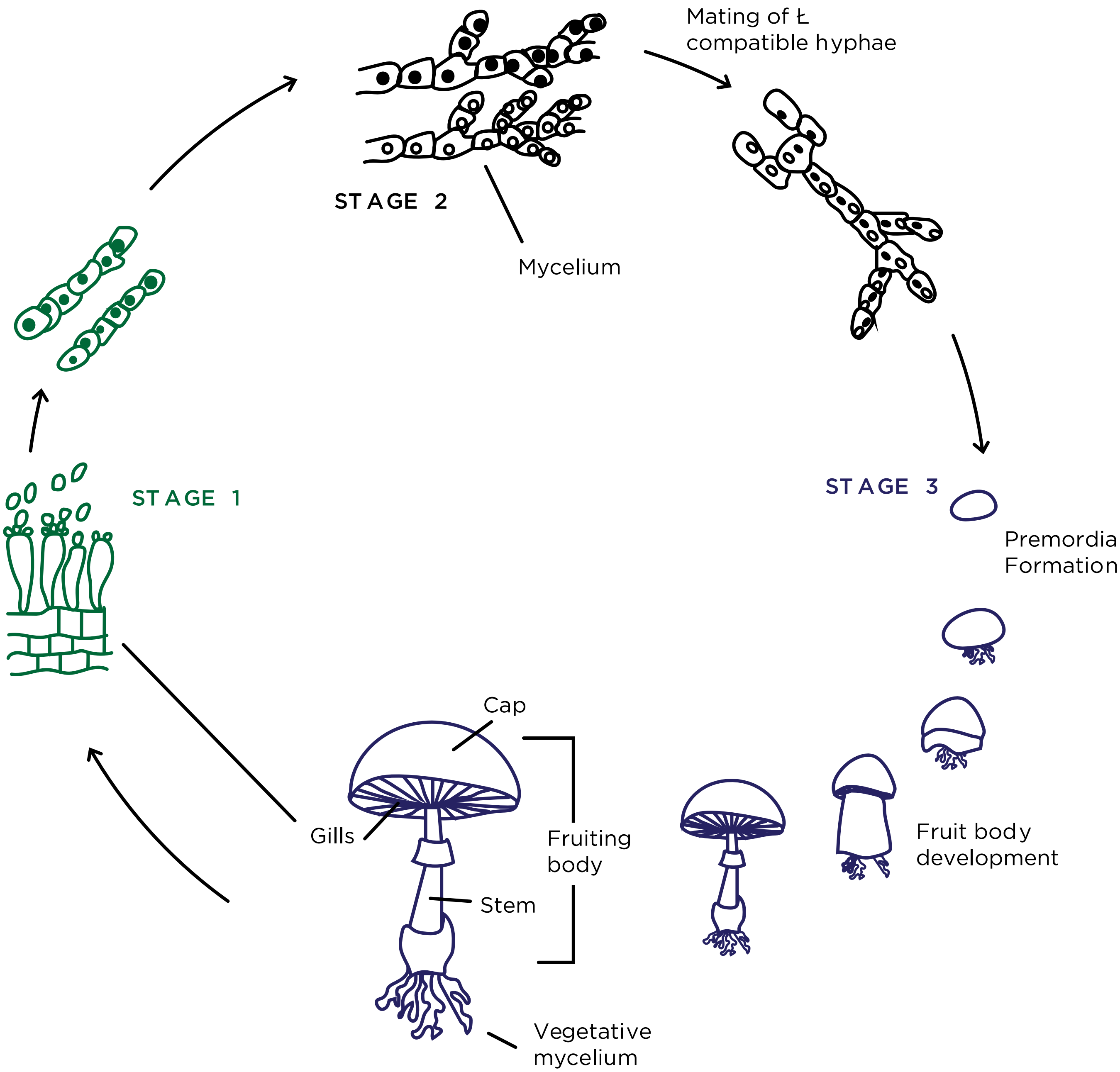
HANNAH SHUFRO | SMALLHOLD

MUSHROOM GROWTH CYCLE



The lifecycle of a mushroom, which goes through 3 majors stages.

INPUTS (BY LIFECYCLE STAGE)

STAGE ONE: The inoculation of the spores into sterilized starter culture mediums is usually done in specialised laboratory conditions [1,7]. Most commercial growers buy this from dedicated spore producing companies. This paper focusses on large scale inputs and outputs, which we get in the next two stages of the cultivation process.

STAGE TWO: Oyster mushrooms, like most mushrooms, will grow on a vast variety of organic substrates {2,4,8}. The most common component of these substrates is a form of lignocellulose. Lignocellulose is present in substrates made from plant or tree matter (eg: paper, sawdust, cardboard, various grains and husks of various seeds and fruits) {2,4,8}. Therefore mushroom cultivation is a great way to upcycle organic compounds formally known as waste products. The growth medium is supplemented with various other components, such as chicken manure for a nitrogen source and calcium carbonate and calcium sulfate which act as a buffer to keep the substrate around optimum pH (5,0 - 6,5). Water content is also adjusted to achieve ideal moisture levels, which is around 65% of substrate weight [2,8].

This process is carried out between 14-28 days depending on the cultivation variables. The environmental conditions during this time consist of a temperature range of 21-24ºC with 90% relative humidity [2]. Maintaining the growing chambers at these optimal conditions requires energy to heat and cool the rooms and to provide the required humidity. This stage does not require any light, so no consideration is given to illumination; however, energy is used to keep the climate conditions optimal.

STAGE THREE: The final stage of the process is the fruiting stage. Fruiting bodies are the edible, above ground parts of the mushroom. By this stage the mycelia has grown throughout the substrate and a change in the environmental conditions (temperature & light) initiates the fruiting bodies to form and grow up above the substrate. Fruiting can occur at a range of temperatures depending on the strain of mushroom and its natural growth conditions [1,7]. Therefore, depending on the strain grown, temperatures are adjusted to between 18-30ºC. The fruiting of the mushroom will only be initiated after 12 hours of light. 80-210 lux light intensity from the blue light spectrum is needed to produce the correct, marketable fruiting bodies [converted to PAR with fluorescent lamps as light source: 1.1 - 2.8 µ mol/m²/s. An important side note here is that PAR nor Lux is the right unit to use for mushroom growth, yet due to the lack of another unit and the fact that PAR and lux are commonly known among farmers, these units were used.

Mushrooms are usually harvested in 2 rounds, called flushes. The first flush will occur between 7-14 days after fruiting initiation and the second flush another 7 days after that. Subsequent flushes can be harvested every 3–7 days, however yields decline [1,7].

While increased CO_2 concentrations do not affect the mycelial growth in the second stage, a CO_2 concentration of over 600 ppm (atmospheric CO_2 is around 400 ppm) will cause the fruiting bodies to be malformed, therefore extraction of CO_2 is important [7].

OUTPUTS FROM THE MUSHROOM GROWING PROCESS AND THEIR POSSIBLE USES

The first obvious output are the mushrooms themselves. For the small blue economy mushroom farmer the best spacing is to have maximum 20 kg of wet substrate per cubic meter. With an average conversion rate of 18%, substrate into mushrooms, a production of 3,7kg oysters mushrooms per cubic meter per cycle can be expected [9] Other sources from bigger and more specialised mushroom farms report a conversion rate of total substrate weight to harvestable weight of about 30-40%. Here 20 kg of wet substrate would produce around 6 - 8 kg of mushrooms. If the cities waste streams are to be valorized through mushrooms, more research is needed to optimize production for the small blue economy mushroom farmers.

This also leaves a large amount of used mushroom substrate. This, previously considered waste product, is now getting lots of attention as people look to utilise this substrate for other value generating purposes, like composting, biofuel, insect feed and animal fodder [4].

Used substrate used as animal fodder produces even higher value animal fodder, as the mycelia excrete enzymes which break down the cellulose structure and make the material easier to digest and more nutritious for animals. These enzymes, which are excreted during mushroom growth can also be isolated, as many of them have unique and useful properties. One such example is Laccase which can break down certain environmentally toxic pollutants [4].

The spent mushroom substrate could also be used as a supplement to **black soldier fly production**. This would provide a convenient link between two systems which could complement each other.

Additionally, the CO_2 produced during stage two and three of the life cycle can be linked to other processes which require an input of CO_2 such as commercial horticulture growth facilities.

MUSHROOMS
CONCLUSIONS

Fungi are fantastic organisms to create a lot more value with the available resources of our society. This is proven by the many blue economy mushroom companies that have popped up all round the world, using spent coffee waste as substrate for growing oyster mushrooms. Yet, there are a lot more unused organic waste-streams inside cities, and an enormous amount of mushroom-species that that can be used to re-valorize them. Not only for food, but also as building materials, clothes, paint, medicine, and so forth. One thing is for sure, our cities have not seen the last of mushrooms.

HANNAH SHUFRO | SMALLHOLD

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INSECTS

INTRODUCTION

Insects have been critical to, and a main component of, human food production since the dawn of agriculture. Honey is the most globally applied example of humans capitalizing on insect products, and pollination and pest control by insects is currently common practice in greenhouses. However, insects can also be a high quality source of protein for humans and livestock which can be grown very sustainably, such as grasshoppers and crickets. Some species, like the black soldier fly (BSF), thrive on very low quality organic waste. By converting organic waste into protein, Black Soldier Flies reduce waste and produce sustainable protein. These larvae are perfectly suited as feed for livestock and fish, providing a sustainable alternative to chicken/fish feed. Particularly in regards to farmed fish, these animals are fed a diet usually containing 40 to 50% fishmeal, an industry term for the pelletised non-marketable byproducts of fin fishing and trawl catches of small marine fish. But most of the world's fishmeal is made from whole fish, which adds extra pressure on fish stocks in the ocean. Big gains in sustainability can still be made in regard to protein sourcing for livestock as this has a big environmental impact. Multiple companies worldwide are starting to focus on converting organic waste into protein using BSF. The biggest are: Protix, Enviroflight, Enterra, Dipterra, Co-prot, Agri-protein and Ynsect. It is a relatively new market expected to reach 500 million USD within the next 5 years. This chapter explores the potential of BSF as waste upcyclers in a vertical farming food producing ecosystem.

INPUT: *LIFECYCLE*

The BSF goes through multiple life stages: egg, larvae, prepupae, pupae and adult fly. Harvested eggs are incubated for about four days before the larvae hatch and are transferred to a feeding source4. The larval life is composed of six stages, which take around 10 to 14 days. After which the BSF develops into a prepupae and approximately 5 to 10 days later into a pupae. After at least 10 days under optimal conditions flies will start to appear from the pupae. The flies are able to produce eggs 2 days after hatching and have lifespan of around 10 days. The lifespan can be almost doubled when the flies are fed with sugar water or pure sugar. This is used in breeding to increase their lifespan and reproduction 2. If conditions are sub-optimal, larvae and pupae can survive for months in a sort of dormant state.

INPUT: *LARVAE CULTIVATION*

BSF farming is still a new industry and cultivation systems are not shared. Systems range from stacked crates to trenches. The larvae are fed daily and their diet is kept moist. When the larvae are fully grown, they will be sieved to separate them from the substrate and feces mixture. Larvae can then be dried and produced into larvae meal or fed directly to livestock.

INPUT: *ABIOTIC FACTORS*

The main abiotic factors influencing BSF cultivation are: temperature, humidity and oxygenation. The optimum temperature is between 27Ð and 30Ð14. Relative humidity should be measured inside the substrate, as the larvae live inside the substrate. The optimum ranges from 50-70%14. Air should be replenished often enough to prevent CO_2 buildup. Larvae are photophobic and need to be kept in darkness.

INPUT: *BIOTIC FACTORS*

Density of the larvae in their container and the microbial community are the main biotic factors. Optimal larvae density ranges from 1 to 5 larvae per cm2 8. As the substrate is organic waste, a lot of microbes will be present and microbial breakdown of the substrate will occur. The BSF is able to profit from this via a reduction in their development. Microbial breakdown of the substrate can potentially increase the Food Conversion Ratio (FCR).

INPUT: *DIET*

BSF larvae can utilize a wide range of feed, manure, vegetable waste, meat and fish offal. The diet influences a number of parameters, like the development time and the body composition. When reared on cow or swine manure, the amino acid composition of the larvae differs significantly between both diets [4]. When fed with fish byproducts, they can contain a high amount of omega-3 fatty acids [12]. Insects are able to survive on a suboptimal diet due to their ability to process their feed after ingesting it, but for industrial production more research into diets is needed. In an experiment the following ingredients were tested in [4] different blends: spent brewers grain, beer yeast, cookie remains, beet molasses and bread [6]. For BSF, a combination of 60% spent grains, 20% beer yeast and 20% cookie remains yielded the best results. The survival rate (86% vs 75%) and the feed conversion ratio (1.4 vs 1.8) were better compared to the control treatment using chicken feed [6]. Another experiment showed that larvae could process as much as 6.5 kg/m^2/day of feed, thereby producing 145 g/m^2/day of dry larval mass [1].

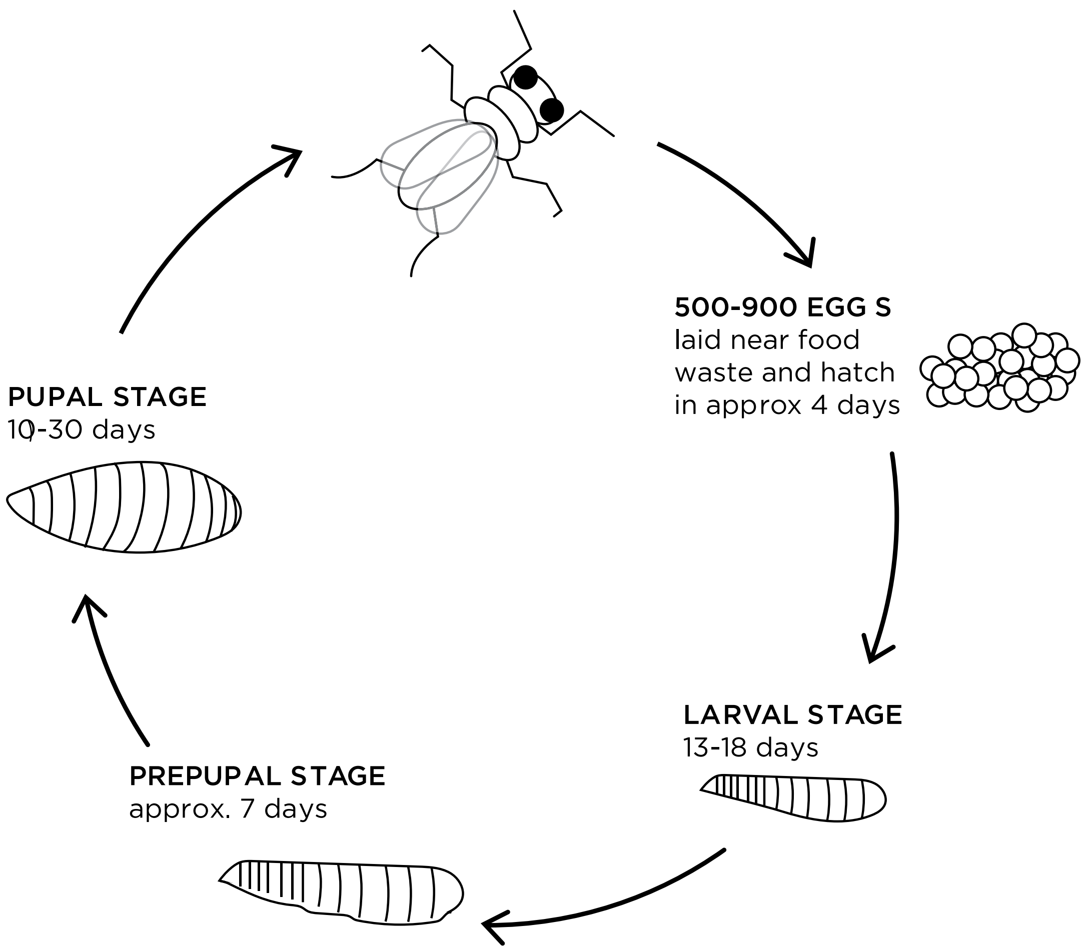
INPUT: *EGG PRODUCTION*

An important part of the process is the rearing of new larvae. When flies are appearing from their pupal case, they are transferred to an enclosure in which they can fly. In this enclosure a temperature between 27C and 30C and a relative humidity of 75% should be maintained [14].

Adequate lightning is very important at this point. There are two ways of providing light: via natural sunlight by putting enclosures outside, in a greenhouse, or by providing artificial light with halogens or LEDs. The adult flies need light to be able to mate as the male fly captures females in flight. It is able to do so by seeing the contrast of the black insect body against the sky. This contrast is strongest in the ultraviolet part of the spectrum [7]. Optimal light intensity is reported to be between 135 - 200 μmol/m^2/s17.

In the enclosure a laying bin is provided, consisting of a container with a substrate of decaying organic matter to attract the flies to lay their eggs. Usually a piece of cardboard is provided for the flies to lay their eggs on, but flies will lay eggs in any crevice close to a source of decaying organic matter. Solutions like thin wooden planks stacked on each other have better reusability than cardboard, making this one of the methods used by large scale producers. The eggs should be removed daily from the breeding enclosure and incubated separately under optimal conditions. When the eggs have hatched, feed quality is very important for the survival of the young larvae. After 2 to 3 days this is less important, and the larvae can be fed with a lesser quality diet.

BSF LIFE CYCLE



Lifecycle of a black soldier fly, which goes through several stages, each with its own unique needs and uses.

OUTPUT: *MAIN PRODUCT*

The main products of BSF production are the larvae. Depending on the feed, the dry matter content of the larvae ranges from 35 to 45% of their initial weight 15. Protein makes up about 40% of the dry matter. It has to be noted that the nutritional composition of BSF varies depending on the diet.

Dried larvae can be milled into larvae meal to be incorporated into a blended diet, or fed directly to insect eating organisms as dried or live insects. Another possibility is to separate the protein, fat and chitin from the insect body. This approach might be the most economical utilization of the BSF, but processing of BSF is still problematic and more research is needed. Chitosan can be made from chitin and can be used as a paint solvent. Experiments have been performed in which the protein element in diets of livestock have been replaced (partially) with dried BSF. These experiments serve more as an indication that it is possible to replace traditional protein with insect protein. As multiple factors can influence the nutritional composition of the BSF.

Sums up a few results of feeding studies on livestock with BSF replacing the protein.
All values are based on the control diet of the respective animal (set at 100%).

ORGANISM	SUBSITUTING	% SUBSTITUTION	WEIGHT GAIN %	FEED EFFICIENCY %	SOURCE
BROILER CHICKEN	Soybean + fat	100	96	103	(HALE, 1973)
RAINBOW TROUT	fishmeal	25	100	100	(St-Hilaire et al., 2007a)
EARLY WEANED PIGS	dried plasma	50	104	109	(Newton et al., 2005)

Next to the sustainability gains of feeding larvae grown on waste to livestock, feeding live larvae to chickens might induce more natural behaviour, reducing problems like feather picking. The exoskeleton contains a high amount of chitin, which is rumoured to strengthen the immune system of broiler chickens.

OUTPUT: *SIDE PRODUCTS*

BSF are able to utilize a lot of the organic matter which they are fed. The output is a mix containing the feces of the insect (frass) and left over substrate. This residue resembles compost. When the residue (5%) was mixed in with plain sand (95%) dry weight production of (Sorghum sudanese) was only 22% lower compared to a control grown on potting soil [4]. If a precise formulation for potting soil including BSF residue is made, these yields might be more similar.

The BSF waste, when combined with straw, might also be used in growing mushrooms. As a testament to the true circular nature of BSF and mushrooms, BSF larvae can also feed on leftover substrate from mushroom production. Similarly, homesteaders and preppers growing BSF site BSF waste as perfect for earthworms. Using BSF waste to grow mushrooms or earthworms could be a value adding proposition, as using mushrooms or earthworms to further break down waste makes nutrients more easily available for plants. For both of these uses, there is not yet supporting scientific research.

INSECTS

CONCLUSIONS

BSF have a lot of potential to become a staple in livestock feed and organic waste management. Larvae contain high amounts of protein and fat and are well suited to replace fishmeal in livestock diets. Yet, more research needs to be done to establish diets for optimal growth and nutrient content of the larvae. Combining BSF production with earthworm and mushroom production might be a good way to minimize the waste products of these three organisms.

IMAGE: SEPPE SALARI

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"Any other daring thinkers out there are encouraged to investigate creative and reasonable applications for these systems."

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IMAGE: HANNAH SHUFRO | SMALLHOLD

APPLICATIONS
& INTO THE FUTURE

The goal of this report is to find synergies between different growing systems which could improve the profitability and sustainability of a vertical farm. They can be classified into two parts: abiotic and biotic synergies. Using a Tilapia-Basil aquaponics system as the starting point, we believe it's possible to link in black soldier flies and oyster mushrooms to create an ecosystem that produces food and uses outputs from other systems to produce very little to no waste.

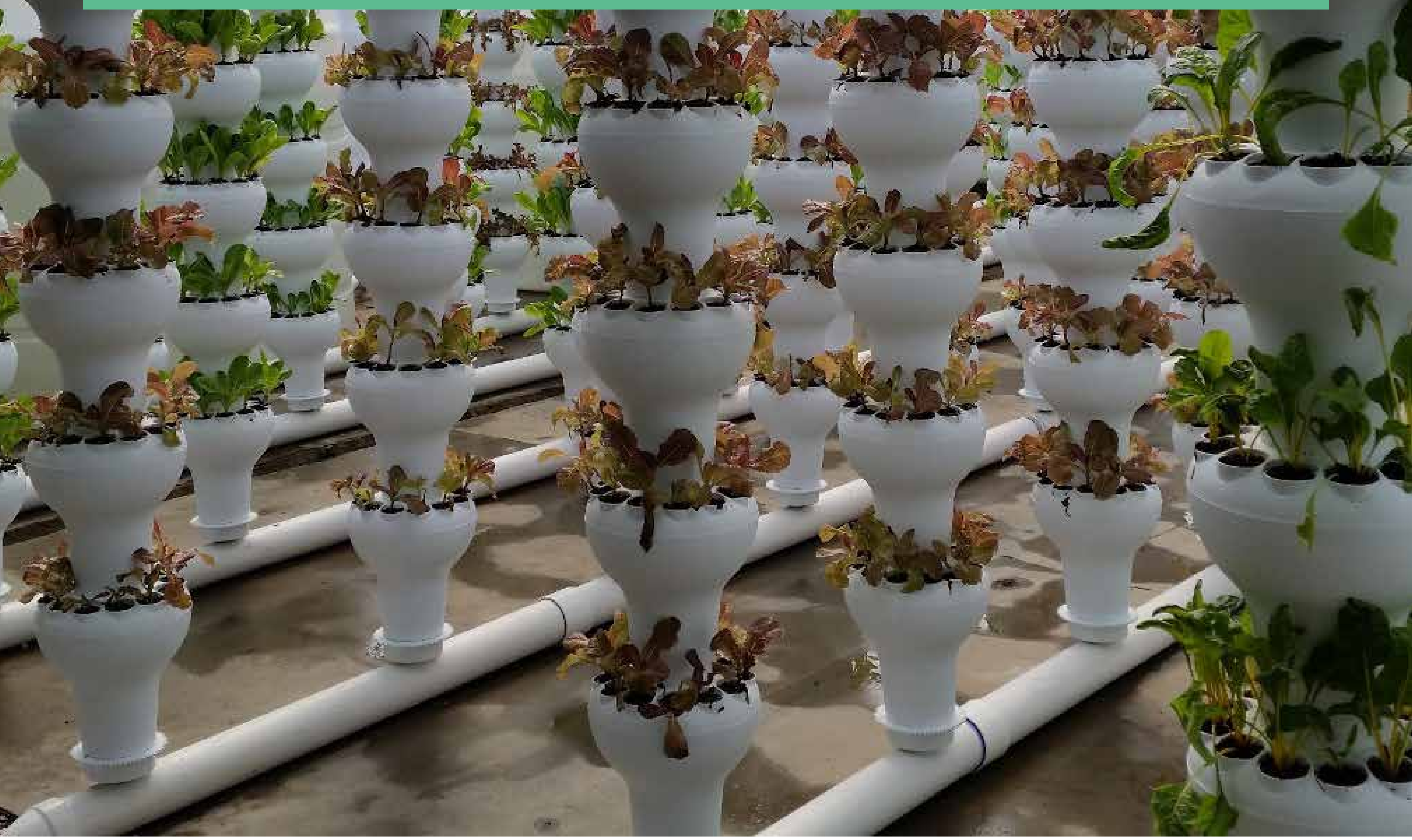


IMAGE: METRO GROUP

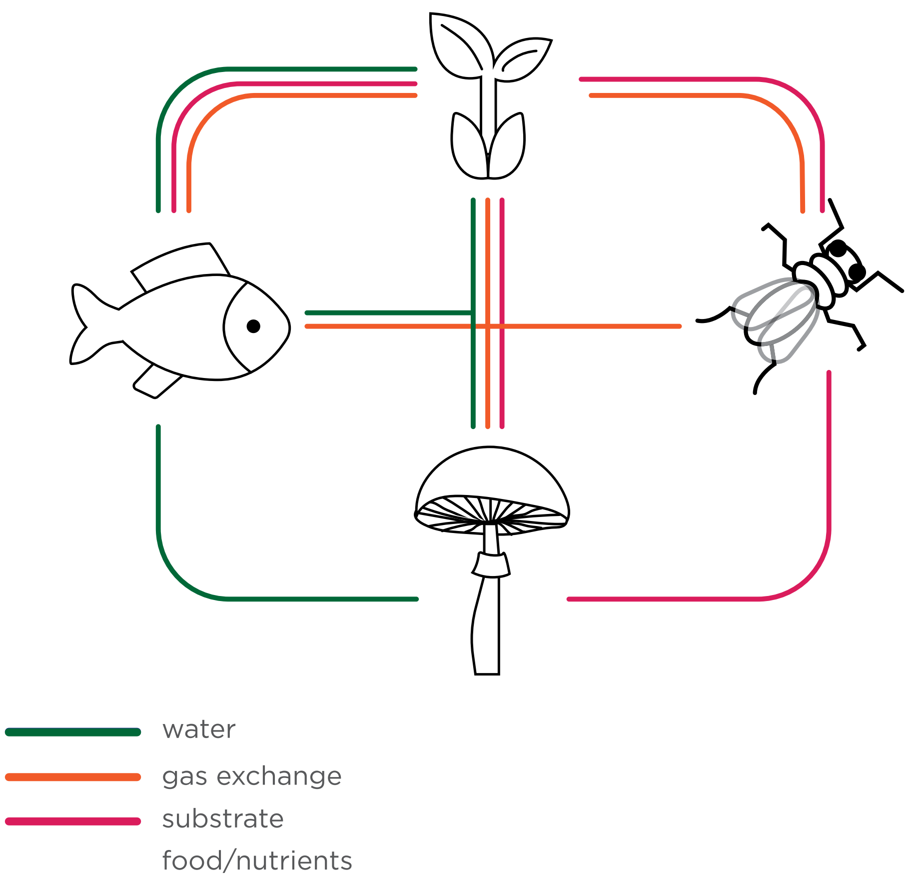
CIRCULAR ECONOMY TO ECOSYSTEM ECONOMY

In this paper, we only briefly touch on the concept of the circular economy as a frame of reference for why building an AMI-style system should be implemented. As green business practices and sustainability efforts become more commonplace, they also become more financially reasonable. Regenerative business practices are going to be driving forces in the future, and the vertical farming industry is poised to break into that realm with the implementation of AMI.

In terms of the difference between circular economies and ecosystem economies, this was a conversation that emerged a few times. Eventually, the term ecosystem economy was selected because a system such as what AMI envisions is not closed, similar to an ecosystem. A circle, although there is no beginning or end, is a discrete unit. An ecosystem can grow, and involves a web of overlapping benefits and uses. In the following sections, the complexity and compliments of the overlays amongst systems in the AMI vision will be further discussed.

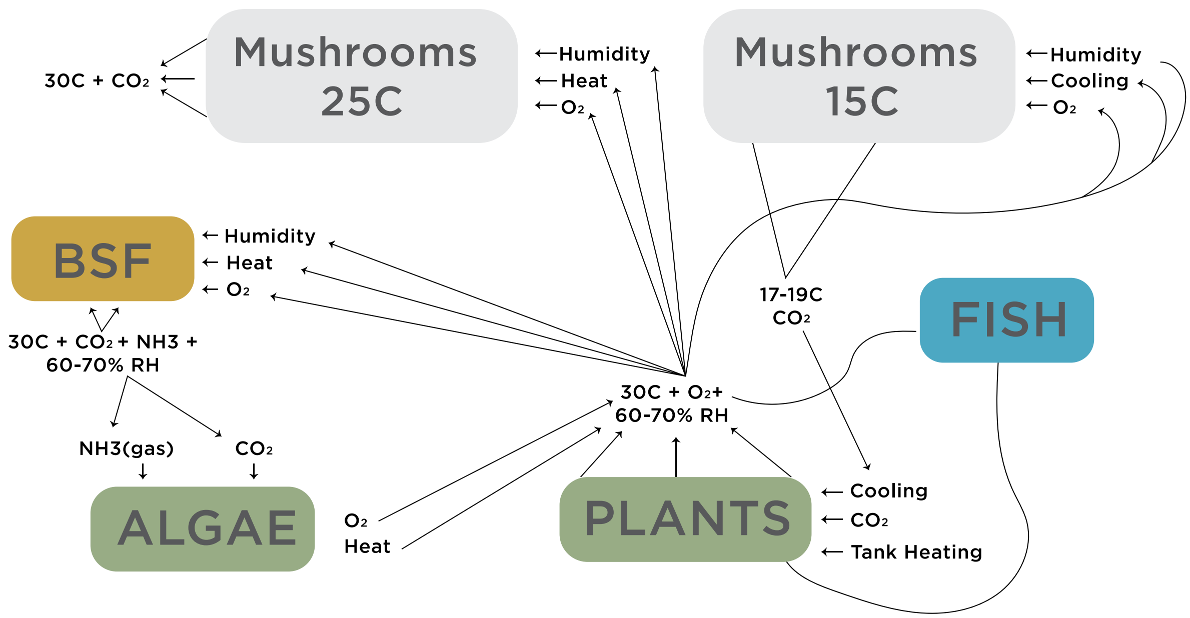
In the future, we look forward to a more structured and official conversation on the economics of an AMI system.

Basic overlaps of biotic and abiotic compliments in our hypothetical AMI system.



ABIOTIC

Basic overlaps of biotic and abiotic compliments
in our hypothetical AMI system.



CLIMATE CONTROL

All organisms need their optimal climate for fast growth. Usually this is done by ventilating/heating/cooling/humidifying air. This requires energy and could be (partially) replaced by a smart flow of air through multiple growing systems.

To lower energy inputs for environmental control, it is of paramount importance that the location where these chambers are being built have conditions that are stable, and already similar to the required conditions. For example, growing mushrooms underground makes for a more efficient cultivation system. Underground mushroom growth rooms will have a steady temperature and is easily insulated from light and temperature changes.

TEMPERATURE

In a vertical farm using artificial light, a lot of heat is produced by the light systems and the environmental control systems. This heat would normally be dissipated out of the facility, but could be used to heat insects and/or the water for the fish. Creating a system where heat energy can be stored and shuttled to other systems which need the extra heat would greatly reduce the overall energy costs.

HUMIDITY

About 90% of the water that is taken up by plants is transpired, increasing the humidity of the air. Plants can tolerate a wide range of humidities, but to keep

Basic overlaps of biotic and abiotic compliments in our hypothetical AMI system.

it in a optimal operating window, water vapour has to be removed from the air. Mushrooms on the other hand need a high Relative Humidity (RH) for growth and fruiting. BSF also need moist air to keep the substrate from drying out. It could therefore be possible to save dehumidification costs by pumping excess humid air to the mushroom growth facility, thus reducing the plant growth chambers humidity without large energy cost involved in dehumidification.

CO_2/O_2 CIRCLE

Plants need CO_2 and provide O_2 for fish, insects and mushrooms. Combining these flows would reduce the need for CO_2 fertilization of the plants and reduce the outside air that is needed for the insects. If air is circulated between plants and insects, it could eliminate the need of any outside air. If air is passed through the plants, it will scrub it of CO_2, increase the humidity and heat it when the air is used to cool the LEDs. Insects like hot, humid and O_2 rich air. So a combining them might prove a challenging golden combination.

However, a key question is, do the plants reduce the CO^2 levels enough to make the air suitable again for BSF? And, will the BSF in turn produce enough CO_2 to make the plants happy?

BIOTIC

INTRO

In the natural world, one organism's waste is another organism's life force. The bird that eats a berry digests everything but the seed, inadvertently planting another berry bush which will go on to grow on the worm waste and decomposing matter in the soil. This model, of waste reuse, is inherent to biological cycles and hopefully, one day, vertical farming and CEA techniques.

BSF VS FISH

For optimal Tilapia production, a diet of 30-50% protein, depending on life stage, is required. At the same time, black soldier flies body composition can be composed of 40% protein based on their diet. However, BSF are what they eat, and therefore are not rich in omega-3 except when fed with high omega-3 substrate. Tilapia diet would still need other supplements, even with BSF high in omega-3, because Tilapia are not purely carnivores.

FISH VS PLANTS

Similarly, waste from the Tilapia can be used to fortify Basil production, as in traditional aquaponics. Fish feeding mostly on BSF will have a less fine-tuned diet than fish feeding on pellets. Because fish will not take up all the nutrients from the BSF, these excess nutrients will be available to the plants via fish feces.

PLANTS VS BSF/FUNGI

In a system which grows composters and decomposers long side plants and animals, the applications are infinite. Waste from the Basil plants can now be utilized as a component in the medium for mushroom growth or black soldier fly diet.

FEED & SUBSTRATE

Fish feed is a very unsustainable product because it contains so much fishmeal, which still requires trawling the oceans and incorporates all the problems associated to such practices. Including BSF in fish diets can significantly reduce the need for fishmeal. BSF can be grown on waste streams, which makes that the BSF has a lot of potential to increase the profitability and sustainability of an aquaponics system in a vertical farm. The larvae can be fed alive or made into a meal to be mixed with other ingredients to create a wholesome feed. Most optimal would be if the other ingredients needed could be grown in this system as well. Algae and BSF meal could potentially be an almost complete fish feed.

URBAN WASTE

Urban areas produce lots of organic waste, which can easily be repurposed and utilized in agriculture. Around the world, laws and policy are the biggest hurdles facing this solution to waste streams, while cultural acceptance and lifestyle shifts may also be stunting the growth of this solution. But, using waste in this way is not impossible. Examples already exist, like used coffee grounds from coffee shops that are used to produce oyster mushrooms.

Potential urban waste streams available for utilization include:

- Restaurant vegetable waste and food leftovers as black soldier fly substrate
- Discarded or old food from supermarkets for both black soldier flies and mushrooms
- Greywater, with appropriate treatment, can be transformed in valuable sources of nutrients and water can be recovered up to 70% for sanitation purposes
- Heat from factories in urban industrial areas, which could be linked with the vertical farms reducing the energy input
- CO_2 from combustion of natural gas can be stripped from the exhaust gasses and used by the plants
- Plant transpiration water can be condensed from the atmosphere and re-used for plant production or potable water

WASTE VS BSF

Organic waste can be a headache to deal with in urban areas. It attracts flies and other vermin, which has historically been a problem; however, this also shows the potential organic waste has for fly rearing. BSF can thrive on virtually any organic waste stream.

An important factor to keep in mind when using waste streams must be the source of the waste. For instance, BSF can grow on sewage sludge, yet feeding these larvae to fish for human consumption will raise some sanitation issues, at the least. These larvae produced on less-than-ideal organic waste can still be a marketable product, as ingredients in biodiesel and chitinase.

Interesting streams that be could be utilized to produce human-consumption friendly products include restaurant waste, residential organic waste, supermarket excess, and organic farm produce which is deemed not suitable for market.

BIOTIC (CONT.)

PRODUCTION WASTE

The applications and options for this project are seemingly endless as the linear approach to businesses and consumption is becoming more regulated. Projects looking into aspects such as eggshells which can be used for $CaCo_3$ to raise pH levels for mushroom substrates, or chicken manure to be used as nutrient supplement for mushroom substrate can be positive steps for the vertical farming circles. At the same time, these practices may encourage the consideration of vertical farming partnerships in best management practices developed by other industries.

IMAGE: BRIGHTBOX

RESEARCH NEEDS

The excitement and novelty of this idea and approach is what makes it challenging. There is very little available research out there on how to begin intertwining the inputs and outputs of individual systems to create a coherent and functional business.

A major lack of information comes from lacking knowledge in the chemical profile of waste products. In a system where waste becomes food which then becomes waste and food again, following the nutrient contents, efficiency of metabolism, and biological requirements for diet are critical.

While projects such as the European Space Agency's (ESA) MELiSSA and the Chinese Lunar Palace strive to develop bioregenerative life support systems (BLSSs) on a relatively massive scale, we hope to scale the application of this idea down in order to encourage development of the technologies and processes. If we can grow this process through collaborative research projects and entrepreneurship, we may foster a greater diversity of approaches, all with their own applications and lessons.

For researchers looking to put theory to practice, we imagine a system that successfully runs a two-level sample vertical farm, looking at less traditional couplings, such as plants and mushrooms or black soldier flies and fish. With researchers experimenting with these setups and collecting reliable data, we can one day see large-scale systems with varied products and economic applications.

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MOVING FORWARD

This report is just the beginning of a new progressive agriculture branch of thinking in closed system production: how can communities profit, both monetarily and environmentally, from a waste-neutral or waste reduced production model? We have laid out the skeleton of what this conversation may look like, but there is still so much to question, test, and discuss. Areas such as black soldier fly production and mushroom culture still need significant research, from both scientific and marketing groups. The lack of research regarding everything from optimized diets to understanding outputs was compromised by the numerous unknowns in these fields.

Furthermore, there are plenty of questions to consider in how many levels can be successfully integrated into a system of this kind, as well as species types, In this report, we were limited to four categories of products. In the future, it would be interesting to consider systems which focus on algae, bacteria, vegetables or fruits, other types of fin fish, or even other aquatic species.

Beyond the biological aspects, there are the mass and energy requirements that must follow the laws of physics in the conservation of mass and conservation of energy. Successful systems will have to understand the dynamic relationships of the flow of mass (Carbon, Oxygen, Nitrogen , Hydrogen), as well as the thermodynamics of the energy flows and storage.

Additionally, beyond the biological aspects, we did not touch on, or briefly brushed over, urban planning, infrastructure, or installation. These, along with geographic region, wastewater use, local economic demands, and legal understanding are also underserved. Any other daring thinkers out there are encouraged to investigate creative and reasonable applications for these systems.

We see the future as a place where circular systems are researched as readily as linear systems are researched today. The future of optimization will no longer focus on one system but look at how that system can fit into a bigger, circular system and in this way function as both a sustainable process and product. We believe that as circular systems become more visible people will start to connect the dots in other areas as a fundamental shift in the way we think about our products and systems takes place, from isolated, to interconnected and circular.

“We have laid out the skeleton of what this conversation may look like, but there is still so much to question, test, and discuss.”

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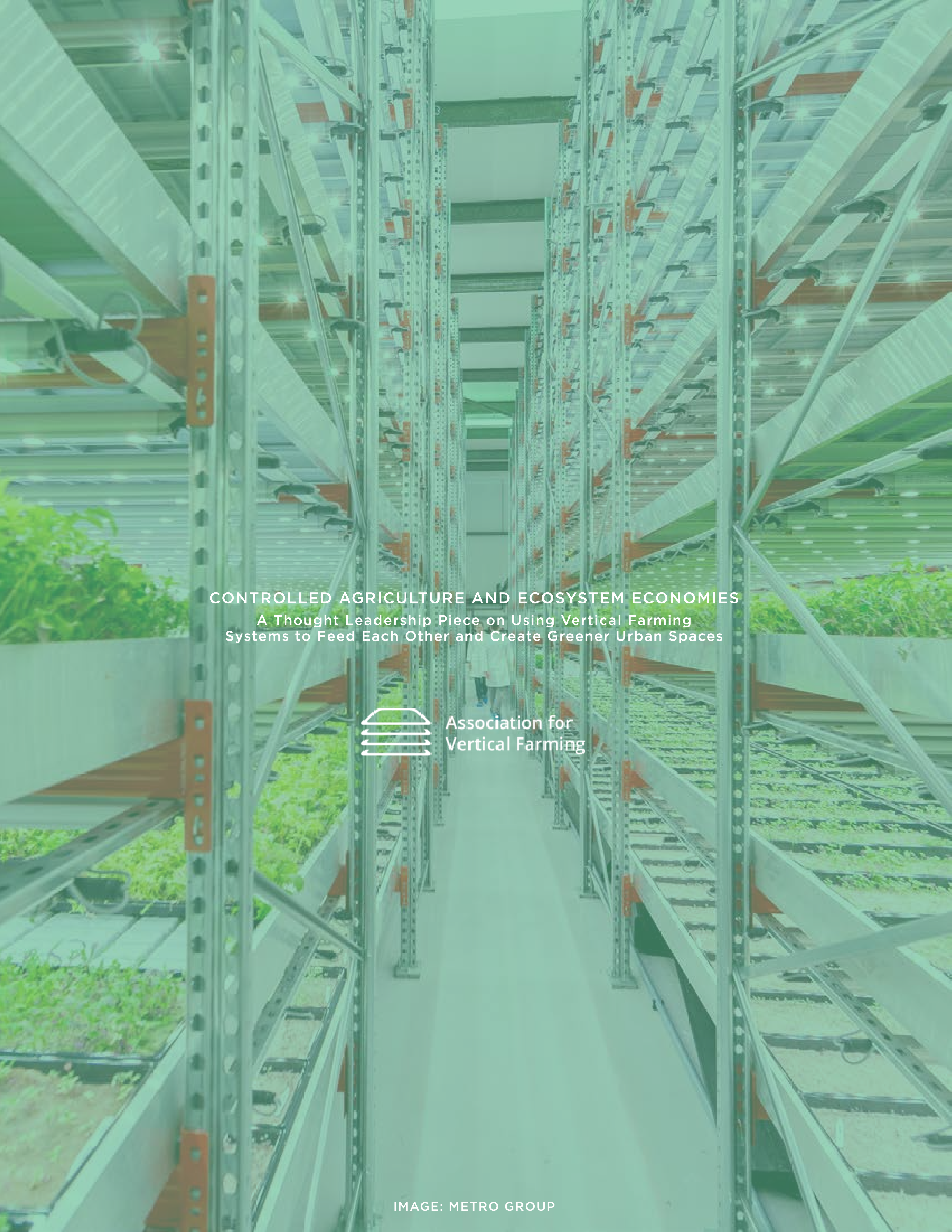

CONTROLLED AGRICULTURE AND ECOSYSTEM ECONOMIES

A Thought Leadership Piece on Using Vertical Farming Systems to Feed Each Other and Create Greener Urban Spaces

Association for Vertical Farming

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