DISENO y GESTION DE UN PROCESO PARA RECICLAR DESECHOS ORGANICOS CON LA LARVA *Hermetia illucens* PARA PRODUCIR HARINA DE LARVA

GRANT EVEREST CANARY

Proyecto de Grado: Para Obtener el grado de Magíster en Diseño y Gestión de Procesos

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Abstract

As a basis for analysis, this study establishes that food supply for the next several decades will be stretched nationally and internationally as population growth and fuel production demands increase. Aquaculture and the production of land based polyculture farmed fish is the food industry best positioned to take advantage of the demands on food supplies. The problem for this industry is that at present farmed fish are dependent upon fishmeal as a protein source and annual production of fishmeal has peaked. This is because the wild stocks harvested to produce fishmeal are at or beyond their sustainable production capacity. More sources of fishmeal to meet rising demand are not likely to be found.

This study analyzes Black Soldier Fly Larvae (*Hermetia Illucens*) as a sustainable alternative to fishmeal to sell to animal feed producers. Four research studies were performed to fill gaps in current knowledge regarding optimal feed substrates and growth conditions, anti-fungal properties of leachate from the process, and anti-bacterial properties of the larvae. In addition, a pilot production facility was constructed by interconnecting the Bio-Pod technology pioneered by ESR International and the egg collection methodology designed by Dr. Craig Sheppard and Dr. Jeff Tomberlin.

Using existing data and data developed from the research and pilot facility, a model of the larvae cultivation process was developed using VENSIM software to analyze profitability as a function of the adjustable variables in the model. A second model was developed that modeled the sustainability of the Fishmeal industry and the subsequent affect on the price and availability of fishmeal. Because larvae-meal is a product replacement for fishmeal, this price was used as the sale price for larvae-meal in the larvae cultivation model. This latter model represents an innovative future archetype for the field of the logistics and systems modeling as it forecasts the price of a maximized eco-system product as a function of its management. Many of our industries, such as the automobile industry, timber industry etc have become essential yet rely on unsustainable resources or soon to peak resources. Substitute goods will need to come to market and the market prices which they receive will be a function of the management of the previous resource. Using the two systems models, scenarios were forecast and a business plan was developed for the process.

Table of Contents

I. **Introductions (Introducciones)**

Overview……………………………………………………………6

An Introduction to Logistics and Systems Modeling…………………… 6

An Introduction to Environmental Economics and Ecosystem Services.. 7

An Introduction to the Fishmeal Industry …………………………… 9

An Introduction to the Study of *Hermetia Illucens* Larvae…………….. 10

An Introduction to Food Waste and Food Waste Recycling Systems….. 14

II. The Objectives of the Study…………………………………………….. 18

II. Pre-Investigation (Pre-Investigación)

Presentation of the Problem……………………………………………..20

III. Investigation (Desarrollo)

Introduction to the Scientific Studies Performed…………………………… 40

Study 1: Substrate Degradation………………………………………………. 42

Study 2: Starches & Meat As Substrates………………………………………49

Study 3: Pathogen Hindrance by Cultivation Leachate……………………… 57

Study 4: Inhibition of Pathogens by *Hermetia Illucens* ……………………… 61

Future Research…………………………………………………………..67

IV. Pilot Larvae-Cultivation Factory Design Description…………………… 69

V. Development of the VENSIM Models

Model 1: Fishmeal World Production Model………………………………… 75

Model 1a: Historical Validation of the Fishmeal Model…………………….. 81

High and Low Price Scenarios For Fishmeal Production…………………….. 84

Model 2: Larvae Cultivation…………………………………………………..86

The Business Plan…………………………………………………………95

VI. Conclusions From the Study (Conclusiones)……………………………..103

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I. Introductions

Overview

This study is presented as an innovation in the field of logistics as it begins to blend the fields of logistics and the developing field of environmental economics. The latter of which was recently legitimated with the recently elected US President Barack Obama establishing a USDA Office of Ecosystem Services and Markets.[1] The objective of this study is to blend the two fields by modeling world fishmeal production, fishmeal price as a result of management practices, and the impact on the aquaculture industry's growth potential. By modeling these aspects of the fishmeal industry, the market opportunities of a fishmeal substitute can be determined. Unlike other new products that enter the market and are cheaper or more technologically advanced, this study will show that the lack of fishmeal to meet the demand of an indispensable industry provides ample market opportunity. Accordingly, this study additionally constructs a systems model of a larvae meal production process for production of a substitute good based on the pilot factory. This systems model is designed to be a decision making tool for scaling the industrial process to an industrial level. A business plan is presented at the conclusion of the study with the financials based upon the outputs from the decision making model and fishmeal management model.

As an interdisciplinary study, a number of fields are represented each of which requires an introduction. The following are introductions to Logistics & Systems Modeling, The Fishmeal Industry, The Study and Cultivation of Hermetia Illucens Larvae, and Food Waste Recycling Systems. At the conclusion of the introductions to each of these fields, the fields are linked and an outline of project goals is given.

An Introduction to Logistics and Systems Modeling

An American biologist of Austrian origin, Ludwig von Bertalanffy, invented what we know today as "the systems approach" by constructing the foundation of the philosophy of systems: that "organized wholes of any kind should be describable, and to a certain extent explainable, by means of the same categories, and ultimately by one and the same formal apparatus."[2] Bertalanffy published his first widely read work in 1945. In 1948, an American mathematician at the Massachusetts Institute of Technology, Norbert Wiener, worked together with an IBM engineer and physiologist to publish a groundbreaking book on Cybernetics. This book lead the way for more interdisciplinary works that would build a science around the creation of communication, control, and data capturing from dynamic systems.[3]

From these two sources of inspiration, a tremendous amount of interdisciplinary work commenced in fields such as economics, marketing, managing, and industrial production. However, it was Jay W. Forrester's *Industrial Dynamics* in 1961 that founded what we know today as *the methodology* of "systems dynamics."[4] In this methodology, the structure of a system is paramount, and is modeled using mathematically defined relationships of stock and flow system components over a period of time. In this process, delays and holdups cause shortages or overflows

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[1] Worldchanging, "USDA Office of Ecosystem Services and Markets," Worldchanging.com, Julia Levitt, 6 Jan 2009, http://www.worldchanging.com/archives/009278.html (accessed 7 Jan 2009).
[2] Markus Schwaninger, *System Dynamics and the Evolution of Systems Movement: A historical perspective.* (St. Gallen: Universität St. Gallen, 2005)
[3] See note 2.
[4] Jay W Forrester, *Industrial Dynamics* (Waltham, MA: Productivity Press, 1961), 479

in the quantity available. This modeling is today described as the modeling of a Dynamic System and is considered a sub-field of logistics.

From Forrester's work, many other theories emerged, such as catastrophe theory, chaos theory, and complexity theory. From each of these, mathematical expressions are connected to philosophical, metalogical, and ethical considerations. More recently, the software packages developed for systems dynamics have been applied to world population growth and resource consumption by Donella Meadows.[5] The model done by Meadows produced both startling and unexpected results and was presented to the Club of Rome—starting much of the environmental movement. The model is a fine example of what the field of systems dynamics has come to be known for: following a careful process to create models of systems that accurately resemble real systems, then analyze and understand the relationships demonstrated in the model as it is run over time.

Similarly, this is the purpose of modeling fishmeal supply and it's sustainable limit of production and demand and the necessity of aquaculture industry growth: to carefully construct a systems model that allows the understanding and analysis of the relationships demonstrated in the models. From this analysis the market opportunities for a substitute good can be determined.

System Dynamics modeling has been chosen as the superior method of modeling because it has four specific characteristics that make it more accurate, realistic, and revealing than other modeling disciplines. These four advantages are[6]:

1. The models are feedback driven and can model closed systems such as those that self-regenerate (autopoetic), as well as those models that are open and receive information and energy, from outside the boundaries of the structure of the system.

2. The model is formalized and transparent. Because of this, assumptions and logic used to create the model are more easily recognized. In addition, it is more easily discussed. Finally, as all parts are mathematically formalized, the level of realism that can be achieved is higher than in other modeling disciplines such as econometrics.

3. There is qualitative and quantitative analysis. The focus is not solely on numerical answers to an equation, but the insights into behavior of a model given changes to these variables.

4. Powerful software packages are able to work in collaboration with other software tools.

The software package chosen to model the systems in this study is VENSIM[7] designed by Jay W. Forrester. While it lacks in modern graphics, it is extremely functional and one of its most appealing aspects is that it is available for free and thus the models built as a part of this study are transferable without barrier.

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[5] Donella Meadows, Daniel Meadows and Jørgen Randers, *The Limits to Growth* (New York: Universe Books, 1972)
[6] See footnote 2.
[7] Ventana Systems Inc., Vensim® PLE for macintosh version 5.5d. Copyright (1988-2005)

An Introduction to Environmental Economics and Ecosystem Services

Ecological economics hinges on the concept that nature's ecosystems provide goods and services that intersect with human economies. Examples of these goods and services include clean water, waste treatment, and oxygen production. In the literature of ecosystem services analysis, these services are reduced to five sub-fields, as described by Gretchen C. Daily's article "Management objectives for the Protection of Ecosystem Services" and cited online.[8,9]

"Provisioning services": which include the seafood and terrestrial animals, the basis for future pharmaceuticals and other industrial products such as timber, and energy such as hydropower and biomass.

"Regulatory services": which include the sequestration of carbon and atmospheric regulation, the decomposition of wastes, the treatment of toxic substances, and nutrient provision and recycling.

"Supporting services": which includes the air and water purification, the pollination of crops and dispersal of seeds, and the control of diseases and pests.

"Cultural Services": which provide the spaces and terrains for recreational experiences, the primary matter for scientific discovery, and inspiration on a cultural, spiritual and intellectual level.

"Preserving Services": which include redundant species diversity and genetic codes for future use, resources for uncertainty, and the protection of future options.

The examination of ecosystem services dates back to Plato in 400 B.C.[10,11] when he noted that deforestation could cause soil erosion and the destruction of springs. In contemporary academics it was first presented in 1864, when G.P Marsh argued against the existing premise that earth's resources were infinite by using soil fertility in the Mediterranean as evidence.[12,13] Unfortunately the academic study of ecosystem services did not coalesce as a field until the late 1940's when Osborn, [14,15] Vogt, [16,17] and Leopold[18,19] promoted the idea of 'natural capital.' The term 'ecosystem services' was coined by the Study of Critical Environmental Problems report published in 1970 by the MIT press.[20,21] This report listed pollination, fisheries, climate regulation and flood control as some of the essential services provided by eco-systems.

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[8] Wikipedia Online Encyclopedia. "Ecosystem Services." Wikipedia Online. http://en.wikipedia.org/wiki/Ecosystem_services#cite_note-Daily_2000-10 (accessed 14 Jan 2008)
[9] G.C. Daily, "Management objectives for the protection of ecosystem services."*Environmental Science & Policy 3 (*2000): 333-339.
[10] See note 8.
[11] G.C. Daily, *Nature's Services: Societal Dependence on Natural Ecosystems* (Washington: Island Press, 1997), 392pp.
[12] See note 8.
[13] G.P. Marsh, *Man and Nature.* (New York: Charles Scribner, 1864 (1965)), 472pp.
[14] See note 8.
[15] F. Osborn. *Our Plundered Planet*. (Boston: Little, Brown and Company, 1948), 217pp.
[16] See note 8.
[17] W. Vogt, Road to Survival. (New York: William Sloan, 1948), 335pp.
[18] See note 8.
[19] A. Leopold, *A Sand County Almanac and Sketches from Here and There.* (New York: Oxford University Press, 1949), 226pp.
[20] See note 8.
[21] "Man's Impact on the Global Environment*." Study of Critical Environmental Problems*. (Caimbridge: MIT Press, 1970), 319pp.

The field of Environmental Economics as described by the US National Bureau of Economic Research, "undertakes theoretical or empirical studies of the economic effects of national or local environmental policies around the world."[22] In this field, valuation of direct or indirect use of eco-system services is a key topic. The field of environmental economics is, though differing in name from the study of ecosystem services, inexorably involved in attempting to valuate the five categories of ecosystem services to perform cost benefit analyses of environmental policies.

Topics of concern for this study in the field of environmental economics include: market failure, externalities and common property. A market failure is when the market fails to distribute resources in an efficient manner. An externality is a type of market failure in which an individual performs an action that affects other people which is not included in the market price of the product or service. Non-excluded common property is another type of market failure in which it is too expensive to exclude individuals from accessing a natural resource and the "tragedy of the commons ensues" as Garrett Hardin's 1968 Science article described.[23] While many groups have designed common property management regimes, in the case of most fisheries it is still too expensive to exclude, catch and/or penalize cheaters.

An Introduction to the Fishmeal Industry

As described by the Fishmeal Information Network, fishmeal is "the brown flour obtained after cooking, pressing, drying and milling whole fish and food fish trimmings. It is produced almost exclusively from small, bony species of pelagic fish (generally living in the surface waters or middle depths of the sea), for which there is little or no demand for human consumption."[24] Species which are included in this category include: anchovy, horse mackerel, menhaden, polluck, capelin, herrings, blue whiting, pout, sandeel, sprat, sardine, and pilchards.[25] While most species are caught solely for the production of fishmeal, a small portion of fishmeal is produced from by-catch which is unwanted fish caught by fisherman in their nets.

Producing fishmeal requires about four to five tons of whole fish to produce one ton of fishmeal. The largest producer is Peru which produces approximately one-third of total world production which is between six and seven million metric tons annually.[26] Other major producers include Chile, China, Thailand, the U.S.A., Iceland, Norway, Denmark and Japan.

The Reuter Agency has established a price quotation reporting system on the Hamburg CIF (cost, insurance, and freight) market. However, there are no cash or futures markets on fishmeal despite failed attempts to establish them.[27] This is likely due to the fact that fishmeal commodity trading is highly volatile and though fishmeal stocks may be regulated, stocks only permit three months of advance forecasting which is low compared to other commodities. This has lead to the necessity to establish information services such as the Hammersmith Co.'s weekly newsletter on information and price points regarding fishmeal production.[28] An additional irregularity about the fishmeal market is that the market is not transparent and transactions are private and confidential

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[22] National Bureau of Economic Research, "NBER Working Groups Descriptions," National Bureau of Economic Research http://www.nber.org/workinggroups/ee/ee.html (accessed 14 Jan 2008).
[23] Garrett Hardin, "The Tragedy of the Commons", Science, Vol. 162, No. 3859 (Dec1968): 1243-1248.
[24] Fishmeal Information Network, "Feeding Fishmeal and Fish Oil," Fishmeal Information Network, http://www.gafta.com/fin/index.php?pge_id=5 (accessed 11 Nov 2008).
[25] The Fish Site, "The benefits of fishmeal in aquaculture diets," University of Florida http://www.thefishsite.com/articles/200/the-benefits-of-fishmeal-in-aquaculture-diets (accessed 3 December 2008).
[26] See note 24.
[27] Marie-Hélène Durand. "Fishmeal Price Behavior: Global Dynamics and Short Term Changes." (Montpellier: ORSTOM), 467
[28] Hammersmith Ltd Blog, The. http://hammersmithltd.blogspot.com/

and conducted by only about thirty traders worldwide on behalf of livestock feed companies.[29] This is agreeable to feed producers as the feed manufacture industry is a "black box" industry in which feed producers consider sources of protein and all ingredients and quantities trade secrets.[30]

Fishmeal is the preferred source of protein for nearly all feed makers for terrestrial and aquaculture diets as its addition, "increases feed efficiency and growth through better food palatability… nutrient uptake, digestion and absorption."[31] In addition, high quality fishmeal provides a balanced amount of all essential amino acids, phospholipids, and fatty acids.[32] High quality fishmeal is between sixty-five and sixty-seven percent protein, and is either steam dried which preserves amino acids or flame dried which reduces quality and is noted as FAQ (fair average quality) in the trading price.[33]

In terrestrial animal diets, fishmeal typically is five percent or less on a dry matter basis, while fish diets may contain 5-7% for some species of fish such as Tilapia and up to 40-55% for marine carnivorous fishes.[34] Inclusion rates vary largely depending upon feed manufacturers and breeder preferences, fish type, and the stage of fish development.

Comparable substitutes for fishmeal in feeds are nearly all plant based. As Miles and Chapman describe in their article, "*The benefits of fishmeal in aquaculture diets*," plant based proteins are "associated with indigestible non-structural carbohydrates (oligosaccharides) and structural fiber components (cellulose), which are not associated with animal proteins."[35] These block digestion and efficient utilization of the proteins. Animal proteins are more digestible than plant based proteins. Though Plant based proteins vary, protein digestibility in plant based feeds is only 77-96%, while fishmeal is consistently above 95%.[36] Additionally, plant based proteins have different essential amino acid profiles with different deficiencies. Of the ten essential amino acids, proteins in cereal grains are deficient in lysine and methionine while soybeans and legumes lack methionine and cystine.[37] Finally, some plant based proteins contain anti-nutritional factors that limit uptake or digestion or are simply toxic. As an example, lathyrogens in chic peas hamper collagen formation.[38] Gossypol is found in cottonseed meal/oil and is toxic to animals and lowers male fertility.[39] The Kunitz trypsin-inhibitor is found in uncooked soybean meal and prevents the trypsine enzyme from breaking down dietary proteins.[40] In contrast, fishmeal contains no anti-nutritional factors, and its palatability, thought to be due to glutamic acid which is a non-essential amino acid, increases consumption by fish and animals.[41]

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[29] See note 27.
[30] See note 27.
[31] See note 25.
[32] See note 25.
[33] Wayne Bacon, Hammersmith Ltd, e-mail Message to the Author, 5 July 2008.
[34] See note 25.
[35] See note 25.
[36] See note 25.
[37] See note 25.
[38] See note 25.
[39] See note 25.
[40] See note 25.
[41] See note 25.

An Introduction to the Study and Cultivation of *Hermetia Illucens* Larvae

The first contemporary studies of Black Soldier Flies (Hermetia Illucens) and their larvae were completed by three researchers, Furman, Young and Catts in 1959.[42] They noted that the larvae naturally controlled populations of houseflies. The larvae were left alone until around the 1970's as researchers began searching for cheaper poultry feeds. Larvae are part of a natural diet for poultry and as researchers examined different fly species and their larvae, Hale examined *Hermetia Illucens* larvae in 1973.[43] In 1977 Newton, Hale, Vooram and Barker examined their use as a feed supplement for swine. These larvae at the time were known as "latrine" larvae and were naturally found in manure piles of large poultry, pig and cattle operations.[44] Through the 1980's and 1990's researchers began to investigate what the larvae were doing there and it was noted that they reduced manure load in addition to naturally controlling populations of house flies which are a disease vector.[45,46,47]

Since that time, researchers world-wide have been developing additional information about the larvae as the larvae have been described as native to many areas including most of the Western Hemisphere and the Australian region from Samoa to Hawaii.[48] Black Soldier flies have also been found throughout South America[49,50] and Asia.[51] In this analysis they were found to be native to Medellín, Colombia.

Global research has developed a lot of information about Black Soldier Flies useful to this study's aims to cultivate the larvae in an industrial process. The larvae have been described to prefer temperatures of 35°C (95°F) for the consumption of waste[52]; however research in this analysis disagreed with these results, likely due to the humidity levels in the experiment and the elevation of Bogotá. Humidity levels of 70% were found to cause the maximum development rate of the Black Soldier Fly in manure.[53]

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[42] D. P. Furman, R. D. Young, and E. P. Catts. "*Hermetia illucens* as a factor in the natural control of *Musca domestica* Linnaeus." *Journal of Economic Entomology* 52, (1959): 917-921.

[43] O. M. Hale, "Dried *Hermetia illucens* larvae (Stratiomyidae) as a feed additive for poultry," *Journal of the Georgia Entomological Society* 8 (1973): 16-20.

[44] Gary Newton, C. V. Booram, R. W. Barker, and O. M. Hale. "Dried *Hermetia illucens* larvae-meal as a supplement for swine." *Journal of Animal Science* 44 (1977): 395-399.

[45] C. Sheppard, "House fly and lesser house fly control utilizing the black soldier fly in manure management systems for caged laying hens" *Environmental Entomology* 12 (1977): 1439-1442.

[46] G. L. Newton, D. C. Sheppard, S. A. Thompson, and S. I. Savage. "The soldier fly, a beneficial insect: house fly control, manure volume reduction and nutrient recycling." (presented a the nuisance concerns in animal manure management: Odors and flies conference, Gainesville FL, University of Florida) Pages 106-116

[47] D. C. Sheppard, G. L. Newton, J. Davis, G. Gascho, S. Thompson, S. Savage and K. Bramwell. "Using soldier flies as a manure management tool for volume reduction, house fly control and feedstuff production," (Southern Regional SARE Program, 1998)

[48] Black Soldier Fly, "Hermetia Illucens," North Carolina State University. http://ipm.ncsu.edu/AG369/notes/black_soldier_fly.html (accessed 3 June 2008).

[49] Gloria Arango Gutiérrez; Rodrigo Antonio Ruiza and Humberto Véleza. "Compositional, Microbiological, and Digestibility analysis of the protein of Larva-Meal from Hermetia Illucens in Antioquia, Colombia." (Medellin: University of Antioquia, 2004), 8.

[50] Gerardo Larde, "Recycling of Coffee Pulp by Hermetia Illucens (Diptera: Stratiomyidae) Larvae," *Biological Wastes* 33 (1990): 307-310.

[51] Dr. Paul Olivier, Telephone Interview Discussing Travels and Residence in Asia, 16 July 2008.

[52] Dr. R. Newby, "Use of Soldier Fly in Organic Waste Management," message on "Compost and Soldier Fly" message posted on 2 Sep 1997, Ibiblio digital library. http://www.ibiblio.org/london/orgfarm/composting/Compost+Soldier-fly-larvae.txt (accessed 5 April 2008).

[53] See note 52.

The larvae themselves are quite hardy. They can be fully submerged in rubbing alcohol for up to an hour without negative effects.[54] Little literature is available regarding optimum Ph; however, cited in a paper by Dr. Newby is the following: "The larvae tolerate a wide range of pH and will survive well in compost derived exclusively from decomposing citrus fruits (Brues 1928)."[55]

Despite surviving in difficult conditions as larvae, the mature flies are weak fliers and do not venture inside houses or structures.[56] Additionally, they do not bite as they have no functioning mouth parts and consume no food as emerged flies. As adult flies they only live 8-9 days, require only water, and survive off body fat stored in the larval stage.[57] For these reasons, they are not a vector of disease as many flies including the common housefly are.[58] In fact, as discussed earlier, *Hermetia Illucens* have been found to repel common pests such as the housefly in commercial poultry operations.[59]

Additional advantages to using the larvae include that they have been found to reduce harmful bacteria in organic wastes such as manure[60] and when manure has been used as a larvae feed substrate they have been found to reduce manure mass by 50%, and total nitrogen concentration by 62%. This is important because when left untreated excess nitrogen from manure is a water supply contaminant. In addition, their rapid consumption and aeration of the substrate has been found to reduce odors and therefore presumably methane formation and off-gassing.[61] This latter fact means that an industrial process using black soldier fly to treat manure would be eligible for carbon sequestration credits. In the carbon trading market, methane is considered twenty three times more potent than carbon as a green house gas and therefore one ton of sequestered methane is worth twenty four tons of sequestered carbon.[62] This could prove to be an important source of revenue for a larvae cultivation process. However, additional research to determine the extent to which methane sequestration occurs is required before the credits can be certified and traded and that is outside the scope of this study.

At present, researchers have begun to examine the use of black soldier flies as a fish feed due to the need to find a replacement for fishmeal in animal feeds. While flies are part of a fish's natural diet, little work had been previously done on larvae-meal as a fish feed or a substitute product for fishmeal. To date, studies of fish species fed black soldier fly larvae have only been performed with rainbow trout, *Oncorhynchus mykiss*[63]; channel catfish, *Ictalurus punctatus*[64]; and blue tilapia, *Oreochromis aureus*[65]. This initial research has shown that in the case of rainbow trout, the

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[54] Dr. Paul Olivier, "Desechos Organicos Transformada a Comida de Peces y Pollos," (presented at the Universidad de la Sabana, Colombia, 14 April 2007).
[55] See note 52.
[56] See note 54.
[57] Jeffery Tomberlin, et. al. "Selected Life-History Traits of Black Soldier Flies (Diptera: Stratiomyidae) Reared on Three Artificial Diets," Annual Entomological Society of America 95(3)(2002): 379-386
[58] See note 48.
[59] See note 45.
[60] M.C. Erickson, M. Islam, C. Sheppard, J. Liao, and M.P. Doyle. "Reduction of *Escherichia coli* O157:H7 and *Salmonella enterica* serovar Enteritidis in chicken manure by larvae of the black soldier fly," *Journal of Food Protection* 67 (2004):685-690.
[61] Larry Newton, et. al. "Using the Black Soldier Fly, *Hermetia Illucens*, as a value added tool for the management of swine manure," Report for Mike Williams, www.cals.ncsu.edu/waste_mgt/smithfield_projects/phase2report05/cd,web%20files/A2.pdf (accessed: 6 June 2005).
[62] Hugh Whalan, Environmental Credit Corporation, Telephone Interview with the author, 29th Nov 2008.
[63] Sophie St-Hilaire, et. al, "Fly Prepupae as a Feedstuff for Rainbow Trout, *Oncorhynchus mykiss" Journal of the World Aquaculture Society* 38 no. 1 (2007): 62
[64] K. Bondari & D. C. Sheppard, "Black soldier fly larvae as a feed in commercial fish production," *Aquaculture* 24 (1981):103–109.
[65] K. Bondari & D. C. Sheppard. "Soldier fly *Hermetia illucens* L., as feed for channel catfish, Ictalurus punctatus (Rafinesque), and

larvae can replace 25% of fishmeal use and 38% of fish oil use with zero adverse effects.[66] Thus, for the purposes of this study the larvae are treated as a near perfect substitute. However, much research remains to be done as there is significant room to improve the larvae further as a feed. For example, in the article by St. Hilaire et al 2007, manure fed larvae do not have a high percentage of long-chain unsaturated fatty acids generally desirable for carnivorous fish. However, the authors note that feeding larvae different substrates is likely to affect the larvae composition. For example, in one study where larvae were fed fish offal compared to larvae fed manure, lipid content of the larvae increased 30% and omega-3 fatty acids increased 3%, both increases were within twenty four hours.[67] This study therefore aims to begin the undertaking of examining the effects of different substrates in the composition of the larvae.

Black soldier fly larvae grown on food wastes have not been studied. To date, larvae have only been fed manure, fish offal, and controlled diets of processed feeds for scientific research. This study identified that managing food wastes with larvae was a critical area needing research as few options were available to food waste producers such as groceries, warehouses, schools and corporate campuses for the environmental treatment of food wastes. In the United States, these food waste producers often pay a premium for environmental treatment of the wastes in order to maintain a green public image. Having identified this, it was clear that the processing of food represented a critical market opportunity. The initial wastes to feed the larvae in this study were chosen based upon the most profitable wastes to receive from waste producers.

In order to produce a larvae-meal to the feed companies exact specifications, this study examined the consumption rate of the waste substrate by the larave, biomass development, and protein development first and foremost. The purpose of this was to begin to analyze what food wastes the larvae could consume and which food wastes resulted in optimum growth versus diminished growth or death.

It should be noted that this research is the beginning of a long process to establish a database of how different wastes, and different combinations of waste affect larvae composition, biomass development, and total weight. This study represents only a beginning step in understanding larvae composition development.

Additionally complicating the research is that different larvae compositions may be more suitable to different species of fish, as well as differ depending upon the development stage of the fish. This is because fish species respond differently to different types of feeds, as do fish in different stages of maturation. While a company producing larvae will be responsible for studying how the larvae develop different compositions, feed companies will be simultaneously coordinating their efforts in order to research the development of different fish at different stages of development with different larval compositions. This is a multi-year project requiring the investment, infrastructure, and personnel of multiple feed companies. Accordingly they have the infrastructure and resources to execute such a study and will want to utilize these resources to maintain the information as a trade secret and competitive advantage.

Due to this level of uncertainty regarding the substitutability of the larvae-meal for fishmeal, the strategy of the economic analysis of the larvae-meal is to treat the larvae as a near perfect substitute due to the fact that the existing data shows that larvae-meal can be substituted for significant quantities of fishmeal without adverse effects.

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blue tilapia, Oreochromis aureus (Steindachner)," *Aquaculture and Fisheries Management* 18 (1987):209–220.

[66] See note 63.

[67] Kate Cranfill, et. al. "Fish Offal Recycling by the Black Soldier Fly Produces a Foodstuff High in Omega-3 Fatty Acids." *Journal of the World Aquaculture Society* V38 No. 2 (2007).

Additional future studies of black soldier fly larvae are likely to investigate the chitin levels of the larvae as it is theorized that chitin in the larvae exoskeleton may cause a slightly higher feed conversion ratio (gram fed/gram weight gained) as the chitin is indigestible. However, this same Chitin has a relatively high market price ($10-$1000/kg depending upon quality)[68] and extraction of the chitin from the larvae as an industrial process could become an additional revenue stream. This is already the case for the shrimping industry in many nations including Newfoundland. Applications for Chitin include waste-water treatment to bond to heavy metals as it is insoluble in nearly all solvents, chitin as a vehicle for drug delivery, film for fruit preservation, and fiber structures for wound and burn dressing.[69]

An Introduction to Food Waste and Food Waste Recycling Systems

As the Swedish International Water Institute noted in their 2008 report, "Saving Water: From Field to Fork –Curbing losses and Wastage in the Food Chain" 30% of food produced globally is wasted or lost in between the field and the fork.[70] This signifies that there are large wastages of food in the farmer's field, transporting from farmer to distributor, from distributor to warehouse, from warehouse to the grocery, and from the grocery to the home. Additionally, there are food wastes from processing, pulping, and cooking food both at the industrial, commercial and residential level.

In developed countries, much of the food waste at the commercial level is simply being landfilled. Landfills in the state of California charge between $20 and $120 per ton to receive any waste depending upon landfill location in urban or rural space.[71] The alternative option is to compost the wastes at compost facilities. However, compost facilities have only succeeded in the United States as they are able to charge a fee to receive the food and yard wastes and in many cases are government subsidized to increase landfill diversion and extend landfill life. The tipping fee is their primary source of revenue, not the compost itself. Composting operations in Colombia have remained very small as in most cases they must pay to receive the waste and they make their primary profit on the compost itself. The problem with relying on the compost itself is that the composition is rarely uniform in nitrogen, potassium and phosphorus. Farmers accustomed to petroleum based fertilizers and soil amendments expect exact percentages of these nutrients. Colombian composters cannot meet these expectations.[72] Therefore organic compost is usually sold at a reduced market price and the industry remains stunted.

The consequence of stunted compost operations in the United States results in the landfilling of food-waste and a waste of the water used to grow the food. Agriculture is the world-wide number one user of water. The figure of 30% wasted food means production systems are utilizing 60% more water than they need to in a time of increasing water scarcity. It also represents a large waste of pesticides and fertilizers, both of which are petrol-derived products in a time of increasing petrol scarcity. Finally, it represents a huge waste of nutrients in that once landfilled, the valuable and nurturing nutrients are rarely ever recovered.

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68 Government of Newfoundland & Labrador, "Minister announces new licences for the processing of shellfish waste," News Releases, posted May 29, 2001, http://www.releases.gov.nl.ca/releases/2001/fishaq/0529n01.htm (accessed 4 Dec 2008).
69 Government of Newfoundland & Labrador, "Backgrounder: Chitin/chitosan and Other Products." News Releases, posted May 29, 2001, http://www.releases.gov.nl.ca/releases/2001/fishaq/0529n01.htm (accessed 4 Dec 2008).
70 Swedish International Water Institute, "Saving Water: From Field to Fork," (Stockholm: International Water Management Institute, 2008): 21. www.siwi.org/documents/Resources/Papers/Paper_13_Field_to_Fork.pdf (accessed May 2008).
71 Swedish International Water Institute, "Saving Water: From Field to Fork," (Stockholm: International Water Management Institute, 2008): 6. www.siwi.org/documents/Resources/Papers/Paper_13_Field_to_Fork.pdf (accessed May 2008).
72 Patricia Rojas Torres, Agro Humus Ltda., Interview with the Author, 21 July 2007.

These initial findings regarding the poor recycling of food waste lead to a much more in depth pre-investigative assessment of food waste collection, handling and processing through interviews of academic, corporate, and government officials in the United States and Colombia, site visitations in the United States and Colombia, as well as attendance of conferences on the subjects. The question throughout this research was how to best position a larvae treatment process to take advantage of existing food waste collection infrastructure. To understand existing collection methods, waste sources were categorized into six major sources and their collection methods and handling were analyzed. These six major sources are analyzed below:

Waste Source 1: Residential Food Wastes

Home waste is the least clean of all organic waste sources, due to the lack of a sorting system and poor consumer awareness.[73] It is also the most difficult to collect as it is the least sanitary, most labor-intensive, and furthest distance apart. It is also found only in relatively small quantity-concentrations. Entering into collection of food waste poses significant challenges as many waste transport companies already exist and are much better equipped, financed, and in many cases already collecting the food waste. Discussions with Greg Schoenbachler at Silver Springs Organics revealed that the easiest method to enter into the market is to work with waste transport companies to receive food waste that they are already hauling and charge them a tipping fee lower than competing waste processing.[74]

Waste Source 2: Restaurant Food Wastes

Restaurant waste comes in more substantial quantities, however, conversations with the representatives of the City of Modesto, CA revealed that training restaurant employees to properly separate the waste is often a difficult task as there is high employee turnover, especially in fast food restaurants.[75] The experiences of experimental city programs working with restaurants to divert food waste varied from excellent to terrible. These experimental programs noted that an additional obstacle for restaurants is the storage of the food waste. Many restaurants lack storage space; or, what space they have is monitored carefully by public health inspectors. This further demonstrates the necessity to work with both waste haulers and their customers directly to insure proper training and proper storage.

Waste Source 3: Industrial Processing Food Wastes

At the industrial level some industries have found suitable ways to increase revenue streams by utilizing pulp or processed food waste. However, many such as AgroFrut in Medellín, Colombia prefer to focus on their core business of fruit juice sales. They have looked for but not been able to establish suitable partners to utilize their pulp waste and therefore they landfill it.[76] In the case of a Colombian coffee company which produces instant coffee and lots of used coffee grounds, 18 tons of coffee grounds are collected monthly for which it is paid a fee of 95 pesos/kilo.[77] In the case of a Bogotá milk

[73] Professor Jose Maria Castillo, La Javeriana Universidad, Interview with the author, 5 Sept 2008.
[74] Greg Schoenbachler, Silver Springs Organics, Interview with the author, 14 April 2008,
[75] Holly King, agricultural program coordinator, City of Modesto, CA., Interview with the author, 23 April 2008.
[76] Agrofrut s.a., site visitation by the author, 28 Jan 2008.
[77] Javier Mauricio Ramierez, GPAS s.a., Interview with the author 8 March 2008.

company, 40 tons of waste are collected per month for which it is paid a rate of 70 pesos/kilo but the purchaser must sort it.[78] These wastes are utilized as animal feed additives.

Given the opportunities in other markets to be paid to receive wastes, these options are less desirable. This is especially true in the United States due to the fact that ethanol producers are beginning to compete and pay for the industrial wastes due to their need for large volumes of consistent organic material to ferment.

Waste Source 4: Crop Agriculture Wastes

Farming operations have waste in the form of rotted, over-ripe or unpresentable food products—yet in lesser volume than industrial wastes. However, they too differ from most other sources of waste in that they will not pay for pickup of these wastes at the field. This is because they have the option to till the food waste into the soil as a soil amendment. This returns nutrients to the soil, yet the breakdown of the food waste robs nitrogen of the soil.[79] Were farmers to participate in a food-waste to larvae-meal program, it is estimated that they would expect to be paid approximately five cents per pound of waste.[80] This makes them a less than ideal target market at the point of production as other waste sources pay to have waste removed and processed.

Interviews with farmers have suggested that instead the pain crop producers feel is not at the field, but when shipments to groceries are rejected by the grocery stores. A story relayed by one farmer revealed that in one such case, this farmer sent a shipment of pumpkins to a Vons grocery store at a transport cost of $1000. Vons rejected the shipment as unfit for sale, which forced this farmer to pay an additional $1000 to ship the pumpkins back to his farm where he composted them. The total cost to the farmer was $2000 plus labor.[81] As rejected shipments are a common problem for farmers, this presents a ripe market opportunity to accept rejected shipments of food at a reduced cost to the farmer.

Waste Source 5: Super Markets & Open Air Markets (Plaza Mercados)

Supermarkets and open-air markets also have food waste problems. In Colombia open-air markets produce a moderate to high volume of clean, separated waste. Transport costs are reasonable and the collection infrastructure exists, however, the consumer/employee awareness is low and underutilized in most cases. In the case of Bogotá, 17 publicly-owned open-air markets produce an average of 406.5 tons monthly of organic waste.[82] Many of the smaller Colombian open-air markets are without formal contracted waste haulers and due to pollution are being subjected to government regulation. Larger open-air markets utilize Aseo Capital which is paid approximately 156 pesos per kilo.[83] The organic waste is currently disposed of in a landfill, and a Universidad Nacional research team was contracted to investigate other options for processing the organic waste.

Colombian super-market food waste differs in that there is sufficient volume and corporate organization such that all supermarkets have negotiated contracts in which companies purchase the food waste and recyclables. One interview revealed that for a monthly quantity of 80 tons and

[78] See note 76.
[79] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC) 2008: p33.
[80] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC) 2008: p29
[81] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC) 2008: p34.
[82] Oscar Suarez, Programa de Investigacion Sobre Residuos Solidos (PIRS), U. Nacional, Interview with the Author, 22 Feb 2008
[83] See note 82.

daily pick-ups at 74 locations, the waste hauler paid 10 pesos per kilo to the supermarket for recyclable wastes. The hauler then sorted the wastes and re-sold the food wastes at a profit to pig farmers located around the perimeter of Bogotá. The necessity of the hauler to do the sorting lowered the price of the recyclables. Another supermarket chain in Bogotá sorts its waste, and because of this for a monthly quantity of 60 tons, and twice-weekly pick-up at 4 locations, the waste treatment company was paid 85 pesos per kilo for food waste.

United States supermarkets differ in that they pay haulers to remove food waste and the haulers in turn pay landfills or composting centers a tipping fee to receive and process the waste. Developed countries differ in this regard because the distance between food production and point of sale is much larger. [84] This creates a much larger cost to transport food wastes to farmers and in most cases eliminates the option. Landfills in the urban periphery offer a much more cost-effective option and as already mentioned charge supermarkets between $20 and $120 per ton depending upon their location.[85] Some supermarkets such as Ralph's and Vons (both owned by a larger holding company) have established their own composting operations that remove organic waste in empty delivery trucks. The waste is composted at a company owned facility and re-packaged to be sold in stores.[86] An extremely innovative system, they are the only supermarket chains organized in such a manner. As one company has already taken this step, it is very probable that there is a market opportunity to convince other supermarket chains to follow suit with sub-contracted food waste to larvae-meal facilities.

Waste Source 6: Commercial Food Waste – Stadiums, Schools, & Corporate Campuses

In the state of California, 29.2% of commercial waste is organic and 18% of that is food waste, approximately 3,565,086 tons of food waste annually.[87] Corporate waste volume in the United States is characterized as large, clean, and separated. Recycling of food waste by commercial operations greatly varies yet always involves a waste hauler. Companies interest in food recycling directly correlates to the importance of a company's environmental image. Therefore the companies to target for involvement in any food-waste to larvae-meal program are companies with brands where environmental image matters.

As one example, Disneyland in Los Angeles, California pays haulers $49 per ton ($27 transport/$22 tipping fee) to remove and process the 50-60 tons a day of waste the theme park generates. 18% of this generated waste is food waste for a total of 4,140 tons per year. The park self-describes itself as "actively looking" for alternatives to divert recyclable wastes including food wastes to reduce costs and increase image.[88]

A similar situation exists with universities which in the United States maintain large stadiums. The University of California Davis generates 1,200 tons of food waste a year while the University of California Santa Cruz generates 177 tons of food waste per year without a stadium. These Universities pay approximately $50/ton to landfill their wastes. The future for these Universities to reduce cost and increase environmental image is to pay less to compost than to landfill. This is already the case for Stanford University which pays $30/ton to compost their food wastes and $44/ton to landfill their waste.[89]

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[84] See note 70.
[85] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC, 2008): 26.
[86] See note 85.
[87] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC, 2008):18
[88] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC, 2008):46
[89] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC, 2008):48

Waste Source Targeting & Conclusions

After reviewing the six waste sources and their collection and handling, it becomes clear that the best model for a larvae-meal production facility would be a dual revenue stream model. In such a model, a food waste facility would charge a tipping fee to companies that transport food wastes from customers that have been trained to separate it. It would then produce the larvae-meal and charge feed companies, thus receiving a dual revenue for both the input and output.

To accomplish such a model, the critical factor is to target and approach industries willing to pay to have their waste transported and processed. As mentioned, the willingness to pay corresponds directly to the importance of a green image. Below in the figure a diagram shows which waste sources should be principally targeted:

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Above: Comparison of waste source willingness to pay and green image importance[90]

Above it is shown that universities, supermarkets/corporate campuses, and resorts are the most willing to pay for food waste processing and care most about their brand's environmental image. These are therefore the industries that should be targeted first and foremost when seeking to establish a larvae-meal production facility and connect it to a source of food waste.

Additional conclusions that can be made from this figure and assessment is that if universities, grocery stores and resorts are the primary targets, that the place to locate a larvae-meal facility is the United States as it has a less developed infrastructure to recycle food wastes in these sectors.

II. The Objectives of the Study

The overarching objective of this study is the <u>design</u> of a larvae-meal production process ready to be built, tested, and managed at an industrial scale. Extra emphasis is to be placed on the word design as this word encompasses the necessary work of background research, lab research, process

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[90] Alex Berger & Ryan Cunningham et. al., "Waste Stream Opportunities," (Los Angeles: BioSystems Design LLC, 2008):48

modeling, process trial, logistics planning, revenue modeling, market research, client targeting, and finance development.

To achieve all of these aims it was necessary to turn to systems modeling and logistics. In this thesis, two systems models are presented. The first model is an analysis of fishmeal production at a global level. This model was necessary to determine if there was a market for larvae-meal and at what price it might be sold at. The innovative aspect of this model for the field of logisitics is that it recognizes that an eco-system product is at maximum production capacity and that because of the capacity limits there is a market opportunity for a substitute good. However, the model recognizes that a substitute good will only attain the price of the existing product and that therefore the management decisions to overproduce or sustainably manage the maximized product affect the market entry price of the substitute good. Placed into context, fishmeal production is at capacity. If fishmeal producers over-fish or sustainably manage the fishmeal stock, the market entry price of larvae-meal will be affected. This is an innovative feedback model that is likely to become a necessary model in many industries as more eco-system products reach their max sustainable production limits. It is unlike how most products come to market by being superior or cheaper.

In this study, the fishmeal management model was utilized to forecast scenarios in which fishmeal management decisions and aquaculture industry growth yielded different fishmeal prices. These forecasted fishmeal prices were then used as estimates for the market entry price of larvae-meal. The different scenarios and market entry prices were then inputted into the second model that was designed to model the larvae-meal production process and profitability. Based on the quantity of larvae produced, its market price, and the costs of production, profitability could be modeled. This second model is essential as it determines the economy of scale required for the process to be profitable.

To construct these two models a lot of information was required. The sub-goals of this project were to develop this information for the models and the additional supporting information to meet the overarching aim to develop a larvae-meal production process. These sub-goals are categorized and explained below:

Process Information Sub-Goals

To construct the second systems model of the larvae-meal production process, it is necessary to attain the following information.

a. The costs of labor, machinery, and utility operating costs
b. Estimates of the time required for each process step based upon the test facility
c. Material input and output.
d. Machines required for varying levels of input and output (scaling)

Fishmeal Management Modeling Sub-Goals

To adequately model the effects of fishmeal stock management upon fishmeal price, it is necessary to obtain the following information and meet the following sub-goals:

a. Answer: Is the aquaculture industry (which requires fishmeal) an essential industry?
b. Construct a model of macro fishmeal production and management without becoming lost in the complexity of the details.
c. Determine production and price history
d. Determine sustainable production limits
e. Estimate realistically the necessary growth of the Aquaculture industry
f. Determine an elasticity of demand for fishmeal

Revenue Modeling Sub-Goals
To adequately model revenue, the fishmeal management model must connect to the larvae-meal production process model with a realistic projection of the price of a ton of fishmeal/larvae. This permits the larvae-meal production process to model profitability based on fishmeal stock management scenarios. Additionally, the price points for tipping fees must be accurately assessed. To insure that the models function, the sub-goals must be met:

a. The Fishmeal management model must project a realistic price for fishmeal
b. Tipping fees must be researched and estimated for the larvae-meal production model
c. The larvae-meal production model determines the level of scale required for profitability

Test Facility Sub-Goals
A test facility is required to test the assumptions of the industrial design. A facility for scaleable larvae-production has not before been attempted. Therefore, the sub-goals are:

a. Construction of a test facility
b. Analysis of the facility's design viability
c. Analysis of potential improvements for the design

Laboratory Research Sub-Goals
Investors seeking to build a larger facility will require information about how the process is likely to evolve, and a full disclosure of potential safety risks inherent in the process. The sub-goals of the laboratory research are to:

a. begin studies about substrate and larvae development with a logical research trajectory
b. confirm knowledge of the liquid bi-product's anti-pathogenic properties
c. confirm process safety procedures

Market research Sub-Goals
For a process to be viable it must alleviate customer pain or take advantage of a market opportunity for a profit. The target clients and location of those clients must be determined. The sub-goals therefore are to:

a. determine the waste source clients to target
b. determine the additional revenue models such as tipping fees that should be pursued
c. determine the optimal waste source client location: Colombia or the USA

Competitive Research Sub-Goals
To determine the market opportunity for larvae-meal production for a business plan, investors will require an assessment of the competition. To assess the competition and determine a strategy to compete, it is necessary to meet the following sub-goals:

a. Identify any competitors that may be attempting to produce larvae-meal
b. Develop a business plan and strategy to out-compete
c. Produce the accompanying financials for the business plan.

The achievement of these sub-goals informed the design of the two innovative systems models and permitted them to function. The aggregation of the two models and the achievement of each of the sub-goals is determined sufficient information to construct an industrial scale test facility.

III. Pre-Investigation

Presentation of the Problem:

After significant research into world population growth and world food supply, this assessment established that aquaculture and the production of farmed fish was the only food industry with the potential to keep pace with world population growth. This answered the question: is the aquaculture industry a necessary industry that can be permitted to stagnate as described in the sub-goals? The problem for the aquaculture market is that most farmed fish are dependent upon fishmeal as a protein source in their feed. The production of fishmeal, because it comes from wild stocks, is at or beyond its sustainable production capacity. More sources of fishmeal to meet rising demand are not likely to be found. Therefore, if a sustainable fishmeal substitute is not found, one can expect that world food supplies will not keep pace with population growth and malnutrition and famine will occur in many places while the price of fishmeal will go up dramatically as a scarce resource. Both are already happening.

Using these facts as a starting point, the purpose of this project was established: to design a process that created a sustainable substitute product for fishmeal. This project found after significant research that Black Soldier Fly Larvae (*Hermetia Illucens*) cultivated in Bio-Pods designed by ESR International were a viable substitute for fishmeal and a potentially scalable commercial process. Furthermore, the inputs used to feed Hermetia Illucens larvae include organic waste and food waste. The recycling of this "waste" not only made the process sustainable but potentially more profitable as these wastes are normally disposed of for a fee by landfills and composting companies.

The findings of the pre-investigation were presented by Grant Canary and Dr. Paul Olivier at the conference titled "Desechos Organicos Transformada a Comida de Peces y Pollos" on April 14, 2007. Grant Canary presented the macro analysis of world food supply and fisheries and Dr. Paul Olivier discussed the Black Soldier Fly and its potential. Despite that this was already presented, these facts are critical as a general framework and therefore it is important to backtrack and substantiate the claims in the framework with evidence found in the pre-investigative research.

The above framework breaks down into six distinct claims that need substantiating:

1. Population growth is and will continue to jeopardize world food supplies in a grave manner.

2. Aquaculture and fish farming is the only food industry that has the potential to keep pace with population growth demands for several decades.

3. The aquaculture industry's growth is constrained by a lack of fishmeal, a resource that is at or beyond its sustainable yearly production capacity.

4. If a fishmeal substitute was found, the aquaculture industry could continue to expand.

5. Black Soldier fly Larvae (Hermetia Illucens) are an appropriate fishmeal substitute.

6. The cultivation of black soldier fly larvae is scaleable.

Substantiating Claim 1: Population growth is putting World Food supplies in jeopardy.

The path to substantiating the first claim is a long one. It must be noted that many of the sources substantiating claims one through three relate to Lester Brown, a world resources analyst who founded the World Watch Institute and now heads the Earth Policy Institute. This is for good reason. Brown functions as a cipher of multiple environmental and government organizations that focus on one thing alone. Brown's talent is the ability to correlate their facts into a coherent macro-picture of interrelated causes and effects. Additionally, he does not simply correlate facts into a picture of fire and brimstone. His ostensible goal is promoting the solutions to problems. He regularly publishes new versions of his book *Plan B* and while half the book reiterates the problems of resource use, the other half of the book is always devoted to solutions, their progress, and good news. The fact that he updates is also of critical importance as environmental problems *can* improve. This makes him a unique and valuable source. Wherever possible, a third party source is used to corroborate Brown's assessment.

The path to substantiating claim one begins with an analysis of population growth models. It follows by analyzing the growth potential of food production industries that are an alternative to aquacultural food production. The conclusion that is evident is that land based food production of crops and animal protein have reached a near maximum yield. Furthermore, gains in productivity for these existing industries are paltry in comparison to the loss of productivity from environmental degradation resultant from mounting population pressure. The population models described below enumerate the population pressure in numbers, the detailed analysis of environmental degradation describes the effect of these numbers.

Population Growth

Research into population growth revealed a variety of growth models. In 1998, the United Nations established a model with three variants, a low, a medium and a high. Janet Larson, an expert in environmental policy describes the three models, "…the low-fertility scenario has population peaking at 7.5 billion by 2040 and then falling to 7.4 billion in 2050. The medium-growth scenario has the world hitting 8.9 billion by mid-century, with growth slowing until population peaks at 9.2 billion around 2075. The high-growth variant brings us to 10.6 billion by 2050 and 14 billion by the end of the century."[91] As a comparison, the world population in November of 2008 was roughly 6.73 billion.[92] World resources analyst Lester Brown of the Earth Policy Institute guesses the annual growth number on average will be around 70 million people each year.[93]

The simple explanation in response to the question: what is wrong with population growth is that earth's resources will at some point in the near future fail to be able to support *all* life with clean water, air, food, and materials for shelter and clothing. Land based food production requires crop and range land which is a finite resource. A first look at cropland and rangeland on which food is produced shows that the earth's landmass is approximately 10% cropland, 10% rangeland, and 20% forests, the other 50% is desert, mountains or ice.[94] Yet this vast quantity of land is reaching its maximum production capacity. World grain production area from 1950-1980 was increased from 587 million hectares to the

[91] Janet Larsen, "World Population Grew by 76 Million People in 2004: 3 Million Added in the Industrial World and 73 Million in the Developing World," published online 2004. Earth Policy Institute. http://www.earth-policy.org/Indicators/Pop/2004.htm (accessed 4 Nov 2008).
[92] "U.S. and World Population Clocks," U.S. Census Bureau, http://www.census.gov/main/www/popclock.html (accessed 10 Nov 2008).
[93] Lester Brown, "World Population, Annual Addition, and Growth Rate, 1950 to 2000, with Projection to 2050," Earth Policy Institute, "http://www.earth-policy.org/Indicators/Pop/Pop_data.htm (accessed 5 Nov 2008).
[94] Lester Brown, *Outgrowing the Earth.* (New York: WW Norton, 2004), 85.

historical peak of 732 million hectares to meet the food demands of population growth. During this period before the green revolution, adding cropland was the only strategy to keep food supplies in line with population. However, despite this landmass addition, our population increased from 2.5 billion to 6.1 billion over the same period which resulted in a net *decrease* of cropland area per person from 0.23 ha/person to 0.11ha/person. In 2000, due to management failures, our world grain production area has decreased from 732 million ha to 656 million hectares.[95]

Since the historical peak cropland area in 1980, cropland has become a nearly zero sum game. There is little cropland left to expand into on a macro scale.[96] To make matters worse, productivity gains on the land that is being utilized have been slight and they have been the only means left by which to increase yield. Croplands increased productivity by an average of 2% annually from 1950-1990. Since 1990 however, these cropland productivity gains have fallen off to only a 1% increase in productivity per year.[97] As one analyzes the mounting losses in productivity due to unsustainable management, productivity increases from technological progress are not keeping pace with exponential population growth. In fact, when one takes a comprehensive approach as Mathis Wackernageal and an international team did in 2002, it was determined that in fact "humanity's collective demands first surpassed the earth's regenerative capacity around 1980…" The report that was published for the United States National Academy of Sciences went on to describe that "…today global demands on natural systems exceed their sustainable yield capacity by an estimated 25%."[98] From the perspective of food supply from cropland, population pressure will likely cause the demand on global cropland to increase; this in turn will likely cause present mismanagement practices to increase for short term gain, which will ultimately cause the amount of useable cropland to decline over the long term.

Mismanagement: Causes of Declining Cropland & Rangeland

The causes of declining cropland generally fall into four major categories each of which are management failures: Topsoil loss and land degradation, desertification, urbanization, and water depletion. What is important to note is that each of these four factors contribute to each other. Because of this the exact reduction in cropland and rangeland for each mismanagement practice is not available. The overall picture to keep in mind is that each of the four categories has contributed to the overall reduction over the last 26 years from 732 million ha to 656 million ha, a net loss of loss of 76 million ha. In the following analysis, examples will be given on a case study basis to illustrate how these losses are occurring. Cropland and rangeland numbers will be given when available. Also, due to the fact that the United States and China are two of the world's biggest grain producers, they will be discussed as case studies most often.

Mismanagement Practice 1: Topsoil Loss and Land Degradation

Topsoil is roughly the first 2 to 8 inches of soil that contains microbes, nutrients from decayed plants, fungi that fix nitrogen, and worms whose digestive tracts create hummus from fine rock grains

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[95] Janet Larson, "Population Growth Leading to Land Hunger." posted online 23 Jan 2003, Earth Policy Institute. http://www.earth-policy.org/Updates/Update21_printable.htm (accessed 6 Nov 2008).

[96] The exception is Brazil, however, doubts remain about the environmental cost to be incurred by expanding agricultural land into forests and savannahs as well as the number of years at which the soil will be viable. Source: www.earth-policy/org/books/out/index.htm

[97] See note 95.

[98] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 11

and plant matter. Plants fix their roots in topsoil and without it's nutrients and living organisms, plants don't grow. Many agricultural hotspots such as the great plains of the United States are revered due to their deep topsoil which depending upon the region can take from 100-500 years per inch to form.[99,100,101] Despite this fact, farmers all over the world are using practices that cause topsoil to be blown away by wind or carried away by water. This occurs when areas that are too sloped or too dry are tilled or grazed. In the case of sloping land, what is occurring is that the search to expand cropland or grazing pasture has often sent farmers higher and higher up mountains and hills. As the land is tilled or grazed, vegetation covering it is removed and water and wind are free to carry the topsoil away. In the case of dry soil, the search to expand cropland and rangeland has caused farmers without adequate access to irrigation water or who are simply in very arid regions to till the soil anyway or permit their animals to graze in order to produce food. Dust storms carry the light dry topsoil away.

The extent to which land degradation and topsoil loss are occurring is tremendous. The world cropland area is roughly 656 million hectares (does not include rangeland), yet Lester Brown writes in *Outgrowing the Earth*, "land degradation from both water and wind erosion in the world's vulnerable drylands is extensive, affecting some 900 million hectares, an area substantially larger than the world's grasslands."[102] When Brown describes the "vulnerable drylands" he refers mostly to Africa, Asia, and the Middle East. However, even in the United States, the National Academy of Sciences determined that, "cropland in the U.S. is being eroded *at least* ten times faster than the time it takes for lost soil to be replaced (emphasis added)."[103]

The most well known historical example of over-plowing and over expansion into grassland, and the subsequent topsoil loss is the great dustbowl of the 1930's in the United States. Other examples include the Virgin Lands Project in the Soviet Union. During this project, the former Soviet Union plowed an area of arid grassland the size of Canada and Australia's combined wheat-land in the attempt to turn it into cropland. At its peak in 1980 it reached 25 million ha, however the useable area gradually declined to 13 million ha after the large topsoil losses. Today a comparison of land fertility reveals that after these topsoil losses this area only achieves a marginal 1.1 tons/ha of wheat compared with France's breadbasket that achieves roughly 7 tons/ha.[104]

Mismanagement Practice 2: Desertification

While the affect of topsoil loss on soil fertility and total useable cropland and rangeland cannot be measured directly, the secondary affect of topsoil loss can. Desertification occurs when topsoil is removed and gritty subsoils are unprotected by vegetation. The soils can become mobile sand dunes that are blown onto grassland and kill vegetation. This destabilizes additional soils that in turn begin to blow around. In this manner deserts expand, and villages, roads, and electricity lines can become buried or destroyed by mobile dunes.

Desertification occurs in various stages and is carefully measured on a country by country basis. Areas with the fewest management practices and in the driest regions appear to be the hardest hit. In

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[99] Science Daily, "Soil Erosion Threatens Environment And Human Health, Study Reports," posted online 23 Mar 2006, http://www.sciencedaily.com/releases/2006/03/060322141021.htm (accessed 10 Nov 2008).

[100] Lester Brown, *Building an Economy for the Earth,* (New York: WW Norton, 2001), 53

[101] "Land Degredation," University of Michigan, posted online 1 Nov 2006, http://www.globalchange.umich.edu/globalchange2/current/lectures/land_deg/land_deg.html (accessed 10 Nov 2008).

[102] Lester Brown, *Outgrowing the Earth.* (New York: WW Norton, 2004), 82-83

[103] Tom Paulson, "The lowdown on topsoil: It's disappearing" *Seattle PI.* 22, Jan 2008, http://seattlepi.nwsource.com/local/348200_dirt22.html (accessed 10 Nov 2008).

[104] Lester Brown, *Outgrowing the Earth.* (New York: WW Norton, 2004), 83-84

Brazil 58 million ha have been affected. In India 108 million ha are affected. China is observing desert expansion at a rate of 360,000 ha/year and the merging of deserts into vast mega-deserts. In other countries, 70% of all of Mexican land is vulnerable, 80% of all Kenya's land is vulnerable, and Yemen is perhaps the worst off with 97% of all land in some stage of desertification.[105]

Remembering that 656 million hectares is the total cropland and that rangeland is roughly double that, these numbers are not insignificant and represent only a partial sampling. New practices are being developed such as no-till farming, however they have yet to take a strong hold in most parts of the world including the United States.

Mismanagement Practice 3: Urbanization

As countries convert to industrialized powers, cities that were necessarily founded on some of the best cropland and best topsoil begin to expand and pave over that topsoil for parking lots, warehouses, residential developments, factories, freeways, and transfer stations. While analyzing the most recent countries to industrialize, Lester Brown noticed a pattern that he named "Japan Syndrome." In the cases of the three most recent countries to industrialize, Japan, South Korea and Thailand, all of the countries already had a high agronomic density which is defined as less than 0.8 ha/person. In each of the cases, in the course of industrializing, all three countries converted from grain exporters to grain importers. Japan now imports roughly 70% of its grain.[106] What occurred is that first land was converted to non-agricultural use for factories and then residential developments to house the workers, roads to transport them, warehouses to house the goods, parking lots for vehicles etc. Secondly, farmers abandoned marginal land to seek jobs in the city. Third, because there was less labor available, labor became more expensive and multiple cropping (growing two complimentary crops in one year on the same land) became financially impossible. Fourth, as incomes rose from factory work, land was shifted to supply the increased demand for fruits and vegetables. All four of these factors caused the dramatic decline of grain production.

Unfortunately for world grain supplies, China and its massive population is the fourth country to follow Japan, South Korea and Thailand's lead. India is right behind China. The problem is that world grain supplies cannot support a China that imports 70% of its grain. Simply put, were every Chinese citizen to consume two extra beers a year, the grain required to produce those beers would equal the entire Norwegian grain harvest.[107] Yet China has already become an importer and is actively pursuing a western growth model that is not sustainable.

The most obvious example of this fact is that despite having a strong bike culture, China is actively pursuing an automobile based economy. In the United States paved land per car averages 0.07 ha. In Germany, the UK, and Japan it averages 0.02 ha/car. If China were to adopt car ownership equal to that of Japan (1 car per 2 people) it would have 640 million cars (it has only 13 million now). At 0.02 ha/car nearly 13 million ha of land would need to be paved. This is half of China's 23 million hectares of rice land which produces 120 million tons of rice.[108] Despite obvious indicators that this policy of an automobile based economy doesn't make sense, China pursues it regardless.

The land that *isn't* being paved is losing productivity because it is losing its workers. In China it was previously common practice to grow winter wheat for half the year (4 tons/ha) and corn the

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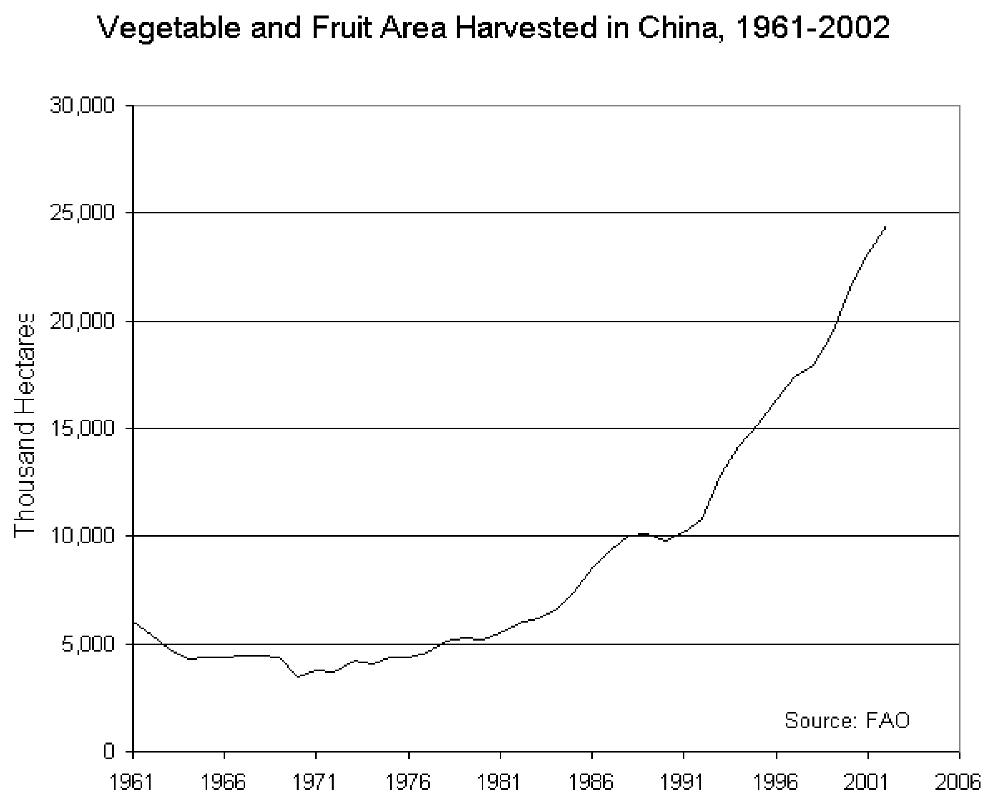
[105] Lester Brown, *Outgrowing the Earth.* (New York: WW Norton, 2004), 86-87.
[106] U.S. Department of Agriculture (USDA), "Production, Supply, and Distribution," electronic database, www.fas.usda.gov/psd,
[107] Lester Brown, *"Who Will Feed China?"* (New York: WW Norton, 1995), dust jacket.
[108] Lester Brown, "Paving the Planet: Cars and Crops Competing for Land." Earth Policy Institute, posted online 14 Feb 2001, http://www.earth-policy.org/Alerts/Alert12_printable.htm (accessed 10 Nov 2008).

second half of the year (5 tons/ha). They can be grown on the same plot of land in one year and collectively yield 9 tons/ha.[109] However, this requires a cheap source of labor. This cheap labor source is disappearing as farmers leave the fields and go to the city to become factory workers. Without a cheap labor supply, double cropping is not a financial possibility. Observing China's forerunner Japan, the decline in total ha harvested in Japan per year due to these same two phenomenon was that in 1960 Japan harvested 5 million ha and in 2005 it harvested only 2 million. This is despite having four times the world average rice production subsidy.

Finally, in China we see that factory workers with higher incomes have already begun to desire fruits and vegetables. While all people should be entitled to more fruits and vegetables, grains are more efficient to produce and store. In a zero sum game where food shortages appear eminent, converting grainland to fruit and vegetable production reduces the total food available. The graph below shows the increasing area being converted to grow fruits and vegetables in China nonetheless.



Source: "Chinas Shrinking Grain Harvest" Earth Policy Institute:
http://www.earth-policy.org/Updates/Update36_data.htm

In addition to the increased demand for fruits and vegetables displayed in the graph, increased incomes also result in a greater desire for animal protein products such as beef, pork, poultry and fish. This further decreases the grain available to feed the population because animals are inefficient at converting grain to body weight. Beef products for example require 7 tons of feed (mostly grain) to produce 1 ton of meat (live weight). Pork is slightly better in that it requires only 4 tons of feed to

[109] Lester Brown, *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble.* (New York: WW Norton, 2006) Chapter 9 section 2, available online: http://www.earth-policy.org/Books/PB2/PB2chp9_ss2.htm (accessed 1 Nov 2008).

produce 1 ton of meat. Chicken are better still in that they require only 2 tons of feed to produce 1 ton of meat. Fish are the best in that depending upon species they can be between 1:1 and 2:1 ratio of feed to meat.[110] This statistic is an important one that will be returned to when this analysis examines the solutions this project proposes.

The result of these four effects is that China's harvested grain area fell from 90 million hectares in 1998 to 76 million ha in 2003.[111] Regarding the land that is being harvested, the already described lack of labor for double cropping reduced productivity. In addition, the factory workers increased purchasing of fruit, vegetables and meat resulted in an efficiency decrease. And yet, this triple assault on food production hasn't even begun to discuss water shortages in China and other parts of the world which are further impinging on world food production. Simply put, people, industry, and agriculture all need water. If there isn't enough of it, its division isn't always allocated to food production. If it is, it isn't always well thought out.

Water Depletion

Globally, 70% of world water use is for irrigation.[112] Water keeps soils moist so they don't blow away and irrigation increases yield. However, water demand on aquifers in many parts of the world is exceeding supply.[113]

Aquifers work in one of two ways, they are either replenishable and absorb snowmelts and rains, or they are fossil aquifers and when they run out they are never available again. The Ogallala Aquifer under the great plains in the US and the Saudi aquifer being over-pumped to produce wheat are examples of fossil aquifers. Whether renewable or replenishable, as aquifers are over-pumped the water table drops and wells run dry. The problem with this is that as wells run dry farmers either don't irrigate and may lose topsoil to dry conditions, which is what has happened with 24% of US land since 1980, or they drill deeper wells and keep over-pumping.[114]

The World Bank calculates that three basins in China are being over-pumped: the Hai, the Yellow, and the Huai.[115] It calculates that the Huai is being over-pumped by 40 billion tons/yr and that when it runs out, the reduction in grain harvest will be by 40 million tons.[116] To make matters worse, it is not just farmers over-pumping the basin. Industrial producers compete with farmers and often win due to the fact that 1,000 tons of water can be used to produce 1 ton of wheat ($200) or to expand output of industry by $14,000 (70 times as much).[117]

The result of all this analysis is that in China's case, it already has a shortfall of 70 million tons of grain per year. This is the equivalent of Canada's entire grain harvest.[118] As it continues to industrialize, this number is likely only to get worse. Zhou Guangzhao, head of the Chinese Academy of

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[110] Lester Brown. *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble, (*New York: WW Norton, 2003) Chapter 8, section 4 Online at, http://www.earth-policy.org/Books/PB/PBch8_ss4.htm (accessed 18 Sept 2008).

[111] Lester Brown, "China's Shrinking Grain Harvest: How its Growing Grain Imports Will Affect World Food Prices," available online 10 March 2004, Update 36, http://www.earth-policy.org/Updates/Update36_printable.htm (accessed 12 Sept 2008).

[112] Lester Brown, *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble.* (New York: WW Norton, 2006), Chapter 9 section 3, available online: http://www.earth-policy.org/Books/PB2/PB2ch9_ss3.htm (accessed 1 Nov 2008).

[113] Alex Kirby, "Dawn of a Thirsty Century." *BBC Online*, 2 June 2000. http://news.bbc.co.uk/2/hi/science/nature/755497.stm (accessed 2 Nov 2008).

[114] Lester Brown, *Outgrowing the Earth.* (New York: WW Norton, 2004), 101.

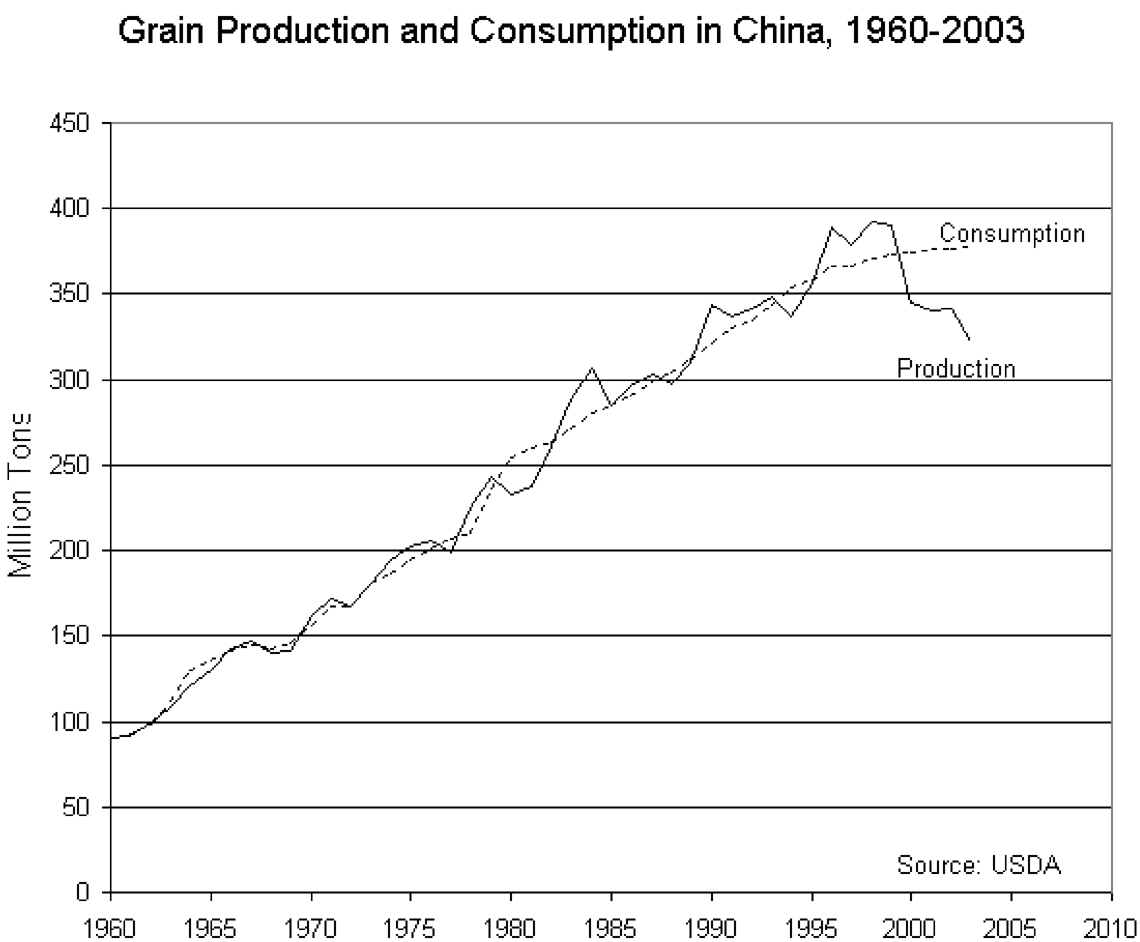
[115] Susanne Wong. "China Bets on Massive Water Transfers to Solve Crisis," World Rivers Review, posted online 15 Dec 2007, http://internationalrivers.org/en/node/2397 (accessed 2 Nov 2008).

[116] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 71

[117] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 78-79

[118] See note 105.

Sciences is on record saying, "…if national consumption reaches the level of Chinese affluent costal consumption, and the nation continues to squander its farmland and water resources, then China will have to import 400 million tons of grain from the world market. And I am afraid, in that case, that all of the grain output of the United States could not meet China's needs."[119] The graph below perhaps illustrates this fact better than any words could.



Source: "Chinas Shrinking Grain Harvest" Earth Policy Institute:
http://www.earth-policy.org/Updates/Update36_data.htm

The graph displayed describes how worrying China's situation is. However, even if it is resolved, India, with an annual economic growth rate slightly behind China's at around 6-7% and a population expected to overtake China's in 2030, seems to be following the exact same path as China.[120]

Land Based Food Production: The Crux

[119] See note 111.

[120] Lester R. Brown, "China is Replacing US as World's Leading Consumer," *New Perspectives Quarterly,* 2005. Available online at http://www.digitalnpq.org/archive/2005_spring/11_brown.html (accessed 14 Sept 2008).

To summarize, it is clear that the first claim of the framework is valid. The overall picture is established with the fact that 76 million ha of cropland has been lost in 26 years. Beneath this overall picture the causes of this cropland loss have been stitched together from a patchwork of world statistics and case studies. After analyzing the larger picture and the underlying causes, it is clear that world food supply from landmass production appears to be overwhelmed by demand, likely to only get worse, and that improved productivity has been paltry in comparison to the losses that have been incurred.

Substantiating Claim 2. The Aquaculture Industry Can Keep Pace (for a few decades)

Having ruled out landmass food production as industries that can keep pace with the demand from population increase, the focus now turns to water based systems of food production. Here it is important to take note that in this analysis aquaculture is strictly defined as the growth and management of fish in ponds or caged in existing bodies of water. It does not include the catch of wild populations of fish. The reason for this distinction is that the world's fisheries are not in much better shape than the earth's cropland—they are at maximum production. In fact, 75% of fisheries are at *or beyond* their sustainable capacity.[121] In 2003, 29% of ocean sea fisheries were in a state of collapse, defined as less that 10% of their original population.[122] Some stocks have already collapsed.[123] In summary, like cropland, oceanic fisheries are a zero sum game. Their production is capped at between 90-100 million tons per year and is not likely to increase.[124]

Furthermore, oceanic fishery production is actually likely to decrease in production capacity due to four factors. One, over-fishing is likely to continue and stocks will collapse and take time to recover if they ever do. Two, fish spawning habitats in mangrove forests, wetlands, and rivers continue to be destroyed. Three, coral reefs upon which fish depend heavily are in rapid decline. Four, the increase in the number and size of "dead zones" (large bodies of water without dissolved oxygen for the fish to breathe) will continue to plague fish stocks that have reproduced and avoided being caught. Each of these causes will briefly be discussed as they are important to understand that supplies of wild fish will likely decline, not remain stable. Following, the growth potential of the aquaculture industry will be assessed.

Oceanic Production Problem 1: Over-fishing

Global over-fishing is only a recent phenomenon. As late as 1950, world catch was only 19 million tons per year. However, after World War II the numerous production increases from transferred wartime technology resulted in increasing catch totals. As a result, in 1997 the world catch hit 93 million tons.[125] This is near or around its sustainable limit depending upon who one talks to. Yet, in most cases fishing has continued.

The reason for this is that over-fishing is a political problem. When any government restricts fishing, that government is effectively eliminating jobs or cutting income. Neither is popular. Thus the common course of action is to take action only when there is a problem. This results in action that is too little too late.

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[121] Lester Brown, *Plan B 2.0: Rescuing a Planet Under Stress and a Civilization in Trouble.* (New York: WW Norton, 2006), 93-96

[122] Richard Black, "'Only 50 years left' for sea fish," *BBC News Online,* 2 Nov 2006, http://news.bbc.co.uk/go/pr/fr/-/2/hi/science/nature/6108414.stm (accessed 18 Sept 2008).

[123] Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006), 411.

[124] See note 121.

[125] See note 121.

This pattern of action has been observed again and again. In the 1950's the large yellow croaker off the coast of East Asia was over-fished to the point that in just two decades, catches had decreased by more than 90%. This was despite the implementation by China of one of the world's first programs of conservation. Today in 2005, restocking has still not restored croaker populations.[126]

While the latter example is truly historic, even as recently as in 1992, the five hundred year old Canadian Newfoundland cod fishery was closed because fish stocks had collapsed. 40,000 jobs were lost. It was reopened under political pressure and after only a short few years of "recovery," and was again shortly closed due to continuing problems. Today the fishery has still not recovered. Many other species including cod, haddock, and whiting under control of the European Union are under similar pressures. Fish species specifically used to produce fishmeal have also been over-fished to the point of collapse. Japanese sardine stocks have not recovered, nor have North Atlantic Capelin stocks.[127]

The problem with the collapse of one species is that other species depend upon these species for food, predator control, or any other number of reasons. Eliminating one species is like pulling one thread out of a cloth, eventually the cloth will become unraveled. This is what concerns Boris Worm of Dalhousie University in Nova Scotia. Leading a team of twelve international scientists, Dr. Worm and his colleagues analyzed the world's 63 large marine ecosystems and examined all fish and invertebrate catches from 1950-2003. These catches made up 83 percent of fishery yields over the past 50 years.[128,129] The research found that 29 percent of all the species in the ecosystem had been fished or affected by pollution to the point of collapse, defined as less than 10% of historic levels.[130] These low levels of biodiversity made recovery difficult, and the models developed showed that at the present course, if nothing is done, a 100% collapse (extinction) would occur around 2048.[131]

Oceanic Production Problems 2, 3, and 4: Fish Spawning Habitat Destruction, Coral Reef Losses, and Dead Zones

In addition to oceanic fish stocks being threatened by over-fishing, the habitat in which fish breed is also being developed, destroyed, or polluted to the point that the area is no longer useful for fish spawning. This is a critical factor affecting fish stocks because 90% of oceanic fish rely on costal wetlands, mangrove swamps, or rivers to spawn. Unfortunately, 50% of the mangrove forests that serve as spawning habitat in tropical and subtropical countries have already been destroyed.[132] In industrial countries, large losses of coastal wetlands are also occurring due to development. As a case in point, 95% of Italy's coastal wetlands have been destroyed.[133]

In addition to the destruction of many species' *costal* spawning habitat, the well documented destruction of coral reefs is destroying any other spawning habitat remaining, as well as many species' food and habitat.[134,135,136] Lester Brown writes that between 2000 and 2004, the worldwide share of

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[126] Min Liu & Yvonne Sadovy de Mitcheson, "Profile of a fishery collapse: why mariculture failed to save the large yellow croaker," *Fish and Fisheries*, V9, No 3, Sept (2008), abstract.
[127] See note 126.
[128] See note 122.
[129] Boris Worm, et.al "Impacts of Biodiversity Loss on Ocean Ecosystem Services", *Science* 3, V 314, Nov (2006), 787-790
[130] See notes 122 and 129.
[131] See notes 122 and 129.
[132] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 100.
[133] Lester Brown, *Building an Economy for the Earth,* (New York: WW Norton, 2001), 53.
[134] Clive Wilkinson & David Souter, "Status of Caribbean Reefs after Bleaching and Hurricanes 2005," Global Coral Reef Monitoring Network, http://www.gcrmn.org/statuscaribbean2005.aspx (accessed 23 Oct 2008).
[135] "The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2002." *National Oceanic and Atmospheric Administration*, (2002): 265p.

destroyed reefs [those that had lost 90 percent of live corals] expanded from 11 to 20 percent. Describing a report by the Global Coral Reef Monitoring Network, Lester Brown continues writing that the network reported that, "… 24% of the remaining reefs are at risk of imminent collapse, with another 26% facing significant loss in the next few decades."[137]

The causes of coral reef loss include increased water temperatures and ocean acidification, both of which are caused by higher atmospheric carbon dioxide levels. In addition to these causes, coral reefs are affected by the same pollutants that cause dead zones. These pollutants come from rivers such as the Mississippi river emptying fertilizers, sewage, and sedimentation (topsoil) that it has collected en route to the Gulf of Mexico. In some heavily touristed areas, these pollutants also come from cruise ships that dump sewage into the ocean while in their various routes. The result of the fertilizer and sewage content is an excess of nutrients in the water that feed massive algae blooms. While growing, these algae use the vast majority of the dissolved oxygen in the water leaving nothing for underwater organisms to breathe. This results in "dead zones" where nothing can live. A UNEP report in 2006 noted that between 2004 and 2006 the number of dead zones increased from 149 in 2004 to 200 in 2006.[138] The size of these dead zones has also increased over the years. For example, in the Gulf of Mexico one dead zone now often reaches the size of the state of New Jersey.[139] The result is that if fish do manage to reproduce, find food and a place to live, and avoid being caught, they might still suddenly die from a lack of dissolved oxygen to breathe. This stacking of the odds against fish stocks is consistently leading to the depletion of many stocks and the outright collapse or extinction of others.

Oceanic Food Production: The Crux

What can be surmised from this account of the situation facing oceanic food production is a more detailed account of why oceanic fish catch will not keep pace with global demands for food from an increasing population. Again, an overall picture is established by two facts: first, that 75% of fisheries are estimated to be at or beyond sustainable capacity; and second, that 29% of fisheries are in a state of collapse. World catch will likely remain capped between 90-100 million tons/year if it doesn't outright decline. Having reviewed the problems facing world fisheries and the consequences of ignoring these findings, it is likely that in fact world fish catch will decline on a macro scale as it has in each of the individual cases of fish stocks managed by too little too late government policies.

Aquaculture: Where and How Industry Growth Can Occur

Having established the reason for distinguishing between aquaculture and oceanic production, it is now possible to move into substantiating the claim that the aquaculture industry has the growth *potential* to keep pace with population demands—at least for a few decades. This will be accomplished by comparing aquaculture's previous growth and sustainability to other industries, as well as discussing the technological advances that describe *how* and *what parts of* the aquaculture industry can grow.

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[136] Jenny Marder, "Study: One-third of Coral Reef Species Face Extinction," *Newshour with Jim Lehrer,* 11 July 2008, http://www.pbs.org/newshour/updates/science/july-dec08/coral_07-11.html (accessed 21 Oct 2008).
[137] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 100.
[138] "U.N.: Ocean 'Dead Zones' Increasing Fast." *MSNBC News Services,* posted online, 23 Oct 2006. http://www.msnbc.msn.com/id/15329993/ (accessed 23 Oct 2008).
[139] See note 137.

Aquaculture industry expansion and growth over the past thirty years, depending upon whose numbers one relies on, has averaged between 8-11% per year.[140,141] In plan B 3.0 Lester Brown's data shows an average increase in aquaculture output of 9% between 1990 and 2005. He correlates this with an increase from 13 million tons to 48 million tons out put.[142] The table below compares this growth rate with the growth of other industries as well as the level of efficiency at which these animals convert feed to body weight.

Industry Animal	Feed Conversion Ratio	Market Expansion
Beef/Cow	7 kg feed : 1 kg meat	0.5% per year
Pork/Pig	4 kg feed : 1 kg meat	2.5% per year
Poultry/Chicken	2 kg feed : 1 kg meat	4.9% per year
Fish	1-2 kg feed : 1 kg meat	11.4% per year
Oceanic fish production	Not applicable	0.1% per year

Source: Brown, Lester. *Plan B 3.0.* New York: WW Norton. 2008. Pg. 183

In the table displayed, an interesting correlation occurs. The biggest market expansions have occurred in industries that use the most efficient feed-converting animals. In other words, the more sustainable the animal (requires less inputs for production) the greater that industry's potential for growth in today's increasingly resource scarce economy. This is an excellent indicator for the aquaculture industry due to the efficiency in which many fish species convert feed to body weight.

However, all aquaculture market growth is not equal. Aquaculture as a production method breaks down into two types: The production of fish bred and harvested in ponds or tubes,[143] and the production of fish in cages located in existing bodies of water such as rivers and oceans. The latter has received the majority of the public's attention[144] because this method has been responsible for massive pollution, the infection of wild stocks with diseases from caged stocks, and escaped fish that have out competed wild stocks subsequently reducing the wild stock's genetic biodiversity. In addition to these fiascos, carnivorous farmed fish such as salmon have earned aquaculture a bad reputation as in the 1980's they required 4-6 times their weight in feed to produce 1 kg of salmon. Today, salmon are still not terribly efficient compared to omnivorous fish, however the feed to body weight ratio has decreased to 1.8.[145] The previously inefficient conversion had lead many environmentalists describing the salmon farming industry as an industry causing the collapse and extinction of oceanic fisheries while purporting to be a solution to oceanic fishery collapse.

The latter two problems have received a majority of the attention from the public; however, the problems are not representative of the industry as a whole. Salmon farming represents only 4.7 million tons of output per year from aquaculture (>10%).[146] Secondly, this analysis would like to suggest that

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[140] Andrew Logan, "The aquaculture business can't go on using fish to feed fish," *Fish Information and Services Organization*, 22 Feb 2008, http://fis.com/fis/people/printable.asp?article_id=19&l=e (accessed 23 Oct 2008).

[141] Izzat Feidi, "Could the Growth In Aquaculture Narrow the Gap Between Seafood Supply and Demand?" *Fish Information and Services Organization,* 8 Feb 2008, http://fis.com/fis/people/?article_id=17&l=e&page=1 (accessed 24 Oct 2008).

[142] FAO, FISHSTAT Plus, electronic database, at www.fao.org (accessed 25 Oct 2008).

[143] Ben Block, "New Fish Farms Move from Ocean to Warehouse," World Changing, posted online 29 April 2008, http://www.worldchanging.com/archives/007998.html/ (accessed 29 April 2008).

[144] Kenneth R. Weiss, "Fish Farms Become Feedlots of the Sea," *Los Angeles Times,* 9 Dec 2002, http://www.latimes.com/la-me-salmon9dec09,0,6535872.story?page=4 (accessed 25 Oct 2008).

[145] Communication Partnership for Science and the Sea, "Architects for Sustainable Offshore Aquaculture: Meeting Needs while Maintaining Ecosystem Services," http://www.compassonline.org/pdf_files/SnapShot.Feeds.pdf (accessed 10 Nov 2008)

[146] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 184

caged fish farming will soon be phased out due to its unsustainability and the stiff competition posed by super productive and more sustainable poly-culture production of omnivorous fish pioneered by China.[147,148]

Polyculture production as it was first pioneered, mimics nature by utilizing four different species of carp in the same pond. The carp live at different trophic levels (heights in the water). Silver and bighead carp are filter feeders and live on the top-level near the surface of the water. Grass carp feed on vegetation and live in the middle level. Common carp is a bottom feeder and feeds on detritus on the bottom of the pond. The advantage of this system is that costs associated with pond maintenance, aeration, cleaning, filtering and re-circulation of effluent discharge are all reduced. However, the greatest advantage is that total yields are increased. Using this method and these carp species in the 1960's, researchers achieved yields of 3,750 kg- 4,500kg per ha.[149] In 1995, by adding rice plants and the azolla plant, yield hit 7,039 kg/ha.[150] Additional gains in breeding have also been made through traditional and non-traditional breeding. Using hybrid common carp and a silver carp, in the 1970's and 80's the Chinese achieved 7,500 kg/ha. Using Mandarin fish and longnose channel catfish they achieved 10,500 kg/ha in the 1980's and 1990's.[151] By comparison, US catfish farmers achieve about 4,000 kg/ha and can achieve 5-6,000 with a single year double harvest.[152] Today China is working on numerous polyculture blends that mix different combinations of: crabs, prawns, mussels, crawfish, snails, trout, swamp eel, loach, frog, clarius, and penaeus shrimp, with rice plants, fish, or both.[153] Due to these blends aquaculture farmers in China have been able to reduce feed and maintenance costs, diversify their products for greater market stability, and increase total yield of plant and aquaculture based crops.

The use of rice and other plants in combination with aquaculture products is an especially important point to emphasize as it reveals the true future of aquaculture. By using a variety of plants in the water or on the water's edge there are fewer dissolved solids and excess nutrients in the water as plant roots consume these for growth. This means that discharged water from aquaculture ponds is not contributing to dead zones and coral reef destruction and in the future may even be 100% re-useable *without* expensive recirculation systems. Additionally, plants used on the water's edge can tap the pond's excess nutrients while stabilizing soils and producing a crop. Trees, bushes, and vegetation used in such a manner can provide a buffer against desertification. This latter fact is incredibly important because the FAO estimates that there are "2 billion hectares of marginal land that could be converted to aquaculture, but that that three quarters of it is too dry, too steep, too wet, too cold, or too shallow."[154] Pondering this statistic, one first realizes that the 500 million ha of land this FAO report describes as available for conversion to aquaculture is a lot of potential space for expansion. Secondarily, the marginal lands that the report describes as unsuitable may actually be entirely suitable for use when a non-traditional plant-fish polyculture is used to stabilize soils and reduce/eliminate

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[147] Donny Ponce-Marban, et al. "Economic Viability of Polyculture of Nile Tilapia and Australian Redclaw Crayfish in Yucatan State, Mexico," Universidad de Las Palmas de Gran Canarias. http://www.unitus.it/EAAE_2nd_call/papers/16_ponce_marhan.pdf. (accessed 18 Sept 2008).

[148] Dr. Bert Wecker,, et. al, "Intensive Production of European Catifsh in Polyculture (in german)," Universität Osnabrück. http://www.usf.uni-osnabrueck.de/projects/AquacultureUzbekistan/pdf/IntegrierteTeichsysteme.pdf (accessed 18 Sept 2008).

[149] Li Kangmin, "Rice Fish Farming System," (presented at the Torino Italy, Chamber of Commerce 5 June 2006).

[150] Wu, Tingting. Presentation "Genetic Improvement of Aquaculture Species" Freshwater fisheries research center; Chinese academy of fishery science. Presentationby Li Kangmin. 7 June 2006. Torino, Italy.

[151] See note 150.

[152] Frank Chapman, "Farm-Raised Channel Catfish," *U. of Florida Circular 1052,* July 1992.

[153] See note 149.

[154] "Population Reports," *Johns Hopkins School of Public Health,* Volume XXV, Number 4 December, 1997, www.infoforhealth.org/pr/m13/m13chap4_4.shtml (accessed 18 Dec 2008).

effluent discharge. Given that the unsuitable marginal lands have the same characteristics that were described as putting them at risk of desertification, using plant based polyculture aquaculture may actually buffer against these lands becoming deserts. Furthermore, this buffer could be established for profit and therefore expand more rapidly than national or multinational projects constructed at a loss of taxpayer dollars.

Finally, this fact is key to understanding that there is ample space for aquaculture to expand into. This is critical to the future of the industry because this analysis has already concluded that landmass based food production is a zero sum game and is at maximum capacity.

Due to the advantages of the aquaculture industry, some countries are already taking note and expanding. China's interest in aquaculture has resulted in it being the first major country whose aquaculture output of 30 million tons has surpassed its poultry output. Despite the poultry industry's strong growth, the aquaculture industry's output is now nearly double that of the poultry industry.[155] Thailand and Vietnam are also following China's lead. In 2001, the Vietnamese began a project to develop some 700,000 ha of the Mekong delta into aquaculture production. Today this area now produces some 1 million tons of fish and shrimp per year.[156] Unfortunately, not all international players have been developing equally. Professor Harald Rosenthal, of the University of Kiel in Germany noted in a conference in Rhode Island that, "Europeans produce 12% of the world's cultured fish, Asians continue to produce the lion's share (78%) with America contributing a paltry 4%."[157] While a pessimistic observation when taken at face value, this statement also means there is significant room for the industry to grow in two major economies.

Aquaculture: The Crux

Reviewing the above arguments, it is established that land based aquaculture farming is one of the most efficient forms of converting feed into animal protein. It also has ample marginal land to be developed in. Furthermore, poly-aqua-culture plant-fish systems developed on marginal land could serve as buffers to topsoil loss and desertification. Finally, the aquaculture industry has a thirty-year history of significant growth whereas other food production industries do not. Having substantiated these facts, it is clearly established that the second claim in the framework is justified. Aquaculture is the only known food production system with the potential to keep pace with increasing population demand over the next several decades.

Substantiating Claim 3: Fishmeal is a Constraint to the Aquaculture Industry's Growth

After a lengthy analysis to substantiate that aquaculture is the key to world food supply over the next decades, a much shorter analysis can be used to substantiate the second claim: that the aquaculture market cannot continue to grow without a substitute for fishmeal. This will be accomplished by briefly discussing the mixture of grains and fishmeal in fish feed and the two protein source's recent price jumps in the context of the US and Vietnamese aquaculture industries. The conclusion of this assessment will discuss the future of aquaculture given protein sources increased cost and lack of availability.

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[155] Lester Brown, *Plan B 3.0*, (New York: WW Norton, 2008), 184-185.
[156] See note 155.
[157] "Professor Harald Rosenthal Highlights Recent Trends in European Aquaculture," *Ocean State Aquaculture Association*, Newsletter # 97:1, posted online, 23 Jan 1997, http://www.aquanic.org/newsltrs/state/ri/osaa.htm (accessed 12 Sept 2008).

The effects of a lack of a suitable substitute for fishmeal are seen in the case study of the US Catfish industry. Although the US produces only 4% of world aquaculture products, one of the United State's largest aquaculture products is Catfish and its farmers are going out of business due to feed and fuel prices. Evidence of this fact is that in 2001, Mississippi catfish cultivation acreage peaked at 113,000 acres and by July of 2008 had dropped to 80,400 acres.[158]

In an article for the New York Times in July of 2008, David Streitfeld interviewed catfish farming pioneer John Dillard of Dillard & Co. and described what is occurring. "Feed is now more than half the total cost of raising catfish" he writes. "Corn and soybeans have nearly tripled in price in the last two years, for many reasons: harvest shortfalls, increasing demand by the Asian middle class, government mandates for corn to produce ethanol and, most recently, the flooding in the Midwest."[159] In the interview, Dillard calculates that this year, for every dollar his company will spend raising the catfish, they'll see a revenue (not a profit) of 75 cents. As a result, he's already let go 100 employees and expects to let go another 200. Next year many of his ponds will be planted over with corn. Looking at the causes Streitfeld attributed to the price increases of corn and soy meal in the feed, the mismanagement practices of land based food production quickly come to mind. The harvest shortfalls Streitfeld mentions can be attributed to topsoil loss and decreasing cropland. The increased demand mentioned can be attributed to China's grain production shortfall and need for feed for meat production. The truly pessimistic can attribute the floods to global warming. None of this bodes well for the industry. Additionally, corn and soy meal are not the only ingredients in catfish and aquaculture feed.

The additional cost driving up catfish feed is the fishmeal price jump. Fishmeal prices themselves jumped from a 2005 average from $711/ton to an average of $1141/ton in 2006. Since then, the price has hovered between $1000-$1300/ton.[160] Fishmeal is an essential protein source in catfish feed and makes up 3-34% of the feed depending upon the growth stage of the fish.[161,162] The rest of the feed includes corn, soy, and the wheat-gluten products aforementioned. However, reports have shown that in Catfish feed, over inclusion of protein from plant meals increased the undesired fat content and may retard growth of the catfish.[163] While cheaper than fishmeal on a tonnage basis, even over-inclusion is difficult because as Streitfeld noted, plant meals are in high demand for fuel production and have subsequently tripled in price.[164] All this has lead to large aquaculture feed price increases.

Discussing the fishmeal price jump specifically, aquaculture expert Andrew Logan writes in the Fish Information & Services (FISO) aquaculture trade publication that, "Many industry experts agree that fishmeal, a primary source of protein, has reached its maximum production capacity of less than 7 million tonnes per annum."[165] The implicit assumption being that a scarce resource in high demand results in a high price. Ronald Hardy, director of the Aquaculture Research Institute at the University of Idaho corroborates this describing how multiple fishmeal stock declines and collapses around the

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[158] "US Catfish prices must rise for industry to survive," *Aquafeed Newsletter*, 13 Aug 2008 www.aquafeed.com/read-article.php?id=2479 - 24k (accessed 24 Sept 2008).

[159] David Streitfield, "As Price of Grain Rises, Catfish Farms Dry Up," *Nytimes online,* 18 July 2008. www.nytimes.com/2008/07/18/business/18catfish.html (accessed 24 Sept 2008).

[160] Helga Josupeit, FAO Fish Utilization Service, Italy, e-mail correspondence with the author, 24 June 2008.

[161] Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006)

[162] Bonnie Coblentz, "28 percent more than adequate: Lower-protein feed profitable diet." *The Farm Press,* 11 Oct 2002, http://deltafarmpress.com/mag/farming_percent_adequate_lowerprotein/ (accessed 18 Sept 2008).

[163] See note 127.

[164] See note 159.

[165] Andrew Logan, "The aquaculture business can't go on using fish to feed fish," *Fish Information and Services Organization,* 22 Feb 2008, http://fis.com/fis/people/printable.asp?article_id=19&l=e (accessed 28 Sept 2008).

globe contributed in large part to the 2006 price jumps.[166] Logan continues his argument by explaining that feed companies have taken measures to extend the fishmeal supply and decrease feed costs by decreasing the percentage of fishmeal in feeds. Additionally, due to the aquaculture industry's growth, the industry has developed greater purchasing power when competing with livestock producers for the share of the world fishmeal production. Subsequently, livestock producers have been switching to the alternatives to fishmeal based feeds available to them. Despite all this, Logan writes that, "…many experts within the aquaculture industry… agree that growth of this crucial industry will cease within ten years if substantial new sources of protein are not developed." As evidence he quotes a Norwegian Aquaculture Protein Center report that states, "Trends within the [aquaculture] industry indicate an insufficient supply of protein sources in the future. Fish protein as an ingredient in fish feed is now more or less fully exploited. Alternative sources must be found."[167]

Consultant Peter Edwards and an international team of scientists studied the Vietnamese aquaculture industry in 2004 (before the fishmeal price jump) and came to the same conclusions. Writing for the Australian Centre for International Agricultural Research, he wrote, "Future demand for fishmeal is expected to increase dramatically according to the future projections for [the] growth of aquaculture…as prospects for increased production of quality fishmeal do no look promising, the future of intensive Vietnamese aquaculture is more likely to be influenced by the availability and price of fishmeal and fish oil on the international market."[168]

What is interesting about all of the previous opinions is that most experts never explicitly make the connection of why the industry must continue to grow. Izzat Feidi is one expert who did. Feidi started working for the FAO in 1969 and retired to private consulting in 2000, finishing as the FAO's Chief of the Fish Utilization and Marketing Service. He makes the connection when he writes that to keep pace with global population demands for food, that the aquaculture industry's growth "would require a continuous growth rate at not less than 4-5 percent at global level [measured by production output]."[169] His simple assessment provides an excellent summary.

Fishmeal: The Crux

Multiple multinational organizations such as the FAO and many independent aquaculture specialists are arriving at the same conclusion and speaking out about it. Their reports justify the third claim of the framework: An alternative to fishmeal as a feed for aquaculture must be found for the industry to keep growing. The big questions remaining then, are whether or not black soldier fly larvae are an appropriate alternative, and whether the technology to produce them is scaleable.

Substantiating Claim 4: Hermetia Illucens Larvae Are An Appropriate Fishmeal Substitute

Fishmeal alternatives do exist. An abstracts database run by the Centre for Agricultural Bioscience International (CABI) contains some 700 records describing research into alternative protein

[166] Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006), 413.
[167] See note 165.
[168] Peter Edwards, Le Anh Tuan, Geoff L. Allan, "A survey of marine trash fish and fishmeal as aquaculture feed ingredients in Vietnam," *Australian centre for International Agricultural Research,* 2004, www.apfic.org/modules/xfsection/download.php?fileid=5 (accessed 27 Sept 2008).
[169] See note 141.

sources for use in aquafeeds.[170] The question becomes, why are *Hermetia Illucens* larvae appropriate and why will they out compete other alternatives?

Hermetia Illucens larvae have been tested as a component of feed for swine,[171] chickens,[172] rainbow trout,[173] and catfish.[174] As a replacement for fishmeal, Dr. Craig Sheppard wrote in response to the national marine fisheries service request for public comment that, "Peer reviewed studies show that prepupae meal can replace at least 25% of the fishmeal in a diet with no reduction in gain or feed conversion ratio (FCR) in rainbow trout (St-Hilaire etal. 2007) or channel catfish (Newton et al. 2004)."[175] Because of research conducted by Dr. Sheppard and a select few others, more and more attention is being paid to larvae as the aquaculture industry's quest for alternative protein sources continues. So much attention in fact that one early mover, Florida based Neptune Industries announced in June of 2008 that it "… has received a Letter of Intent to purchase over 40 tons per month of its Ento-Protein, an insect-based alternative to fishmeal, from Zeigler Bros, Inc. of Gardners, PA., USA."[176] In its news brief, it concluded that when it compared feed made with fishmeal to feed made with what it calls "ento-meal," that "the early trial results indicate the fish have no real preference for one over the other," said Lou D'Abramo, a researcher working for Neptune Industries. D'Abramo continued explaining that later studies of hybrid striped bass fed the larvae-meal "…indicated no difference in appearance, flavor or texture of the fish grown on the insect-based diet and those grown on the fishmeal diet."[177] Inquiries into the insect source of the "ento-meal" Neptune is in the process of marketing quickly revealed sources that confirmed that it was in fact solely black soldier fly.

Larvae as a Fishmeal Replacement: The Crux

The scientific sector is agreed that *Hermetia Illucens* larvae are an appropriate substitute for fishmeal. Research into larvae as a feed for catfish, trout, swine, and chicken all conclude that as part of a complete diet it can replace fishmeal. More research will need to be conducted into the optimal feed mixes for each species of fish, however this will take considerable time.

What is more conclusive even than the scientific consensus is that the business community is listening. The first contracts for ento-meal supply were made as recently as five months ago by feed producers. The market will need to see a steady supply and consistent results. If this happens consensus will gradually build behind the larvae as a replacement for fishmeal. The fifth claim in the opening framework is justified: larvae from *Hermetia Illucens* is an appropriate replacement for fishmeal. The question remaining then, is why will the larvae out-compete other protein alternatives and is there potential to scale the market?

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[170] "Insect protein: an alternative to fishmeal?" *Centre for Agricultural Bioscience International,* 10 May 2007. http://cabiblog.typepad.com/hand_picked/2007/05/insect_protein_.html (accessed 10 Aug 2008).

[171] See note 44.

[172] Gutiérrez, Gloria Patricia Arango. "Aportes Nutricionales de la Biomasa de *Hermetia Illucens* en la Cria de Pollos de Engorde." (Medellín: U. Nacional de Colombia, 2005).

[173] See note 63.

[174] Larry Newton, et. al. "Using the black soldier fly, *Hermetia illucens*, as a value-added tool for the management of swine manure," University of Georgia, *Dept. Of Animal. & Dairy Science Annual Report*, 2004.

[175] See note 174.

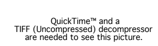
[176] Suzi Fraser, "Zeigler to pioneer insect-based feeds," Aquafeed.com, posted online, 15 June 2008 http://www.aquafeed.com/read-article.php?id=2411 (accessed 16 June 2008).

[177] Bob Ratliff, "Producers may put fish on insect diet," MSU Ag Communications, Posted online, 29 Nov 2007, http://msucares.com/news/print/fwnews/fw07/071129.html (accessed 16 June 2008).

Substantiating Claim 6: Black Soldier Fly Cultivation is Scaleable

Prior to 2006, Black Soldier Fly cultivation was marked by two major problems, a lack of commercial interest in a fishmeal substitute and the lack of a reliable collection system. For these reasons, in Ronald Hardy's 2006 assessment of fishmeal he offhandedly dismissed proteins from insect sources as novelty products.[178] In the previous section, the marked interest of the Aquaculture industry's desire for an alternative to fishmeal has been clearly explained. As a result, Hardy Co-authored a paper in 2007 that studied the use of the larvae for Rainbow trout feed.[179]

The problem of a reliable collection system was solved in 2007 with the invention of the Bio-Pod. After eight years of research, Dr. Paul Olivier of ESR International developed a method in which larvae would crawl out the ramps of a two-foot or four foot diameter circular container.[180] This "self-harvesting" of mature larvae by the species itself eliminated the prohibitively time consuming task of picking out the grown larvae from the waste substrate. The circular design of the device additionally resolved previous design issues in which larvae in rectangular concrete ramp structures would get stuck in the corners and fail to crawl out of the harvesting device. By utilizing a circular design, there are no corners that contribute to "trapped" larvae. Larvae crawl instead along the circular walls (shown in the figure) until they encounter the ramps designed for crawl-off. Crawling up the ramps, they fall into the harvest chute and into the collection buckets.



The Bio-Pod by ESR International
Source: www.thebiopod.com

Dr. Olivier made special effort to make the technology scaleable. This was accomplished by designing them to be made of a roto-mold plastic that dramatically reduced weight from previous concrete designs. He additionally worked with his engineers to insure that the bins were stackable for easier shipping and optimized space on palettes within a shipping container. Without the four innovations named, the technology could not be considered near ready for use in industrial applications. His design is today still the only Black Soldier Fly harvesting technology available for commercial purchase.

Current Issues with Black Soldier Fly Larvae Cultivation

Despite the described innovations in cultivation and the advantages of the larvae itself, there is much work to be done before the bio-pod and Black Soldier Fly Larvae cultivation as a process are ready for industrial scale application.

The problem with the bio-pod, as identified by this analysis, is that it is designed for residential or hobbyist use in small numbers (1-3 bio-pods) with wild populations of black soldier fly. In

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[178] Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006), 414.
[179] See note 63.
[180] See note 54.

contrast, industrial production requires the in-series use of many bio-pods (100+) to be profitable. To operate this quantity of bio-pods requires the management of a large captive population to supply new eggs to the process. As will be described by the models in this analysis, failure to reach a sufficient processing capacity results in an unprofitable business model.

In addition to required additional research in the process technology, there are many holes in the research regarding black soldier fly. With the exception of coffee wastes,[181] little research has been done on individual food-wastes as a substrate for black soldier fly and the substrate's effect on the nutrient composition of the black soldier fly. Given that 30% of food produced in developed countries is lost to wastage in the supply chain, this represents an ample market and supply of wasted nutrients.[182] The importance of studying the individual effects of different feed substrates is that the nutrient composition, fat and protein ratios, are what determine the value of the black soldier fly as a feed for animals.

While larvae have been fed to chicken,[183,184,] pigs,[185] and frogs,[186] only two studies exist[187,188] that use Black Soldier Fly larvae as feed for a fish species to determine the proper percentages and preparation of the larvae. Given the number of fish species in existence for which feeds are formulated, this leaves a long path for researchers to follow.

In addition to research needs in the areas of process technology and optimal feed substrates, there has been no research into the bi-products of Black Soldier Fly cultivation which include liquids, ash, and gas. Informal observation by hobbyists in Vietnam that cultivated both rare orchids vulnerable to *Fusarium Oxysporum* and black soldier fly reported to Dr. Olivier that liquids from the bio-pod had a measurable effect at preventing attacks of *F. Oxysporum*.[189] This would be consistent with findings by Erickson et. al in 2004 that Black Soldier Fly reduced or eliminated harmful bacteria in manure.[190]

Likely due to the ample supply of manure and food waste aforementioned, there has also been no research into the pre-treatment of food waste substrates black soldier fly are known to have difficulty consuming. These include orange peels, grass clippings, avocado pits or other common organic wastes. These could be pre-processed with a shredder, or using efficient microorganisms, worms, or mushrooms to break down the waste and make it available to Black Soldier Fly consumption. The value of this research would be identifying hard to dispose of wastes and charging higher rates to receive and process this waste using the Black Soldier Fly.

Finally, one of the largest gaps in research into process technology is the fact that emerged flies require direct sunlight to mate and it is unknown why.[191] This fact causes problems as cultivation of a managed population indoors or outdoors in cloudy areas is often poor or not possible. Additionally, constructing a confine of materials in which UVB rays pass through to reach a managed population, as well as controlling for temperature poses a serious design problem in the

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[181] See note 50.
[182] See note 70.
[183] See Note 43.
[184] See note 172.
[185] See note 44.
[186] Craig Sheppard & Gary Newton, "Valuable by-products of a manure management system using the black soldier fly," (presented paper at the 8th International Symposium on Animal, Agricultural and Food Processing Wastes, Des. Moine, Iowa, Oct. 9-11), 35-39.
[187] See note 63.
[188] See note 64.
[189] Dr Paul Olivier, Tran Tan Viet, E-mail correspondence with the author, 14 Aug 2007.
[190] See note 60.
[191] Dr. Craig Sheppard, Et. al. "Rearing Methods for the Black Soldier Fly," *Journal of Medical Entomology,* 39(4) (2002): p 695

wrong environment because the two goals are nearly counter-opposite. To date, there has been no publicly published research into reproduction of the BSF using artificial lighting or why the BSF need direct sunlight. However, methods have been developed by a private Spanish solar energy company and studies are also underway by Dr. Jeff Tomberlin of Texas A & M University to publish publicly accessible information on the subject.[192]

IV. Introduction to the Scientific Studies Performed

Due to the gaps in knowledge identified in the previous section, and the necessity to develop information for the systems models, four studies were conducted. While developing scientific studies on all of the areas lacking research was beyond the scope of this analysis, these four studies did establish a solid base by which to design a process technology model using VENSIM software. The aims of these studies were the following:

1. Confirmation of Optimal temperature for larvae growth at altitude
2. Confirmation of larvae consumption rate with food waste as a substrate
3. Confirm the total percentage of waste consumed by a colony and the percentage ash
4. Investigate the effects of specific food waste substrates on the composition of the larvae
5. Investigate the effects of larvae fed meat waste as a substrate
6. Quantify the leachate (drained liquids) from the larvae cultivation process
7. Analyze the composition of the leachate
8. Confirm scientifically the informally observed anti-fungal properties of the leachate
9. Confirm ability of larvae to consume E. Coli and Salmonella without harm.
10. Confirm larvae-meal best practices for meal food safety

About the Studies

All studies were designed, planned and executed by Grant Canary and the researchers named. Two of these studies were conducted at the Universidad de la Salle, and two were conducted at the Universidad Nacional Sede Bogotá. Specially designed equipment was constructed at Universidad de la Salle for studies involving larvae feed substrates and temperature tests. Two greenhouses with dimensions 6m x 20m each were constructed and built at the U. Nacional. The bio-pods placed in these greenhouses were imported by container vessel from Vietnam to supply larvae and waste substrates for the experiments.

Study one, (Baron et. al) was first begun in Aug of 2007 at the Universidad de la Salle. Study two (Rojas et. al) was begun in January of 2008 following the conclusion of study one's laboratory experiments and initial conclusions.

Studies three (González and Canary) and four (Tovar and Canary) were begun simultaneously at the Universidad Nacional after importation of the Bio-pods from Vietnam and construction of the greenhouse facilities was completed in March of 2008.

For clarity in this thesis, all studies are named according to the first researcher named in the investigation as the researchers are distinct. The full articles are included following an executive summary of each of the studies and their specific achievement of a research aim or relevance to the VENSIM models and business plan developed for this analysis.

[192] Dr. Jeff K. Tomberlin, Telephone Interview with the Author, 25 October 2008.

Study 1: The Degradation of Organic Wastes Using the Commercial Production of Black Soldier Fly (*Hermetia Illucens*) 1 May 2008

Ingrid Victoria Gutierrez Baron, Natalia Sanchez Obando, and Grant Everest Canary

Executive Summary

This study's objectives were to analyze the optimal temperature for larva growth in Bogotá, Colombia, as well as to begin a general assessment of optimal substrates for larvae growth. This study was conducted in two phases: In the first phase, 5-7 day old larvae provided by BioSystems Design LLC were grown in specifically constructed chambers to control temperature and determine the optimal temperature for larvae growth. Utilizing 15 experimental growth chambers, it was observed that 30°C yielded optimal biomass growth and efficiency in degradation of the substrate. This differed from the findings of previous experiments.

In accordance with the first research aim described above, the study determined that Larvae grown under environmental conditions considered normal for the city of Bogotá (18ºC +/-2) resulted in a 25% mortality rate, stunted growth, and slow consumption of the substrate. The

optimum temperature for growth at Bogotá's elevation of 2640m (8,661 ft) elevation was determined to be 30ºC. At temperatures greater than 30ºC, there was nearly a 60% death rate. Of the survivors, they were found to be dry, black, hard, and exhibited very little movement. Results differed from those found by Newby et. al 1997.[193] This may have been due to the altitude or the humidity involved in the experiment.

The second phase of the study utilized these same growth chambers to test the consumption of different substrates by the larvae at 30°C. The first substrates tested in the second phase were chosen to determine the optimum biomass yield when larvae consumed three different substrates: banana peels, fruits, and vegetables. The difference in biomass yield between fruits and vegetables was not significant. For this reason, a second study was undertaken to determine the differences in biomass yield between a substrate mix of 50-50% vegetables/fruit; 47.5-47.5% fruit/vegetable with a 5% meat substrate; and a control substrate of banana peels. In this observation, the mix of only vegetables and fruit yielded the highest quantity of bio-mass as well as the highest quantity of protein in the biomass.

In accordance with the second and third research aims described above, twenty larvae in each of the treatments were found to consume approximately between 70 – 100 g / day, resulting in a consumption of 3.5 - 5 g/day/larva. Larvae fed a veg-fruit waste grew to a final biomass weight of between 0.2100-0.2300g. In accordance with research aims four and five, it was found that the larvae fed a substrate of 50-50 veg-fruit waste developed the greatest amount of protein and did it faster than larvae fed other substrates including substrates that contained meat (already synthesized protein). Protein analysis of the unconsumed substrates additionally concluded that larvae fed a veg-fruit-meat left ample protein in their unconsumed substrate. This is likely because the larvae metabolism doesn't produce sufficient lipase enzymes necessary to break the fat tissue and take advantage of its protein content

In accordance with the sixth research aim, leachate production was monitored from the drains in the larvae temperature control device. 350 mL were collected in 23 days from all of the substrate types. This established a ratio of 350mL : 10.5kg or 33.3mL/kg. Liquid density was found to be 0.998g/ml. Analysis of the unconsumed substrate per substrate type is included in the full article.

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193 See note 52.

MATERIALS AND METHODS

Larvae Growth Apparatus Description

The apparatus designed for the growing of the larvae was a modified shelf system with dimensions of 2m tall by 93cm wide by 30cm deep. On each shelf, holes were cut and lidded containers of a 21cm radius were placed flush on the shelf. For each shelf level, the area under the container was sealed and a heating element connected to a thermostat was placed under the 10 cm deep container in the sealed space. Temperatures were maintained with the adjustable thermostat.

Phase 1: Determining Optimum Temp

Optimum temperature studies for Hermetia Illucens have been performed but not at altitude.[194] It was necessary to confirm these studies with the apparatus described. Conclusions were distinct from previous studies.

In this phase 20 larvae in their first instar were acclimatized and then placed in a specially designed apparatus designed for the larvae. Twenty larvae were placed in each container with banana peels and pulp as a substrate. Liquids from the unit were drained by cutting a hole in the bottom of each bowl shaped container and connecting a transparent flexible tubing to the hole. A filter glued over the hole prevented larvae and solids from being drained. Liquids from each shelf drained to different collection buckets.

To determine the optimum temperature for consumption and growth of the larvae, each of the five shelf levels (with three containers each) were operated at different temperatures. The first level operated at ambient laboratory temperature (18ºC) +/-2. The second level was maintained at 20ºC by the heating element, the third level at 25ºC, the fourth level at 30ºC, and the fifth level at 35ºC. The percent humidity inside the containers was measured periodically. Larvae in this phase were weighed and their length was measured every three days.

Phase 2: Experimentation with Different Substrates:

Using the data from the first phase temperature experiment, different substrate mixes were fed to the larvae at a constant temperature of 30ºC to determine substrate consumption and optimal larvae biomass development and nutrient assimilation. In the case of each substrate mix, three growing containers with 20 larvae each were allocated per substrate. Portions of substrate were allocated in 100g every three days. Larvae biomass development over time and the quantity of substrate consumed was recorded every three days.

The mixes tested were 100% vegetable waste, 100% fruit waste, a 50-50 fruit-vegetable mix, a 47.5-47.5 mix of fruit-vegetable and 5% of meat, and finally a 100% banana peel and pulp substrate as a control. The fruit waste substrate included fruits: (papaya, guayaba, melon, mango, apple, and banana). The vegetable waste substrate included: (lettuce, spinach, beet, celery, carrot, and pumpkin.)

Additional Analysis

In addition to analysis of the biomass development, a protein analysis using the Kjeldahl Nitrogen test[195] and Kjeldahl digestion equipment (Hach Brand DIGESTALH) was performed on larvae grown on the varying substrates to determine humidity content, fat, protein and ash in the larvae-meal. Atomic absorption tests were conducted to determine the iron, magnesium and calcium content of the larvae. All

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[194] See note 52.

[195] Dr. D. Julian McClements, "Analysis of Proteins." *U. of Massachusetts,* http://wwwunix.oit.umass.edu/~mcclemen/581Proteins.html (accessed 10 May 2008).

tests were conducted after the larvae reached the pupae stage. Finally, drained liquids collected from the growing containers were collected and their quantity measured.

RESULTS AND DISCUSSION

Phase 1 Results

The data presented in Table 1 refers to the effects of temperature on the development of the black soldier fly larvae. In the following graph the biomass development of the larvae in each of the temperature ranges is shown.

Table 1. Phase 1 Biomass development

Temp °C	Initial Weight (g/larvae)	Final Weight (g/larvae)
18 (+/-2)	0.0125	0.1285
20 °C	0.0125	0.1551
25 °C	0.0125	0.1956
30 °C	0.0125	0.2156
35 °C	0.0125	0.1570

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

In both the 25ºC and 30ºC range the best biomass development was observed. However, the temperature most favorable to biomass development was 30ºC where the larvae obtained the largest average biomass of 0.2175 grams. Analysis was conducted using the ANOVA variance method.[196]

The results found did not correspond to those found by Newby in 1997 which determined an optimum temperature of 35ºC.[197] Humidity in the containers was found to be regularly higher than 75%. This level could have affected the development of the larvae grown in the higher temperature.[198] The altitude of 2600m may also have affected this outcome.

Phase 2 Results

The results shown in Table 2 refer to the growth of larvae when fed each of the five distinct substrates.

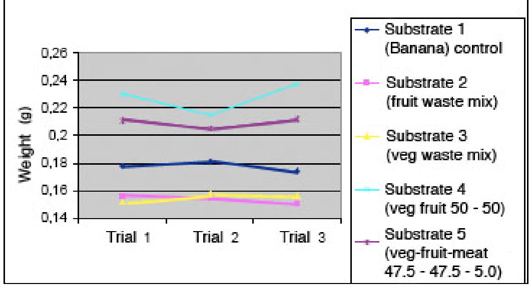
Table 2. Avg. Biomass Developed on Five Substrates

	Avg. biomass g/larva		
Substrate	Trial 1	Trial 2	Trial 3
S1 Control (banana)	0.1782	0.1809	0.1741
S2 (fruit waste)	0.1563	0.1547	0.1506
S3 (veg waste)	0.1518	0.1576	0.1567
S4 (50-50 fruit-veg waste)	0.2300	0.2150	0.2375

[196] Doncaster, C.P. "Examples of Analysis of Variance and Covariance." 31 October 2008 http://www.southampton.ac.uk/~cpd/anovas/datasets/index.htm
[197] See note 52.
[198] See note 52.

S5 (fruit-veg-meat)	0.2111	0.2050	0.2120

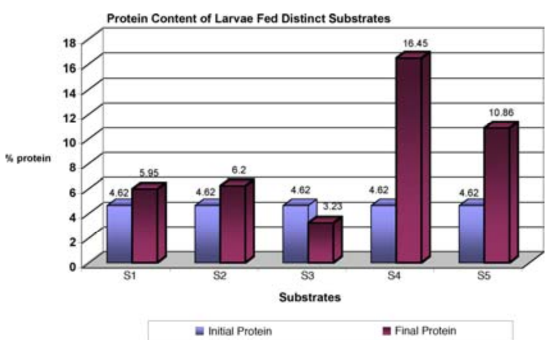
Fig 2. Biomass Acquired by the Larvae fed 5 distinct substrates



In the graph above it is demonstrated that the greatest biomass was developed by larvae fed the 50-50 vegetable fruit substrate. The larvae weighed 0.2375 grams on average. Larave fed the veg-fruit-meat substrate weighed 0.2120 grams (0.0015grams difference) and on average were 2.3 cm long. Data was verified using the ANOVA method.[199]

Results of the Protein Analysis:

Figure 3 shows the protein content of the larvae fed each of the five substrate types.



Larvae fed Substrate 4 were recorded to have nearly 75% more protein than substrate 1, 2, and 3 and approximately 35% more than substrate 5. The hypothesis proposed is that the larvae's production of amylase, celulase, and lipase enzymes may be more suited to the breakdown of the 50-50% fruit-vegetable substrate.

Protein Formation Rate

Figure 4 below graphs the protein content against the time required to mature. Larvae fed substrates 4 and 5 were the quickest to develop protein and mature into pupae (23 days). Regarding the transformation of substrates into protein, Larvae fed substrate 4 which contained no meat developed a higher protein content in the same number of days as larvae fed substrate 5 which contained meat. Larvae fed either of these substrates demonstrated more rapid development than larvae fed substrates 1, 2, and 3. This indicates that combined fruit and vegetable waste results in more rapid larvae development (even when 5% meat is added) than simply fruits or vegetable waste independently.

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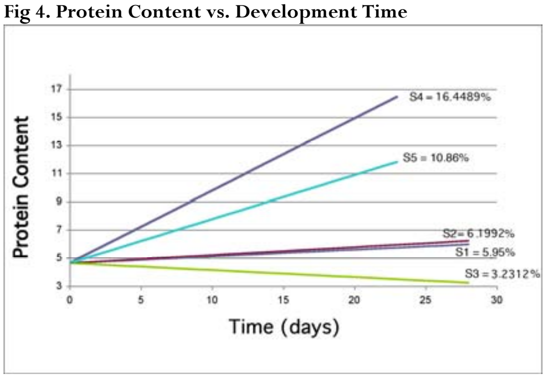
[199] See note 196.

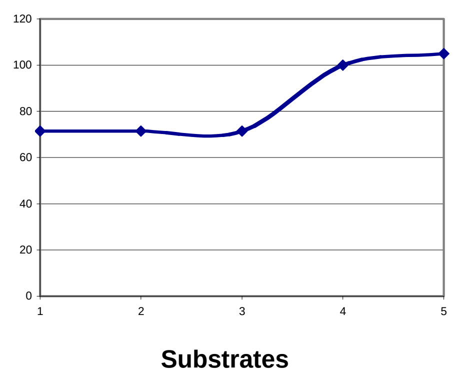
Fig 4. Protein Content vs. Development Time



Substrate Consumption

In each of the substrates, the consumption rate of each of the substrates and the number of days for development were analyzed. In substrates 1 and 2 there was no significant difference in the consumption rate. In substrate 3, the consumption rate diminished slightly. Comparing these results to substrates 4 and 5 one can see a 65% to 70% increase in the consumption rate. Due to the greater performance of substrates 4 and 5, one hypothesis is that the larvae growth is slowed when necessary nutrients are unavailable, and therefore larvae consume less. Necessary nutrients may be missing in fruit only or vegetable only substrate.

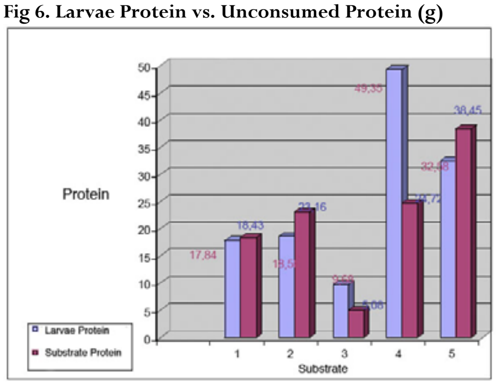
Fig 5. Qty of Substrate Consumed Per Day



Analysis of Unconsumed Substrate

In the graph below, one observes a comparison between the amount of protein developed by the larvae and the amount of unconsumed protein remaining in the feed for each of the five substrate types.

Fig 6. Larvae Protein vs. Unconsumed Protein (g)



It's already been established that the larvae fed substrate 4 developed the greatest amount of protein and did it faster than larvae fed other substrates. However, the protein analysis of the unconsumed substrate demonstrates that there was ample protein available to be consumed by the larvae fed substrate 5. In fact, there was more protein available than the larvae actually developed. From this it can be deduced that the larvae do not assimilate protein well. It is theorized that this is due to the production ratio of digestive enzymes by the larvae, but further study in this area is necessary.

Measurement of Drained Liquid

350 mL of leachate was collected in 23 days from the 10.5kg substrate administered. The resulting ratio is 33.3mL per kg substrate. The density of the liquid was found to be 0.998g/ml.

CONCLUSIONS

-The period of larvae growth can be established between 21-23 days at which time they should have left the bio-pod as an adult.

-The substrate of 50-50% fruit vegetable at 30˚C demonstrated the greatest larval biomass development and highest protein content. One can deduce that protein developed by the larvae is more efficiently developed from fruit and vegetable waste than from meat due to the lack of lipase production which would help the larvae to consume the meat.

-Larvae grown under environmental conditions considered normal for the city of Bogotá (18ºC +/- 2) resulted in a 25% mortality rate, stunted growth, and slow consumption of the substrate when compared to substrates grown at different temperatures.

-From the phase 1 data, one can conclude that temperature directly influences the manner in which larvae develop. Especially due to the fact that the ANOVA analysis showed a significant difference in the development of larvae grown at 30ºC.

-The consumption and elimination of organic waste by means of the larvae Hermetia Illucens is an appropriate method to reduce the quantity of organic waste entering landfills.

-At temperatures greater that 30ºC, there was nearly a 60% death rate. Of the survivors, they were found to be dry, black, hard, and exhibited very little movement.

-Regarding the biomass developed by the larvae, it was found that the 50-50% fruit-vegetable substrate resulted in larvae developing 11.50% more weight when compared to the control (banana substrate). The larvae developed 7.42% more weight when compared to the 47.5-47.5 - 5% substrate of fruits-vegetables-meat. The larvae developed 12.42% more weight compared to the fruit only substrate and 15.77% more when compared to the vegetables only substrate.

RECOMMENDATIONS

-It is recommended that a study be conducted to determine if substrates that are shredded prior to consumption are consumed more rapidly.

-It is also recommended that the drained liquid from the process be identified and examined for the possibility of utilizing it as a fertilizer.

-The remains of the substrate fed to the larvae only represented 2% of the total weight of the substrate fed to the larvae. However, a carbon and nitrogen analysis is recommended to verify the possibility of using this waste as a fertilizer.

-It is recommended that a study using only meat residues as substrates be conducted for more in depth analysis.

-It is recommended that humidity tests be conducted to establish the exact range in which the larvae not only develop biomass in a healthy manner but also more effectively consume substrates.

-It is recommended that an analysis of cost reduction for open-air markets paying waste collectors be conducted to determine potential savings from the process.

-It is recommended that a thermostat and heating element be installed in bio-pods for more efficient larvae production.

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Study 2: Starches and Meat Wastes as Feed Substrates for Cultivating Black Soldier Fly (*Hermetia Illucens*) 1 Oct 2008

Eliana Marcella Gamboa Rojas, Nicolas Jasbon Orozco, and Grant Everest Canary

Executive Summary

In this study, further investigation into research aims three and four was conducted. Larvae were fed Cavassa, Banana, Potato, and Arracacha as well as mixes of these starches, and mixes of these starches that included meat residuals. Larvae that consumed these substrates were analyzed for their composition of humidity, protein, fat, Iron (Fe), Nitrogen (N), Calcium (Ca), and Magnesium (Mg). The purpose of this analysis was to begin developing a portfolio in which a desired nutrient level in larvae-meal can be adjusted by increasing or decreasing the percentage of a type of food waste fed to the larvae. In this study, for example, the inclusion of banana pulp in the feed substrate was shown to increase the iron content in the larvae-meal. Additional findings contributing to the continual development of this portfolio demonstrated that, "the inclusion of beef in the substrate negatively influenced the rate and effectiveness of the decomposition of the substrate." This agrees with the previous study. However, as a tradeoff, calcium content was increased by the inclusion of 5% meat waste products or a percentage of cavassa.

Finally, in this study it was observed that as in the previous study, single substrate feeds resulted in less nutrient rich larvae-meal. This indicates that a single waste producer such as a tomato grower is not desirable as a waste source for the process. Instead, the optimal situation is a location in which larvae cultivators can receive multiple waste streams, and mix substrates to achieve larvae-meal nutrient levels desired by feed producers. Multiple waste streams not only result in more nutritious larvae, but the previous study showed that this will likely result in faster consumption rates, biomass development, and quicker larvae maturation. This is of great importance when considering a larvae cultivation site location.

With regards to the development of information directly useful to the VENSIM profit models, this study built on the previous study's analysis of the quantity of leachate (liquids) obtained from the larvae cultivation process. In accordance with the seventh research aim, this study went on to analyze the leachate's potentially pathogenic properties, and using a most probable number methodology found that it contained approximately 2052 CFU (Colony forming units). This number was high; however, it was, "low enough that pursuant to Colombian law the leachate may be used in agriculture without further treatment." The Colombian law cited is Colombian law article 40, paragraph 1, of decree 1594/84. Having established this, an analysis of the leachates nitrites, nitrates, pH, phosphorus, and ammonium nitrate levels was conducted to establish the value of the liquid as a fertilizer for agriculture. The leachate composition will likely change depending upon the substrate, but it establishes a baseline for comparison, and it is unlikely that it will change so much as to be un-useable in Colombian agriculture.

Additional facts useful to the development of the VENSIM model included one fact that noted that the rate of consumption by the larvae was greatly influenced by the granule size of the substrate. The smaller the granule the less time was required for consumption. This indicates that the consumption rate shown in the VENSIM models may actually be a conservative one as the data is based upon consumption of whole waste products. A food shredder on site may increase food waste throughput in the model, which would increase process speed. Further investigation will be required; however, this fact indicates that the production output of the model is on the cautious side.

MATERIALS AND METHODS

The experiment was conducted in three sequential phases. The three phases started with pure substrates of one ingredient and then became more specific by mixing and introducing new ingredients to make comparisons of larval growth. Results from each previous phase were used to design the following phase of the experiment.

In all cases, the substrate utilized was washed beforehand and the peel separated. Substrates were reduced to small pieces and 100 g portions of peel and fruit were added to each of the containers. Portions were added every seven days. The control temperature used was 30°C.

Equipment

-Kjeldahl digestion equip. (Hach Brand Digestalh)

-HACH machine and reactants (HACH DR 2800)

-Larvae growth chamber[200]

The apparatus used to feed and grow the larvae had four shelves, and in each shelf three plastic bowl containers with lids in which larvae and substrates were placed. Liquids were drained from the containers by cutting a hole in the bottom of each bowl and attaching surgical tubing that drained liquids to a collection. Filter paper was glued over the hole to block solids and larvae from being drained. To maintain a constant temperature of 30°C, heating elements were placed under each shelf and connected to an adjustable thermostat. Thirty degrees Celcius was determined as the optimum temperature for growth in a previous experiment.[201]

Figure 1. Larvae Growth Chamber

Development of the Experiment

This experiment was designed to determine the starch most effective in developing larval biomass. In all cases, 20 larvae were used in each bowl recipient. All substrates added to the bowls were washed before being added to the bowl recipients. In all cases, substrates were added in 100g portions every seven days. This weight was determined by taking into consideration the larvae's consumption needs for a seven-day period. Every seven days the substrates were weighed to determine the rate of consumption over a uniform time period.

In all studies, the Kjeldahl Nitrogen Test[202] was used to determine the protein content of the larvae-meal. In addition to the Kjeldahl test, atomic absorption machine examinations were conducted to determine the total iron, calcium, and magnesium content in the larvae-meal.

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[200] Victoria Gutierrez Baron, Natalia Sanchez Obando, and Grant Canary, "Degradación de residuos orgánicos mediante la producción de larvas soldada negra, *Hermetia Illucen,"* (Bogotá: Universidad de la Salle, 2008)

[201] See note 200.

[202] See note 195.

Experiment Phases

The first phase was designed to determine the larvae's biomass generation when consuming pure starch substrates. The starch substrates studied were potatoes *(Solanum Tuberosum),* cassava (*Manihot Esculenta*), and arracacha (*Arracacia Xanthorriza)*. The three sources were selected for their high consumption in Colombia and thus high generation of waste residuals.[203]

The second phase was designed using the results from the first phase, which showed that the cassava resulted in the greatest larvae biomass development. Therefore cassava was used with other starch and fruit substrate mixes to compare larval biomass development. These mixes were: 30% cassava / 70% banana; 50% cassava / 50% banana; 80% cassava / 20% banana.

Finally, in the third phase meat (beef) was added to starch and fruit sources to make a larvae biomass development comparison. These mixes were: 76% cassava / 19% banana / 5% beef; 95% cassava / 5% beef.

[203] Ministerio de Agricultura y Desarrollo Rural. "Anuario estadístico del sector agropecuario 2001" (2002)

RESULTS AND DISCUSSION

The purpose of the experiment was to achieve the highest possible quality and quantity of larvae-meal by adjusting the diet of the larvae. To satisfy the latter, larval biomass development was measured. In addition, to determine the quality of the larvae, in each of the three phases tests were conducted to analyze macro and micro nutrients that animal feed producers may be most interested in.

Shown below are the measures taken for the biomass developed by the larvae in each of the phases. Larvae were weighed in groups of twenty. The data shows total weight divided by the group number in order to make direct comparisons with other studies done on biomass development.

Table 1. Biomass Acquired by Larva (g/larva)

Substrate	Trial 1 (g)	Trial 2 (g)	Trial 3 (g)	Avg.	Avg. Time (d)
Phase 1					
Cavassa	0.1315	0.1455	0.174	0.150	28
Potato	0.1455	0.1355	0.145	0.141	22
Arracacha	0.111	0.1935	0.1305	0.145	26
Banana	0.1375	0.1660	0.1805	0.161	34
Phase 2					
30% Cavassa + 70% Banana	0.216	0.2215	0.251	0.229	22
50% Cavassa + 50% Banana	0.2115	0.249	0.238	0.232	19
80% Cavassa + 20% Banana	0.239	0.2335	0.2485	0.240	17
Phase 3					
95% Cavassa + 5% Beef	0.196	0.164	0.1745	0.178	24
76% Cavassa + 19% Banana + 5% Beef	0.0985	0.073	0.11	0.093	28

In each experimental phase, larvae were allowed to grow until their fifth instar or until adult. Shown in the time column are the average number of days until maturity was reached. The 80% Cavassa / 20% Banana had the best overall biomass development in the shortest period of time.

In each of the three phases, an analysis of humidity, nitrogen, and protein was also conducted. The results are shown in the table below.

Table 2. Determination of Percentage Humidity, and Protein and Nitrogen Content

Substrate	Humidity (%)	Nitrogen (ppm)	Protein (ppm)
Phase 1			
Banana	36.57	2	1.5
Cavassa	35.35	2	**1.5**
Potato	42.35	1	0.75
Arracacha	45.35	0	0.00
Phase 2			
30% Cavassa + 70% Banana	53.21	3	2.25
50% Cavassa + 50% Banana	54.83	4	3.0
80% Cavassa + 20% Banana	53.43	6	**4.5**
Phase 3			
95% Cavassa + 5% Carne	55.56	13	**9.75**
76% Cavassa + 19% Banana + 5% Beef	53.92	8	6.0

In the results above, one observes that in phase one the Cavassa resulted in the highest protein development in the larvae. In phase two, the 80% Cavassa / 20% Banana resulted in the highest protein development. In phase three, the substrate mix with the highest percentage of Cavassa, 95% Cavassa / 5% beef resulted in the highest protein development.

The quantity of total iron, magnesium, and calcium was determined using an atomic absorption machine. The analysis of each of the studies is shown below:

Table 2. Iron, Magnesium and Calcium Content in Larvae-meal

Substrate	**Fe (ppm)**	**Ca (ppm)**	**Mg (ppm)**
Phase 1			
Banana	0.231	***3.549***	0.420
Cavassa	0.061	1.225	0.419
Potato	***0.331***	1.752	0.552
Arracacha	0.092	1.479	***0.675***
Phase 2			
30% Cavassa + 70% Banana	***0.481***	4.827	***1.590***
50% Cavassa + 50% Banana	0.192	2.858	1.348
80% Cavassa + 20% Banana	0.162	***5.88***	1.381
Phase 3			
95% Cavassa + 5% Carne	***0.105***	***7.627***	***1.545***
76% Cavassa + 19% Banana + 5% Beef	0.038	3.791	1.309

Drained Liquid Analysis

An analysis of the liquids drained from the third phase of the larvae cultivation process was conducted to assess the phosphorus, nitrogen, and pH. The purpose was to determine if the liquid contained base levels of nutrients and a pH suitable for possible use of the liquid as an agricultural fertilizer. The HACH machine process and its respective reactants were used in this analysis.

Table 3. Analysis of Phosphorus, Nitrates, Nitrites, Nitrogen and pH of Drained Liquids

Reagent Phosphate (mg/Lt PO_4^{-3})	**Nitrites (mg/Lt NO_2-N)**	**Nitrates (mg/Lt NO_3^-)**	**Ammonium Nitrogen (mg/Lt NH_3-N)**	**pH**
0.81	0.115	>0.01	0.07	8.4

From the above table, one establishes that the Nitrogen/Phosphorus ratio is:

$$\frac{N}{P} = \frac{0.07}{0.81} = 0.0864\,\frac{mg}{Lt}$$

Microbiological Analysis

This analysis was undertaken to evaluate the presence of contaminating agents resulting from the degradation process. In addition to the third phase substrates, the liquid from the third phase was also analyzed for microbiological contaminants. The results are shown below:

Table 4. Presence of Contaminating Agents in Analyzed Samples

Sample	T.Colif.	Fungi	Yeasts
Phase 3 drained liquid	✓	✓	✓
Larvae-Meal from *80% Cavassa + 20% Banana*	✓	✓	✓
Larvae-Meal from 95% Cavassa + 5% Beef	✓	✓	✓
Larvae-Meal from 76% Cavassa + 19% Banana + 5% Beef	✓	✓	✓

In all cases there is the presence of pathogenic agents. It is important to clarify that it was not possible to obtain quantifying or identifying data in the case of the fungi and yeasts due to the vast number of strains and their varied development patterns. In the case of the Total Coliformes analysis it was possible to obtain specific data which is shown in Table 5. The Colony Forming Units assessment (CFU) followed the most probable number methodology (MPN).[204]

Table 5. Total CFU Found in Samples

Sample	Most Probable Number (MPN)
Drained Liquid	2052 units
Larvae-meal from 80% cavassa + 20% banana feed substrate	776 units
95% cavassa + 5% beef	1340 units
76% cavassa + 19% banana + 5% beef	1576 units

Discussion of the Results

The larvae Hermetia Illucens was observed to be effective at degrading cavassa, potato, and arracacha. During the experiment it was observed that the granule size of the waste affected the time required for the larvae to consume it. The smaller the granule the less time was required.

The results show that the larva fed the 80% cavassa / 20% banana substrate acquired the greatest biomass. This establishes that the process is more efficient when cavassa and a small portion of banana is added due to the banana's soft texture.

Analysis of the iron content showed that the inclusion of banana in the feed substrate increased the iron content in the larvae-meal. The larvae fed the 70% banana / 30% cavassa mix showed the highest iron content. The larvae fed the 95% Cavassa / 5% beef showed the lowest iron content. The 95% cavassa / 5% beef mix did, however, show the highest calcium content. Other feed substrates that included beef also resulted in high larvae-meal calcium content.

Magnesium levels found in the larvae-meal indicate that both the 70% banana / 30% cavassa substrates and the 95% cavassa / 5% beef substrates yielded larvae-meals with nearly equal magnesium content.

Despite positive results from the nutrient analysis of feed substrates containing beef, this analysis showed that the inclusion of beef in the substrate negatively influenced the rate and effectiveness of the

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[204] Oblinger, J.L., and J. A. Koburger, J.A. "Understanding and Teaching the Most Probable Number Technique." *J. Milk Food Technol.* 38(9), (1975), 540–545.

decomposition of the substrate. The beef may also be responsible for the pre-mature death of many young larvae fed the beef mix substrate. This was observed throughout the experiment.

Microbiological Results and Discussion

The results of microbial cultivation demonstrate the presence of coliformes, fungal activity, and yeasts in the drainage liquid as well as the larvae-meal from all substrate mixes. These contaminants were not able to be identified; however, other projects have analyzed some properties of the drained liquid.[205]

As shown in Table 5, Coliformes present in the drainage liquid (phase 3 only) had the highest microbiological growth, likely because the phase three substrates contained beef. In the microbiological analysis of the larvae-meal, the 76% cassava, 19% banana, 5% beef mix exhibited greater microbiological population growth than the other substrate mixes. With respect to the number of colonies found in the sample of the drained liquid, it was found that while the population of coliformes was large it did not surpass the 5000 NPM (most probable number) limit established for agricultural use in the irrigation of short sprout vegetables and fruits that are consumed without washing. This limit is established by Colombian law article 40, paragraph 1, of decree 1594/84.

With respect to the presence of fungal activity in the samples, the liquid from phase three had the least microbiological growth while the samples of larvae-meal and the titulated larvae demonstrated considerable fungal growth. Yeast was found in the drained liquid from phase three and in the larvae-meal that had been fed a mix of 80% cavassa 20 % banana. Evidence of yeast found in the sample of titulated larvae was small.

The key finding is that the liquids drained from the larvae growth process conform to the standards established by Colombian law for use in agriculture without any further treatment. Especially since it has been determined that leachate from larvae cultivation has anti-fungal properties.[206] Yeasts, Fungi and Coliformes found in the larvae-meal can be eliminated entirely by a heat treatment process.[207]

Analysis of Phosphorus, Nitrites, Nitrates, & Ammonium-Nitrogen in Drained Liquid

It must be carefully taken into account that the composition of the leachate depends directly upon the substrate used. In this experiment, the leachate from the larvae growth process stands to benefit a variety of agricultural processes due to its Phosphorus, Nitrite, Nitrate and Ammonium-Nitrogen levels. Notwithstanding, the concentrations of phosphorus and nitrogen of found in the liquids of phase three were very low (0.81 ppm phosphorus, 0.115 ppm nitrates, and 0.07 ppm ammonium nitrogen.) when compared with fertilizer concentrations in which one finds mineral levels of 12ppm phosphorous and 6ppm nitrogen.[208] The nitrogen to phosphorus ratio of 0.0864 mg/Lt of liquid was also very low. Agricultural use may require higher mineral concentrations; or, these lower concentrations may serve agricultural purposes well as due to the fact that high levels of nutrients can kill plants. Further research into application and use of the leachate is suggested to determine the best practices for its use.

Comparison of Results Obtained with Fruit and Vegetable and Starch Substrates

Gutierrez et al (2008) established that the average biomass development for larvae fed 50% vegetables and 50% fruits was 4.3g.[209] Comparing with this study, the average biomass development for larvae fed

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[205] See note 200.

[206] Maria Carolina Lizcano González and Grant Canary. "Evaluation of the fungicidal properties of Leachate from *Hermetia Illucens* Larvae fed Tomato Substrate (*Lycopersicom esculentum*) against *Botrytis cinerea, Fusarium oxysporum and Sclerotinia sclerotiorum,*" (research paper, Universidad Nacional: Bogotá, (2008))..

[207] Luis Fernando Tovar Briceño and Grant Everest Canary, "Inhibition of Pathogens by Hermetia Illucens Larvae." (research paper: U. Nacional de Colombia: Bogotá, (2008))

[208] Abonos Organicos, "Flores Rosas," Rosasvirtuales.net www.rosasvirtuales.net/abonos.html (accessed 10 Oct 2008)

[209] See note 200.

80% cavassa and 20% banana was 4.81g. With this fact we establish that the mix of starches and fruit is more effective at increasing biomass development than that of fruits and vegetables.

With respect to the concentration of minerals in the larvae, the mix of 50% vegetables and 50% fruits resulted in calcium levels of 132.8mg/Lt, iron levels of 3.358mg/Lt, and magnesium levels of 7.800 mg/Lt. The mix of 80% cavassa and 20% banana resulted in calcium levels of 5.88 mg/Lt, iron levels of 0.162 mg/Lt and magnesium levels of 1.381 mg/Lt. Comparing the two, the vegetable-fruit feeds resulted in higher levels of basic necessary elements. This information should inform users designing future substrate mixes.

The protein analysis of the two studies could not be compared due to inconsistencies in the units found and data that didn't exist for suitable conversion of grams to ppm.

CONCLUSIONS

The Black Soldier Fly larvae effectively degraded pure starch substrates as well as those mixed with fruits. With regard to the degradation times, it was observed that the cavassa and banana substrates were degraded the most rapidly. It was also observed that the rate of consumption by the larvae was greatly influenced by the granule size of the substrate. When substrates included beef, the substrate was consumed slower and increased the mortality rate of the larvae. Further research is needed with regards to optimum conditions for the consumption of meat bi-products by the larvae.

The substrate mix that yielded the best results for biomass development was the 80% cavassa 20% banana mix. This leads one to believe that this category of substrate contains the necessary elements for the larvae to develop and acquire a high level of nutrients and protein. However, higher mineral levels may be achieved by adding vegetables as the study by Gutierrez demonstrated.[210]

In addition to these two main findings, this study concludes that microbiological organisms are present in the drained liquid and the larvae-meal. Despite this, their numbers are low enough that pursuant to Colombian law the leachate may be used in agriculture without further treatment. This finding is especially important given that the leachate may have an appropriate use in plant pathogen control.[211] With regard to the larvae-meal, a heat process will eliminate the unwanted organisms.[212]

ADDITIONAL SOURCES CONSULTED

Grant, W. D., P.E. Long. Microbiología Ambiental. Editorial Acribia. España. 1989.

Kuehl, Robert O. Diseño de Experimentos. Editorial Thompson Learning. México. 2001.

[210] See note 200.
[211] See note 206.
[212] See note 207.

Study 3: Evaluation of the fungicidal properties of Leachate from *Hermetia Illucens* Larvae fed Tomato Substrate (*Lycopersicom esculentum*) against *Botrytis cinerea, Fusarium oxysporum and Sclerotinia sclerotiorum*

Maria Carolina Lizcano González and Grant Everest Canary 10 Nov 2008

Executive Summary

This study was designed to build on the analysis of the leachate in the previous two studies and fulfilled the eighth research aim. In the two previous studies, the quantity of leachate produced was recorded and in the second study an analysis of the leachate was recorded. In neither of the two studies were yeasts, bacteria, and fungal agents in the leachate identified.

This study sought to determine a potential profitable use of the leachate bi-product. In 2007, Vietnamese orchid hobbyists working with black soldier fly informally observed that leachate from the BSF cultivation process was effective at preventing the onset of *Fusarium oxysporum* in particularly vulnerable orchid species.[213] This study sought to give scientific confirmation of the effects of the BSF leachate against F. oxysporum and other plant pathogens. Confirmation would provide the potential for profitable use of the bi-product.

This study provided scientific confirmation that in fact the leachate from tomato substrate fed to black soldier fly larvae contained a bacteria, *bacillus sp* that inhibited growth of *F. oxysporum* by approximately 72.2%. The tests were conducted in vitro, using a culture medium mixed with the leachate. Inhibition of growth was measured using the radial growth methodology. The leachate had no effect upon plant pathogens *Botrytis cinerea* and *Sclerotinia sclerotiorum*.

The study breaks ground and indicates that the leachate may be a profitable bi-product in the future. However, this research necessitates that further investigation be conducted before the leachate can become a profitable revenue stream. The leachate must undergo trials in soil-based agriculture for a number of plant species to determine effectiveness and refine best practices. This latter point is especially important given the fourth study to be described in which Black Soldier Fly larvae were demonstrated to have anti-bacterial and anti-fungal properties. The whole picture regarding these properties has not been fully uncovered. A spectroscopy or infrared analysis may be necessary to identify if Black Soldier Fly Larvae have a symbiotic relationship with beneficial bacteria in their intestines or outer coverings.

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[213] See note 189.

MATERIALS AND METHODS

The project was conducted within the premises of the Faculty of Agronomy of the Universidad Nacional de Colombia, Bogotá.

Obtaining the Leachate

Leachate was obtained by adding 10 kilos of tomato waste (Lycopersicom esculentum) to a 4' diameter bio-pod (ESR Int'l, Vietnam) designed for the cultivation and harvesting of Black Soldier Fly Larvae (*Hermetia Illucens*). As larvae consumed the waste, leachates passed through drains in the bottom of the bio-pod and were collected in holding tanks. 20 days later, the Leachates were collected, weighed on a heavy analog balance (Petller P 5000), placed in airtight jars and refrigerated until their use.

In Vitro Testing

The plant pathogens tested were strains of pure *Botrytis cinerea, Fusarium oxysporum and Sclerotinia sclerotiorum*. These were obtained from the Plant Clinic of the Faculty of Agronomy of the Universidad Nacional de Colombia, Bogotá.

Radial Growth Technique

The leachate's anti-fungal properties were assessed by measuring the halo of growth around the fungus relative to the control. This was done by following a radial growth procedure.[214] The test and control were grown in Petri dishes on a Potato Dextrose Agar (PDA Oxoid ®) substrate. This substrate was prepared according to instructions from the manufacturer. 39 grams were added to 1000 ml of sterile distilled water and then placed in an autoclave (All-American) and sterilized for 15 minutes at 121 º C. After cooling, the agar was placed into sterile Petri dishes at a ratio of 50% Potato Dextrose Agar (PDA Oxoid ®) and 50% leachate from the bio-pod. The dishes were left to solidify in a refrigerator at 4 ° C.

7 day old Pathogenic fungi were seeded by using a 3mm diameter circular "cookie cutter" or punch to remove sections of the fungi. These sections were placed (with the plastic punch) in the center of the Petri dishes with PDA and leachate using 10mm long 2mm thick wooden sticks which had been previously sterilized with dry heat. The Petri dishes were sealed and tagged and incubated at 26°C. Radial growth of the pathogens was observed by recording the diameter of the inoculated colony on the second, fifth, and seventh day after inoculation following the radial growth procedure.[215]

As a positive control, a commercial product with active ingredient propamocarb-HCl was used. This product was added to the Potato Dextrose Agar (PDA Oxoid ®) as indicated by the manufacturers instructions. As a negative control, Potato Dextrose Agar (PDA Oxoid ®) was used for all fungal pathogens. Statistically representative data was obtained by repeating all processes four times.

RESULTS AND DISCUSSION □□

The fungi growth rate was measured on the second, fifth, and seventh day. The estimated percentage growth rate obtained indicated that the leachate inhibited the plant-pathogenic fungi. In analyzing the data, it was observed that growth on the second day for all *F. oxysporum* tests was similar. On the fifth and seventh day, all growth rates had increased for all tests.

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[214] M. Martinez, "Manual de laboratorio introducción a la biotecnología industrial." *CEJA.* (1999)
[215] See note 214.

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TIFF (Uncompressed) decompressor
are needed to see this picture.

Table 1. Growth Data of F. Oxysporum

The growth rates between treatments is shown in Table 1. They were below the positive control, meaning that the tomato leachate (Lycopersicom esculentum) inhibited growth of *F. oxysporum* on average by approximately 72.2%. However, what must be noted is that the liquid itself did not inhibit the growth. In all four experiments, a bacteria contained in the liquid grew around the pathogen blocking its growth. A sample of this bacteria was taken and seeded onto an agar plate slide. This plate was incubated at 37 ºC for 24 hours, after which evidence of colony growth was observed. To identify the bacteria, the following biochemical tests were performed:

Table 2. Bacteria Identification Tests

TEST	RESULT
Gram	Positive
Oxidase	_
Catalase	+
Citrate	+
SIM	+
TSI	+
Glucose	+
Indole	_
Urea	_
Coagulase	_

The test results are consistent with the microorganism *Bacillus sp.* which is sometimes used for the biological control of tomato cancer caused by the microorganism *Clavibacter sp*. Additionally, *Bacillus sp*. has been reported to control *F. oxysporum* in the vascular wilt of tomatoes. This study indicates that further research into the origin of the *Bacillus sp.* found in this study should be conducted. Leachate from Black Soldier Fly cultivation applied to Orchids in Vietnam has also been observed to inhibit growth of *F. oxysporum.*[216] This correlation could indicate that a symbiotic relationship exists between *Bacillus sp*. and *Hermetia Illucens* Larvae. The confirmation of this fact could lead to the development of a readily available source of leachate containing *Bacillus sp*. for application in agriculture.

In contrast, this study found that the leachate caused zero growth inhibition of *Botrytis cinerea* and *Sclerotinia sclerotiorum* as growth rate increases were equal to the positive control.

[216] See note 189.

CONCLUSIONS □□

From the results of this investigation it can be concluded:

1. The tomato leachate (Lycopersicom esculentum) from the black soldier fly cultivation process showed positive results in inhibiting the growth of plant pathogen *F. oxysporum.* □

2. In the in vitro test *Bacillus sp.* was observed to control the growth of *F. oxysporum*.

3. The leachate from the Black Soldier Fly cultivation contained beneficial biological organisms for disease control.

RECOMMENDATIONS

To identify the leachate components, it will be necessary to conduct a chromatographic analysis as well as a mass spectrometry analysis and determine what elements of the leachate have anti-fungal features and in what proportion these elements exist in the leachate.

It is also recommended that additional leachates be obtained from varying substrates used in black soldier fly larvae cultivation. The replication of these results and identification of *Bacillus sp.* in different leachates would likely indicate a symbiotic relationship between black soldier fly larvae and *Bacillus sp.*

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Study 4: Inhibition of Pathogens by *Hermetia Illucens* larvae.

Luis Fernando Tovar and Grant Everest Canary. 14 October 2008

Executive Summary

This study was designed to fulfill research aims nine and ten. In the study, Larvae were fed dried dog food that had been inoculated with *E. Coli* or *Salmonella spp*. The study analyzed the colony forming units (CFU) in both the dried dog food substrate and by liquefying larvae and conducting a microbiological analysis. The larvae were found to significantly reduce *E. Coli* populations but not eliminate them entirely. Results regarding the larvae's effect on *Salmonella sp.* were inconclusive. Following these results, it was demonstrated that to follow necessary food safety procedures, mature larvae must be cooked at 65ºC for a short period of time, or 49ºC for longer periods of time. This information informs the VENSIM models when considering cook time and utility costs.

The more innovative discovery in this study was the confirmation that Black Soldier Fly larvae can be fed food wastes *heavily* contaminated with *E. Coli* and *Salmonella spp.* without harm. Given recent scares in the United States about lettuce and spinach contamination, or the recent recall of 65 million kg of beef products contaminated with *E. Coli,* this study establishes that one market in which larvae cultivation can be used is to eliminate these hazardous food wastes. The source of this anti-bacterial effect was outside the scope of this experiment, however, other researchers have noted that the cuticle that coats larvae bodies often contains anti-bacterial substances. There is a likely linkage between the anti-fungal properties noted in study three and the anti-bacterial properties noted in this study. Further research is required.

MATERIALS AND METHODS

Bacteria strains

E. Coli and *Salmonella spp*. strains were supplied in Agar Plate Count from a microbiology laboratory. Replicas of each of strain were grown on Plate Count Agar (Merck) and Nutritional Agar (Merck). Bacteria were grown at 37 ° C for 48 hours.

Inoculums

For *E. Coli*, three initial samples of each bacteria strain were taken from the agar and were grown in MERCK TSB Broth (Casein-peptone soymeal-peptone broth) at 37 ° C for 18 hours without stirring. The same procedure was used for *Salmonella spp* but in this case BHT broth was used and the strain was incubated at 37 ° C for 24 hours.

Larvae Substrate

One kilogram of dog food was sterilized at 121°C and 15 psi for 40 minutes. After sterilization, it was hermetically sealed and left to cool in a refrigerator at 4°C for 24 hours. Later, the dog food was divided into 5 Ziploc bags and inoculated with bacteria. 0.200kg were inoculated with *E. Coli*. The inoculation was done by taking 50 ml of *E. Coli* broth culture and diluting it in distilled water to a total of 250ml, then adding it to the dog food. The same procedure was used for the *Salmonella spp.* inoculation. In both cases, the inoculated substrate was incubated at 37°C for 48 hours. Afterwards, tests were given to confirm the growth of bacteria on the substrate. In the case of *E. Coli*, a sample was taken and extensive growth was found on EMB Agar (Merck). *Samonella spp* growth was confirmed using SS broth (Merck). The SS broth showed a black color which confirmed *Samonella spp* growth.

Testing the Larvae's antibacterial effect

Eight 240 mL polystyrene containers with lids (Barval) received 25g of inoculated substrate (four containers per bacteria). In six of these eight containers 50 *Hermetia Illucens* larvae (removed from feed at 7-10 days) were added. The remaining two containers (one for each bacteria) were used as a control and no larvae were added. As a secondary control, two more containers received 25g of un-inoculated sterilized substrate, only one of these received larvae. All containers were kept in a refrigerator of the same material which was maintained at 30 ° C. The eight total containers were monitored for six weeks to assess the ability of the larvae antibiotic against the bacteria. The microbiological analysis described below was performed weekly to identify bacteria in the substrate. At the end of the six-week period, bacteria in the larvae were identified by removing four larvae from each container and liquefying them in 10mL of distilled water.

Bacteria Identification

The conventional methods recommended by the FDA[217] were used to identify coliforms, fecal coliforms, and *Escherichia coli* (MPN). The procedure recommended by the Food and Drug Administration (FDA) of the United States was followed[218] to isolate and identify *Salmonella spp.* This procedure calls for pre-enriching 25 g of the sample in peptonated water (the pH of the suspension of the sample was adjusted to 6.8 + 0.2). Following this, the sample was enriched in Rappaport-Vassiliadis Broth and Tetrationate Brilliant Green Broth, and then isolated using Sulphite Bismuth Agar, XLD Agar, Hektoen Agar, and then biochemically identified.

The Bacterias' Susceptibility to heat

Isolated bacteria were inoculated in Plate Count Agar, *Escherichia coli* and *Salmonella spp* were both grown for 48 h at 37°C and demonstrated the expected growth. To confirm the bacteria's susceptibility to heat, the bacteria were then exposed to escalating temperatures in the range between 50–80°C in 20 minute periods to confirm heat susceptibility.

RESULTS AND DISCUSSION

Analysis of E. Coli in Substrate

The unit of measure for bacterial growth or decline was the number of colony forming units (CFU). These were measured in both the substrate and the larvae (the latter at the end of the experiment). Figure 1 illustrates the decline of *E. Coli* in the substrate in two samples (shown in red and green) versus the control (shown in blue) during the weeks of the experiment.

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[217] P. Feng, S.D.Weagant, M.A Grant, "Enumeration of Escherichia coli and the coliform bacteria," *Food and Drug Administration* http://www.cfsan.fda.gov/~ebam/bam-5.html (accessed 18 Oct 2008).
[218] W.H. Andrews and T.S. Hammack, "Bacteriological Analytical Manual online," *Food and Drug Administration [Online]* (2007), http://www.cfsan.fda.gov/~ebam/bam-5.html (accessed 18 Oct 2008).

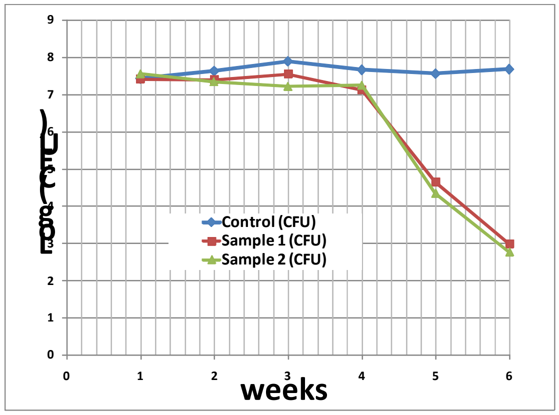

Fig. 1. Behavior of *E. Coli* found in the substrate during the weeks of the experiment.

In Figure 1, the control (in blue) confirms that there was no CFU decline from causes unrelated to the experiment because the control in which no larvae were present (in blue) had a relatively constant number of CFU throughout the experiment. In sample one and sample two (shown in red and blue) the larvae exhibit little effect on the bacteria growth for the first four weeks. However, at the four-week mark the bacterial population declines significantly. In the tests, the bacteria were not entirely eliminated. However, the antibiotic effects associated with the presence of the larvae are clearly perceived after the fourth week.

The timing of the CFU decline presents an interesting correlation with unconfirmed anecdotal evidence that described a mortality rate in the range of 80-90% when larvae before the third instar were grown on only meat substrates.[219] It could be possible that larvae are impotent or unable to disarm bacteria until the third instar. However, it could also be possible that larvae are simply unable to digest meat due to pH and rapid loss of moisture in the substrate. In later studies it would be advisable to monitor daily the CFU and to correlate the exact instar, as well as analyze exactly what antibiotic processes may be occurring in the larvae and when. Additionally, it would be advisable to design a methodology accounting for different sized populations of larvae to determine if a "critical mass" of larvae is necessary to control bacterial growth.

Analysis of E. Coli in the Larvae

At the conclusion of the six weeks, four larvae were removed from the tests to assess whether they had the presence of *E. Coli* on their body. Presence of the bacteria on the larvae could potentially cause problems for using the larvae as a protein source in animal feed. The results of the analysis are shown in Table 1.

larvae	CFU	Control
1	11	13
2	10	17
3	11	17
4	35	22

Table 1. CFU after 48 h incubation at 37 ° C for larvae in contact with *E. Coli* for 6 weeks

Table 1 shows that the Log of CFU counts are quite low when larvae were in contact with the bacteria. This evidence is indicative of the larvae's ability to inhibit the growth of *E. Coli*.

[219] Eliana Marcella Gamboa Rojas, Nicolas Jasbon Orozco, and Grant Canary, "Starches and Meat Wastes as Feed Substrates for Cultivating Black Soldier Fly" (*Hermetia Illucens*)" (research paper, U. Nacional: Bogotá, 2008)

These results are consistent with studies carried out by E. Ramos with other insects,[220] who noted that the cuticle that coats larval bodies possesses antibacterial substances and therefore the potential for pathogens is limited. Also in other studies specifically working with *Hermetia Illucens*[221] it was found that meal made from the larvae was *E. Coli* free and suitable for animal consumption.

Analysis of Salmonella spp. in Substrate

The procedure used for *Salmonella spp* was procedurally the same as that for *E. Coli*. The results are also presented in terms of colony forming units (CFU) and their evolution over time. Data from experiments is presented in Figure 2.

In Figure 2, the control substrate that was not exposed to the larvae is shown in blue. The control again demonstrates that there was no CFU decline from causes unrelated to the experiment. The other two lines (samples 1 and 2) show the growth/decline of the bacteria that were in contact with the larvae.

A look at Figure 2 shows that the *Salmonella spp* log CFU was in the range of 8.2 and 8.6, which corresponds to an order of magnitude of 10^8 CFU. This is not significantly different from the control because the order of magnitude is the same. This shows that the substrate fail to show the antibacterial activity sufficient to inhibit the growth of *Salmonella spp*. Figure 2 shows that although the order of magnitude between control and experiments with the larvae was not large, that after the 3 week-mark there was a minor decline in the CFU number compared to the control. Additionally, in weeks 5 and 6 the amount of *Salmonella spp* is beginning to decline further, so future studies should be conducted over a longer period of time as it is possible that the resistance presented by *Salmonella spp* may be greater than in the case of *E. Coli*. Regardless, in contrast to the *E. Coli* experiment, this result is not conclusive evidence demonstrating that larvae have antibacterial qualities against *Salmonella spp* over a six-week time frame.

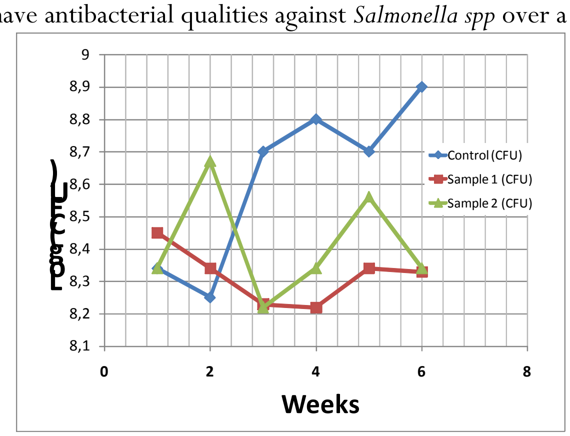

Fig. 2. ***Salmonella spp.*** **behavior, during experiment at substrate**

Analysis of Salmonella spp. in the Larvae

The presence of *Salmonella spp* in the larvae was analyzed in the same way the larvae were analyzed for *E. Coli*. For this analysis, two larvae were taken from each of the sample recipients and were compared with the un-inoculated control larvae. These results are presented in Table 2. Analysis of the table shows that in every case, the presence of *Salmonella spp* in the larvae was higher than in the control which denotes either a possible error in the method or that the bacteria grew in the larvae. This portion of the study is therefore not conclusive. It is suggested that specialized equipment and techniques with greater reliability are required to quantify the larvae's direct effect on *Salmonella spp*.

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[220] E J. Ramos "Insectos como fuente de proteína y sus aplicaciones," (presented at the Congreso de la Sociedad Colombiana de Entomologia conference, Cali, (2003)),

[221] See note 200.

larvae	CFU	Control (CFU)
1	3,39E+06	13
2	5,01E+06	17
3	6,31E+06	17
4	7,94E+06	22

Table 2. CFU after 48 h incubation at 37 ° C for larvae in contact with *Salmonella spp.* for 6 weeks

Despite these inconclusive results, the antibacterial effect of the *Hermetia Illucens* larvae on *Salmonella spp*, should not be wholly discounted. A review of literature shows that according to investigation done by G. P. Arango on larvae-meal, *Salmonella spp* was absent from the product.[222] However, this does not say whether the substrate was exposed directly to the bacterium. Additionally, studies done specifically for Salmonella spp enteric show excellent results.[223]

Due to these studies, crops lost to *Salmonella spp* should not be ruled out as a possible feed source for the commercial production of the larvae. In addition to treating mature larvae with heat, *Salmonella spp* contaminated substrates might also be biologically treated with other substrates that have shown promising anti-*Salmonella spp* effects. These substrates include carrots, which were shown to inhibit both *Salmonella spp* growth and other pathogens (*E. Coli*, *Listeria*, among others).[224]Positive results were also found in the use of garlic[225] and grape waste substrates[226] to inhibit the growth of *Salmonella spp.* Should these biological treatment methods fail, mechanical (physiological) treatment of the larvae by heat after consuming substrates contaminated with *Salmonella spp* was shown to eliminate 100% of all bacteria in the larvae.

Bacteria's susceptibility to heat

Bacteria were subjected to tests of 20 minutes at different temperatures, starting from the lowest temperature to ensure the proper conditions in the furnace in which these the tests were conducted. The results are presented in Table 3. The data is presented in colony forming units (CFU). In the tests, *E. Coli* did not demonstrate a high resistance to temperature. Temperatures higher than 55°C caused the significant decline of microorganisms to levels of less than 100CFU. Temperatures higher than 55°C caused the death of the microorganisms. Results of previous experiments[227] show that in a period of 2 hours at 55°C, the presence of *E. Coli* reaches undetectable levels.

Salmonella spp demonstrated greater resistance to temperature. Significant CFU decline did not begin until 60°C. At 65°C the decline was significant and higher temperatures caused the total absence of the microorganism. It is worth noting that the total time in which the bacteria is exposed to more moderate temperatures increases the antibiotic effect. A study done for different strains of *Salmonella spp* showed that at 49°C, with a total exposure time of 1 hour, that there is a significant decrease in the CFU of *Salmonella spp.*[228]

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[222] See note 200.
[223] See note 64.
[224] C H. Liao, "Inhibition of Foodborne Pathogens by Native Microflora Recovered from Fresh Peeled Baby Carrot and Propagated in Cultures." *Journal of Food Science*, 4 V72, (2007)
[225] M. Kumar, J.S. Berwal, "Sensitivity of food pathogens to garlic." *Journal of Applied Microbiology*, 84 (1998)
[226] Gokturk Baydar Nilgun and Sagdic O. "Determination of antibacterial effects and total phenolic contents of grape (Vitis vinifera L.) seed extracts," *International Journal of Food Science and Technology,* 41, (2006).
[227] C. Turner, "The thermal inactivation of E. coli in straw and pig manure," *Bioresource Technology* 84, (2002), p57-61
[228] J E Vancauwenberge, J. Rodney, and W.F. Kwolek "Thermal Inactivation of Eight Salmonella Serotypes on Dry Corn Flour" *Applied and Environmental Microbiology,* 42, (1981), p688-691

ESCHERICHIA COLI		
T (°C)	t (min)	CFU
37	Incubation	3,98E+05
50	30	5,01E+02
55	30	2,24E+01
60	30	0
65	30	0
70	30	0
75	30	0
80	30	0
SALMONELLA SPP.		
T (°C)	t (min)	CFU
37	Incubation	4,98E+06
50	30	3,93E+06
55	30	7,87E+05
60	30	3,93E+04
65	30	1,97E+02
70	30	0
75	30	0
80	30	0

Table 3. Temperature resistance of E. Coli and salmonella spp.

CONCLUSIONS

The experiment demonstrates that *Hermetia Illucens* larvae have an antibacterial effect against *Escherichia coli*. In this experiment this effect was observed after the fourth week of contact between the bacteria and larvae. After the fourth week, the CFU had significantly declined for the bacteria on the substrate and in the larvae itself there was total absence after six weeks.

In this experiment, there was no significant decrease of *Salmonella spp* in the substrate that was in contact with the larvae; however, due to the data, it is suggested that it is necessary to do further studies on the larvae's antibacterial effects using more rigorous methods

Finally, this experiment confirmed for posterity that at temperatures above 55°C there was no detectable CFU of *Escherichia coli*. In the case of *Salmonella spp*, greater temperature resistance was observed. However, at temperatures over 65°C the presence of colony forming units is barely detectable.

Future Research

The foundation for the future trajectory of research was laid by each of the four research studies conducted. These research studies developed significant process details, but additionally revealed where more research was needed. In the first study, the necessity to develop a database of substrates and their affects on larvae growth and composition was demonstrated.

The second study continued the development of details regarding the feed substrates effect on larvae growth and composition. It was learned that meat products, like fruit peels and yard waste is difficult for the larvae to process. Future research will likely inquire about the possibility of pre-treating these difficult wastes with mushrooms, bacteria, or vermiculture. The decomposition of these food wastes before being fed to the larvae may make them more digestible, as well as produce additional products and revenue streams.

In the third study, it was confirmed that the liquid waste from the process had possible applications as a field amendment to inhibit the *fusarium* plant pathogen in soils. However, field trials and studies of proper application are still necessary before this liquid waste can become a bi-product and revenue stream.

Finally, in the fourth study process safety procedures were established conforming to sub-goal C. More importantly, it was learned that the larvae can consume waste substrates contaminated with *E. coli* without harm. This opens up an additional market to receive *E.coli* contaminated wastes for treatment.

Additional areas for development of the process were revealed by the pre-investigation. There may be the potential for the larvae-meal production process to receive carbon sequestration credits if it is used to process animal manure. However, the manure will likely need to be mixed with additional substrates for optimum larvae growth and nutrient composition. The extraction of Chitin from the larvae to make it more palatable may also be a bi-product revenue stream.

To better understand the areas of innovation that are likely to proceed from this study, the existing process shown on the following page can be compared to the process below it in which the innovation areas are highlighted in green.

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TIFF (Uncompressed) decompressor
are needed to see this picture.

Above: the existing larvae-meal production process.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Above: the larvae-meal production process with innovation areas highlighted in green.

Other areas of future research will likely need to focus on the organization and layout of the waste processing facility with the bio-pods. The existing manner of laying out the bio-pods does not take advantage of vertical space, is space consuming, and does not permit maximum efficiency in loading and unloading the bio-pod. While adequate for small operations, larger operations will need to take this into consideration.

IV. Pilot Larvae-Cultivation Factory Design Description:

As described briefly in the state of the art section titled *Current Issues in Black Soldier Fly Research*, one of the biggest issues for the use of the bio-pod is that it was designed for the residential market to use in conjunction with a wild population of Black Soldier Fly. It had never been used in-series with a captive population of sufficient size to generate eggs for the operation of such a facility. To do this, it would be necessary to wed Sheppard and Tomberlin's rearing methodology and egg collecting methodology[229] with a self-designed factory layout of Dr. Paul Olivier's bio-pods used in series instead of as a residential unit.

Originally, the design and construction of a pilot facility was undertaken and intended to be an addendum to the larger thesis describing an appropriate layout for the bio-pods and reproductive chamber. However, as operations continued at the facility the experience became invaluable. Lessons learned at this facility included the amount of labor required to load and unload the bio-pods and this impacted in no small part both the VENSIM model and the business plan. Additionally, described in detail is the problem of capacity that the pilot facility revealed. For this reason, the description of the pilot facility is included in full in this analysis, but not in the scientific detail in which the articles in the previous section were conducted.

The pilot factory was constructed at the Universidad Nacional Sede: Bogotá. It was comprised of two greenhouses built side by side, each measuring 6m in width by 20m in length. The two greenhouses differ in that one was built of 3mm thick black polypropylene plastic and the other of a clear plastic, specifically Agrolene Verde MX (7.11m^2/kg). The clear plastic greenhouse was constructed for the aerial mating and egg collection of matured black soldier flies. The black greenhouse was built specifically to house the four-foot diameter bio-pods made by ESR International for the cultivation of larvae on food waste.

Temperatures in both greenhouses as well as in the bio-pods were measured using a Thermocrhon iButton product code DS1921H-F5. Humidity was measured using a Hygrochron Temperature and Humidity iButton DS1923-F5. Submerged temperatures and humidity inside the bio-pods were measured by placing a thermochron or hygrochron iButton in a Waterproof iButton Capsule DS9107. These devices permitted constant monitoring and readings were programmed to be taken every 10 minutes. Data was downloaded every week to excel spreadsheets using a USB converter device.

Description of the Larvae Cultivation Greenhouse:

Due to the photophobia of the larvae, the larvae cultivation greenhouse was constructed of black 3mm polypropylene plastic. Due to the larvae mortality rate when in Bogotá's cold average temperatures,[230] the black plastic also helped maintain the temperature at an average of 17.96°C based on 2048 readings over 11 days. However, the greenhouse was not a good insulator of the heat and temperatures at night often dropped below 14°C which was the lowest range of these particular iButton monitors. Suggestions to accommodate temperature drops are described in the suggestions section.

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[229] Dr. Craig Sheppard, Et. al. "Rearing Methods for the Black Soldier Fly," *Journal of Medical Entomology,* 39(4) (2002): p 696

[230] Victoria Gutierrez Baron, Natalia Sanchez Obando, Grant Everest Canary, "Degradación de residuos orgánicos mediante la producción de larvas soldada negra, *Hermetia Illucens,"* (Bogotá, Universidad de la Salle, 2008), 3

The 6m x 20m dimension of the greenhouse was found to be an appropriate size to house 24 four foot bio-pods in two rows of 12, with a 1.75m isle on either side of the rows, and end zones of 2m by 6m at either end of the greenhouse for storing of tools and materials.

To hold the bio-pods above ground, the 24 Bio-pods were raised in groups of three on specifically designed wooden racks approximately 77cm off the ground. Four racks each were placed end to end lengthwise to form two rows of 12 bio-pods. The raising of the bio-pods was required to accommodate the fitting of the collection jars underneath the bio-pods. Additionally, the raising served to protect the bio-pods from the entrance of spiders, lizards, snails, frogs, ants, rats, cats and dogs. To provide extra insure that these creatures did not enter the bio-pods, the feet of the racks were wrapped in plastic and placed in a 30 cm deep trough of water. The bottom of the trough was double lined in the same Agrolene plastic with which the clear greenhouse was built. A pool chlorine was added to the water to kill the algae bloom and other organisms that began to grow in the water despite the extremely limited sunlight. During the course of the investigation, frogs, snails, lizards, spiders, and predatory insects were discovered in the trough. Only a few spiders were ever found to have successfully entered the bio-pods. This was likely due to the lack of pre-fabricated lids that were later designed by the manufacturer. Additional problems included one instance in which a dog did manage to dig under the walls of the greenhouse seeking the dog food that was used as a substrate. However, due to the wooden racks, no damage or disturbance occurred to the bio-pods.

The four foot diameter bio-pods used in this experiment were fabricated as a part of the first ever production run by ESR International of a cultivation tank of this size. For this reason, pre-fabricated lids useful for trapping heat and protecting from predators were not being produced at the time these bio-pods were purchased and imported from Vietnam to Bogotá. To accommodate for this, lids were made using a circularly bent wire to fit around the lip of the bio-pod; fitted onto this wire using an overlapping 10mm sleeve was a circularly cut sheet of black 3mm polypropylene plastic. A latching mechanism of the same gauge wire affixed the circular lid to the lip of the wooden rack to hold the lid firmly down on the lip of the bio-pod. To improve ventilation and limit the condensation inside the bio-pods caused by the day-evening temperature shifts, a 30 cm by 15 cm square was cut out of the plastic lid and a 0.5 mm weave mosquito netting was affixed over it. Additionally, structural wires were affixed across the diameter of the bio-pod to give the lid a dome shape and eliminate the formation of moisture in the dead zones of the previously inversely dome shaped lid.

Additional modifications to the bio-pod included the attachment of a 2m long 2.5uvt, 40w, 110V heating coil attached to the walls inside an experimental bio-pod. Affixed to this coil was a 30A150 degree programmable Thermostat attached to a thermometer. The thermostat was programmed to cut power to the heating coil when the thermometer gave readings higher than 35°C. In this way temperature in the bio-pod was held close to within 35°C. Larvae placed in this bio-pod grew more rapidly and crawled out of the bio-pod approximately two weeks earlier than larvae placed in a bio-pod without these coils.

Larvae were collected using the manufacturer provided clear collection bucket and opaque vertically mounted tube connecting the bio-pod to the collection bucket. It was discovered that wrapping the clear jars in a black plastic bag and spraying the opaque tube with a dark plastic spray-paint resulted in greater crawl-off. This is likely due the larvae's photophobia. An additional benefit of this covering was that larvae left in the collection bucket for more than 15 days transformed to flies. These flies were transported to the mating chamber to allow adequate space for aerial mating.

Mating Chamber Description:

In contrast to the photophobic larvae, mature *Hermetia Illucens* flies require unblocked sunlight to reproduce. Cloud cover and glass and plastic that do not permit the penetration of UVB light has been informally referenced in several studies to prohibit mating.[231,232,233] This was discovered after construction of the greenhouse. The manufacturers specifications of the Agrolene plastic used described that the Agrolene Verde MX plastic permitted transmission of 82% of the light between 390-700mm. However, all UVB light is below 390nm. Therefore, two Sylvania Gro-Lux 39watt F48P12/G UPC 77020448242857 were mounted inside the 0.5mm weave mosquito netting rectangular cube that was constructed inside the large clear plastic greenhouse. These fixtures provide a limited spectrum of UVB light from 350nm to 750nm with a peak at 375nm[234]; however, to increase the range and the reach of the UVB light within the cube, these fixtures will be changed out for two Mega-Ray EURO SB 100 W 220V self-Ballasted Flood lamps that provide the full UVB spectrum (200-380nm) and are designed to be mounted eight feet above the growing area.

The rectangular cube described measures 220cm in width by 410cm length by 328cm height. This surpassed the minimum enclosure area required for aerial mating as described in previous studies.[235] To construct this vertically rectangular cube, at each of the corners guide-wires were attached to the metal buttresses at the roof of the greenhouse and then dropped down to the ground where they were fixed to stakes in the ground for tension. Additionally, a guide-wire was wrapped around the horizontal perimeter of the stakes on the ground and the horizontal perimeter of the buttresses on the roof. The bottom of the cube was made using the same clear Agrolene plastic; this was fixed to the horizontal guide-wires on the ground using a 10mm sleeve. To allow sunlight and proper ventilation, the walls and roof of the cube were fitted with 0.5mm weave white polypropylene mosquito netting that attached to the plastic bottom of the cube and was fitted to the vertical and roof guide-wires using the same 10mm sleeve technique. To prevent flies from escaping, the entrance to the enclosure was constructed as a dual door security system in which one unzips the first door, enters a chamber, re-zips the first door, unzips a second door and enters the enclosure zipping up the second door behind them. Both doors were made of the same 0.5mm weave mosquito netting.

The larger greenhouse was originally constructed to have side and roof ventilation. However, the greenhouse was hermetically sealed after initial tests revealed that the temperatures of the open greenhouse were insufficient for mating. The sealed greenhouse resulted in large temperature swings but an overall temperature within the 20-35°C range. To avoid temperature peaks over 40°C, a 10" Plastic Blade made by FZ product number EC-250 was connected to a programmable Digital Line Model LDTMGO SR 50C Max thermostat. When temperatures reached 35°C, the fan was activated and began pumping air out of the greenhouse. Future recommendations for control of temperature swings is covered in the suggestions section.

As adults, the flies require no food; however, water is necessary for the flies to survive for their full life-span in the hotter peak temperatures of the hermetically sealed greenhouse. To accommodate this, a 150-gallon water fiberglass water tank was attached to a floating valve (the same as in a toilet) which was connected to the agricultural water supply of the Universidad

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[231] Donald Booth and Craig Sheppard, "Oviposition of the Black Soldier Fly, Hermetia Illucens (Dipitera: Stratiomyiade): Eggs, Masses, Timing, and Site Characteristics," *Environmental Entomology* 13, (1984), p423

[232] Dr. Paul Olivier, Personal Correspondence with the author, Telephone interview, 1 September 2008.

[233] See note 191.

[234] "Spectral Power Distributions of Sylvania Fluorescent Lamps," Sylvania Inc, Technical Information Bulletin, p 10.

[235] See note 191.

Nacional. Water from this tank was pumped through a 1.5" diameter plastic tubing by a Clean Water Pump QB-70, 50 Hp, 110V manufactured by Saco. The tubing entered the aerial mating enclosure 70cm above the ground and affixed in the tubing were two ¼" thread nozzles manufactured by Intecmecol and designed to aerially distribute 4 Lt./Hr in a 60cm radius. Water droplets collected on the mosquito netting walls of the enclosure as well as on two plastic plants placed below the nozzles. Water dispersal was controlled with a programmable FD60-U5 digital timer manufactured by UL. Water was dispersed for 7 minute cycles twice daily.

Each of the plants below the nozzles were 80-90cm in height and had 10-20cm diameter leaves resembling English ivy. The leaves are critical for the mating behavior in which male flies territorially defend a leaf and when other flies land upon it, males are grappled and fought off while females are grappled and the two eventually descend *in copula*.[236]

It was observed that the flies made little effort to avoid water and could actually drown in puddles that formed on the plastic lined enclosure bottom. To accommodate for this, pea gravel of 1-3cm in diameter was placed in areas where puddles were known to form. This allowed flies that fell into puddles to crawl on the rocks and dry their wings.

After failures with other designs for pupating larvae incubation, a single bio-pod of four feet in diameter was placed in the enclosure after fly emergence began to occur. This permitted crawl-off larvae to pupate and emerge as flies without manual transfer from the larvae-cultivation greenhouse to the mating chamber which caused a delay. Additionally, wastes deposited within the bio-pod created an attractive egg-laying site for fertilized females.

Operation:

The bio-pod designed by ESR solved the first problem of industrial larvae-cultivation. This was a design problem in which there was no device for the reliable collection of the larvae from the food-waste substrate. While the bio-pod resolved this, it was designed for a residential user or a hobbyist in conjunction with a wild population of black soldier flies, not for in-series industrial use exceeding two units with a controlled population. The aim of this pilot plant design was to wed the egg collection designed and rearing methods outlined by Sheppard and Tomberlin with the in-series use of multiple Bio-Pods designed by ESR International to create a captively managed black soldier fly population and larvae production process.

The egg collection method described by Sheppard and Tomberlin was the key link in linking the two methodologies. In this method, "flutes" of 2-3 layers of corrugated cardboard or plastic are mounted on steaks in the wild above a food waste substrate. Females are attracted to the waste, but seek to lay fertilized eggs in a dry place above the waste. Therefore the edges of the corrugated cardboard serve as natural cracks in which females insert fertilized eggs. This method was adapted and flutes of corrugated cardboard were hung above the waste in the bio-pod. Additionally, steaks with flutes of corrugated plastic were stuck in the waste.

The operational procedure that arose through evolution was to remove a percentage of the crawl-off larvae from bio-pods in the cultivation greenhouse and place them in a sawdust bed with heating coils that maintained a 30C temperature. These flies emerge and eventually mate and lay eggs in the flutes mounted in the bio-pod. When sufficient egg clutches are in the flutes, they are then removed and transferred to the bio-pods in the larvae-cultivation greenhouse where they are

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[236] Jeff Tomberlin and Craig Sheppard, "Lekking Behavior of the Black Soldier Fly (Dipitera: Stratiomyiade)," *Florida Entomologist*, 84(4) (2001), p729

grown and crawl-off thus continuing the cycle. Egg Clutches are groups of an average of 998 eggs.[237]

Observations & Suggestions:

In the development of this pilot plant, several key observations and suggestions are recorded below:

Suggestions & Observations Regarding the Larvae Cultivation Greenhouse:

1. It is recommended that all bio-pods are fitted with a mechanical means of temperature control. This could be a heating coil mounted on the interior walls of the bio-pod or gas heated forced air ducting that is connected between the bio-pods. This would assist in the control of low-night time temperature swings inside the larvae-cultivation greenhouse.

2. A cleaning procedure was developed to eliminate moldy substrates without losing developing larvae. The procedure utilizes temperature within the bio-pod to cause immature larvae that would not normally crawl out to crawl out to avoid the heat. At exact temperatures, the larvae crawl-out can exceed an estimated 95% of the population. Because most of the population is evacuated, cleaning of the bio-pod can occur without loss of population.

3. The collection jars that received drained liquid from the bio-pod collected liquids properly but were time consuming to empty and replace. It is suggested that a singular plumbing system to connect the liquid drainage of an entire row of 12 bio-pods be devised. This would eliminate the need to collect liquids manually. To accompany this, the drains in the bio-pod must be relocated to form a line perpendicular to the crawl-off hole. Currently they are aligned in opposite.

4. To reduce water use, it is recommended that roof water run-off be used to supply protective troughs in the larvae-cultivation greenhouse. This was discovered during an incident in which a leak in the roof from storm damage kept water levels at near perfect levels for a number of weeks. However, it is suggested that troughs be fitted with overflow drains to avoid swamping the facility.

5. To eliminate the use of chlorine in the protective trough, research into the use of plants and fish in the trough to control algae and mosquito larvae is suggested.

6. Further research must be conducted into the vertical stacking of bio-pods to reduce the large quantity of horizontal space that the devices require.

Suggestions & Observations Regarding the Mating Chamber

1. It is suggested that research be conducted to determine if plastic that does not block UVB light exists for construction of the greenhouse.

2. It is additionally suggested that methods for better insulating the greenhouse should be examined. This would allow the use of passive solar technologies to minimize night-time temperature drops. Passive solar technologies use columns of glass with water or concrete to absorb heat in the day and release it at night. This would provide a more energy-conscious method

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[237] Donald Booth and Craig Sheppard, "Oviposition of the Black Soldier Fly, Hermetia Illucens (Dipitera: Stratiomyiade): Eggs, Masses, Timing, and Site Characteristics," *Environmental Entomology* 13, (1984), p421

to keep night-time temperatures high. Failing this, it is suggested that a gas heated forced air system be used to keep temperatures at appropriate levels at night.

3. Additionally, it is suggested that an industrial dehumidifier be attached to the mating chamber. Condensed water should be expelled to the protection troughs in the larvae-cultivation greenhouse.

4. It is suggested that future designs use dual fans at each end of the greenhouse that are activated by temperature controls. One fan should export air, the other should import it for more rapid cooling in the event of a temperature spike.

5. Finally, it is suggested that white, not grey gravel be used on the floor of the mating enclosure. This would aid operators to avoid trampling black adult flies resting on the ground. Grey gravel makes this more difficult.

General Suggestions:

Because manual retrieval and downloading of the iButtons used to monitor temperature and humidity in all cases causes a delay, it is recommended that a wireless 1-wire system that downloads remotely be used in future operations. This system incorporates the iButtons, but information is available via a wireless download at great distances. Additionally, the system includes alarms which notify the operators email if temperatures or humidity exceed desired levels, which is usually the result of malfunctioning equipment.

V. Development of the VENSIM Models

As a part of this analysis, two models were developed using VENSIM feedback modeling software. The purpose of these models was, much like Gulino et. al's VENSIM model of the wood blinds company,[238] to understand how relationships and management of the system affects the outcomes. In the first model, the sustainable or unsustainable management of the sources of fishmeal affects the price of fishmeal over time. The price of fishmeal affects the price of larvae-meal as it is a substitute good. In the second model, the forecasted price from the first model is used to determine the profitability of larvae-meal production. The supporting process details that have been developed throughout the paper in the introductions, pre-investigations, lab research, and pilot operation inform this second model.

Model 1: Explanation of the Fishmeal Management & World Price Model

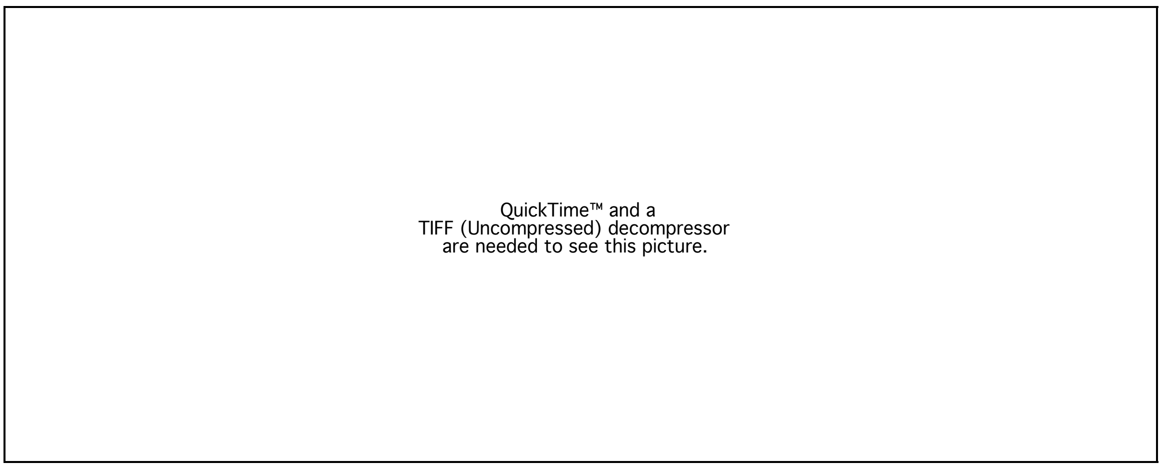

Figure 1: Modeling FM Price as a Function of Aquaculture Growth and FM Production Sustainability

The Fishmeal World Price Model: The Components

Essential to the goal of developing a larvae-meal production process is the understanding if there is a market. As discussed in the pre-investigation and the six substantiated claims regarding the macro distribution of food, the aquaculture industry will continue to exhibit strong growth to meet the demands of a growing population for food if it has a supply of feed for the fish. Indeed the pre-investigation convincingly argues that it is the only industry with the capacity to do so. The question quickly becomes what will the supply of fishmeal for the aquaculture industry look like over the next five to ten years. This answer about supply is what determines the price of fishmeal over the next five to ten years. If sustainable management decisions are made the supply will be low and prices will go up. If unsustainable decisions are made the supply will be high for a few years and prices low, followed by a number of years of extremely high prices and market shocks due to the unavailability of fishmeal. The price of fishmeal, which is assumed to be the price of a larvae-meal substitute, can therefore be forecast as a dynamic system. Below, the same image of the system is broken into discrete components for better comprehension.

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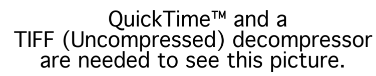
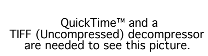
[238] Edith G. Guilno, Claudio Dottori, Edgar Willis, and Francisco Vergara, "Análisis de una empresa del sector maderero desde la dinámica de sistemas," Revista de Dinámica de Sistemas, 2 (2006)



Above: The fishmeal management bubble, aquaculture demand bubble, and economic variables.

Above, the blue bubble is where the fishmeal supply decisions are modeled. This is a classic feedback loop in which over-production results in depletion of the resource. The green bubble is the aquaculture industry's demand as a function of its growth rate. The growth rate can be adjusted for different assumptions and scenarios. The purpose of the model is to show the difference in supply versus demand as highlighted by the circled "unsatisfied demand." By knowing unsatisfied demand, an educated guess can be supplied for the elasticity of demand, and a percent change in price can be found. This percent change is an annual function of the unsatisfied demand.

The innovative aspect of this model is shown in the figure below. In this figure, the fishmeal supply shown in blue is capped. Without destroying the sources of fishmeal the worldwide supply cannot grow at the same rate as the aquaculture industry over the long term as it normally would. This would normally result in a stagnation of the aquaculture industry due to the lack of supply. However, as was discussed in the pre-investigation, because the aquaculture industry is vital to adequate world food supply, its stagnation would result in famine and hunger in many parts of the world as population grows. Therefore, as noted by the arrow in the figure, there is a large market opportunity for a substitute good.

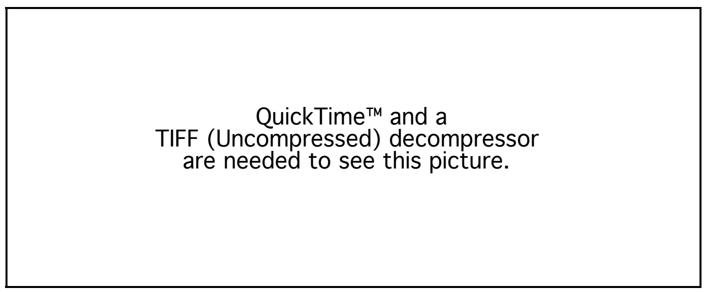


The innovative aspect of this model is that substitute goods normally enter the market because they are cheaper or better in some way. This model recognizes that because an eco-system's provisioning services are maximized, that a new product *must* come onto the market to support the existing market systems as there are no existing alternatives. By modeling the management decisions of the old product, one is able to determine the supply as a function of its poor or efficient management. This enables more accurate forecasting of the market price of the old product and a basis for a market price estimate of a substitute product. This enables accurate planning and development of a substitute good based upon the market price of the old good as a function of management.

As industry's continue to shift due to sustainability problems, this is likely to be a model archetype and an innovation to the field of logistics. Many of our industries, such as the automobile industry, have become essential yet rely on unsustainable resources such as petrol. Substitute goods will need to come to market and the market prices which they receive will be a function of the management of the previous resource—in this case petrol. This systems model archetype has the potential to be very useful in the timber industry and all industries that rely on oil such as the fertilizer and pesticide industry for starters.

Having explained the innovation inherent in the first systems model and the connection to the second model, the details of the first model can best be explained by breaking the model down into three distinct subsystems and explaining each of the variables in the system. As shown in the previous figure, the three subsystems are the production of fishmeal, the growth of the aquaculture market, and the economic equations that model unsatisfied demand and the accompanying price movement. The ultimate result of the model is a fishmeal price forecast. However, the beauty of modeling the system is that by using assumptions, one can establish different scenarios and adjust the variables to meet these scenarios and forecast price. Following the definition of the variables and a validation of the model using historical data, three scenarios will be constructed and their underlying assumptions explained. The accompanying prices forecast by these assumptions are used in the business plan to forecast the company financials.

Subsystem 1: Fishmeal Production



This is a classic subsystem describing the sustainability of the fishmeal industry. The more fish that are harvested for fishmeal, the fewer fish are able to reproduce and restock. Therefore if there is over-fishing, the production of fishmeal decreases in subsequent years. The model takes a macro approach and utilizes fishmeal's historical percentage of total world catch. Data for stock levels of each individual species of fish used for fishmeal were not available and were outside the scope of the research. Additionally, due to the oceanic food-chains which link fish species in specific eco-systems, the collapse of one species leads to collapse or slower recovery and regeneration of another predatory or co-dependent species. Therefore, this model may be more appropriate than attempting to isolate individual species without considering other species in the eco-system.

The components of the system are described as the following:

recovery constant (aux variable) = RANDOM UNIFORM(0.04, 0.09, 30)
The recovery constant is an auxiliary variable that randomly changes between 4% as a minimum and 9% as a maximum. The seed value, which is a randomly selected number the random uniform algorithm begins with, is arbitrarily selected at 30. This auxiliary variable is defined in this way to account for unpredictable events such as el niño and la niña, or pollution causing different rates of recovery etc. Given the disruption of the oceanic food chain and attacks at all levels of fishery food ladders, real recovery rates are widely discussed and uncertain. As discussed in the pre-investigation, some stocks of fish including those used for fishmeal have still not recovered and it is uncertain if they ever will. This approach using the random uniform is taken because modeling all the variables that account for fish recovery rate is outside the scope of this research.

rate of recovery (rate) = (recovery constant)*potential fish
The rate of recovery is the recovery constant percentage, as defined above, multiplied by the potential fish level. In other words, there is greater recovery if there are more fish in the ocean to reproduce.

potential fish (level) = +rate of recovery-FM production rate

initial value = 93.8

This level is set initially at 93.8 million metric tons, the total capture of fish in 2005 according to the FAO report *The State of World Fisheries and Aquaculture 2006* on page 19.[239] Added to this amount every year is the fish that have recovered, found by the rate of recovery. Subtracted from this amount is the production of FM. What occurs with this level is that if the FM production rate exceeds the rate of recovery, there are fewer fish available the following year to be removed for FM.

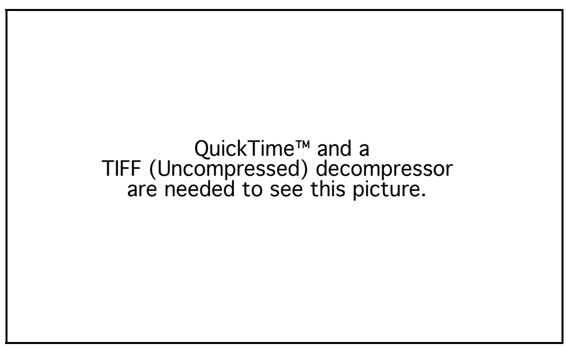
percentage fish destined for fishmeal (aux variable) = 0.064

This auxiliary variable can be changed to model for sustainable or unsustainable fishing. At its initial value of 6.4% it models that 6.4% of world fish capture will become fishmeal.[240,241] If this is increased beyond 6.4%, the level of potential fish drops for the following year, resulting in a constantly decreasing amount of FM available each subsequent year.

FM production rate = potential fish*percentage fish destined for FM

The fishmeal production rate is simply the amount (percentage) of world fish capture that is caught by fisherman specifically to produce fishmeal.

Subsystem 2: Growth of the Aquaculture Market



adjustable percentage increase (aux variable) = 0.04

This variable is a simple adjustable variable that while the model is running in VENSIM, can be changed. It is set at 4% as this is what former FAO official Izzat H. Feidi estimates as the minimum growth rate required to keep up with the growth of the primary producing countries.[242] The actual annual growth rate for aquaculture since 1970 on average is about 8.8% per year.[243]

growth rate (rate) = aquaculture market size*(adjustable percentage increase)

Quite simply this is the size of the present aquaculture market in million metric tons, multiplied by a percentage to find the annual million metric tons of production growth.

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[239] FAO corporate document repository, "The State of World Fisheries and Aquaculture 2006," *FAO Fisheries and Aquaculture Department*, (2007) www.fao.org/docrep/009/a0699e/A0699E00.htm (accessed 19 Sept 2008), p 19

[240] This number is arrived at by the equation (6 MMT / 93.8MMT). 6MMT corresponds to the average FM production between 2002-2005 (see note 194, see note 198) and 93.8 corresponds to the total capture of fish in 2005 (see note 192)

[241] See note 160.

[242] See note 141.

[243] See note 141.

aquaculture market size (level) = growth rate

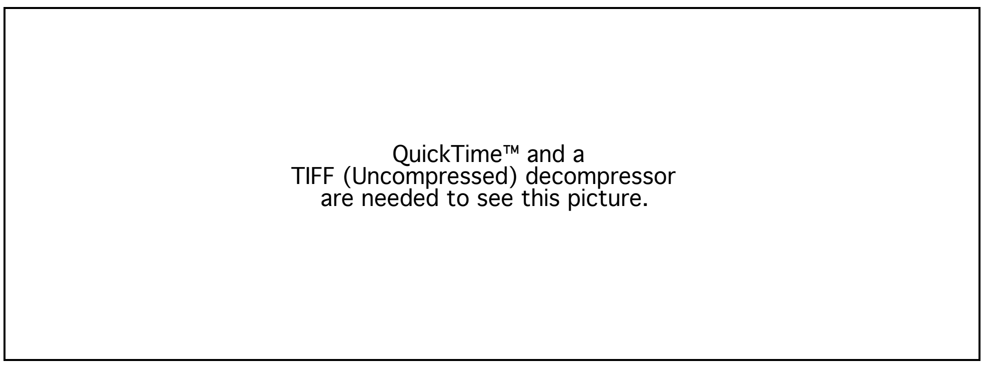
initial value = 47.8

As described above, the aquaculture market size is the present size of the market, added to the annual growth in million metric tons of fishmeal produced. The starting value is set at 47.8 million metric tons, the size of the aquaculture market in 2005 according to the latest data available from the FAO.[244]

FM demand (aux variable) = aquaculture market size*0.13

Assumes that the ratio of 6/46 (6MMT / 45.5 MMT)[245,246,247] is roughly the constant ratio of demand for the fishmeal fixed to current fish production. Therefore, the larger the aquaculture market size, the greater the demand for more fishmeal. This assumes aquaculture companies would ideally like to maintain the current percentage of FM in feed because all known protein substitutes are at this time inferior substitutes as quoted by Ronald Hardy on page 413 of his assessment.[248]

Subsystem 3: Unsatisfied Demand and Price Movement



unsatisfied demand (aux variable) = FM demand-(FM production rate*0.6)

The 0.6 assumes that Aquaculture will never capture more than 60% of the market of FM because it competes against pig and poultry production whose elasticity of demand is also very inelastic (an average of the five largest fishmeal producing countries shows an average elasticity of demand to be 0.24)[249]. This assumption is established to avoid modeling poultry and pork industry growth, demand, and potential substitute products which are outside the scope of this investigation. The confirmed maximum percentage of produced fishmeal that aquaculture has ever purchased is 53.2% in 2003.[250] Therefore, the assumed maximum percentage of fishmeal consumed is deemed to be a high-end maximum estimate.

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244 See note 160.

245 Fishmeal Information network, "Fishmeal and Fish Oil: Summary," Fin: Facts and Figures, http://www.gafta.com/fin/index.php?pge_id=14 (accessed 12 feb 2008).

246 The data 6 MMT is taken from the quote: "Worldwide production has fluctuated between 5.9 and 6.2 million tonnes over the last five years, 2002-2007," (See note 198).

247 The data for 45.5 MMT is taken from Table 1 of the State of the World Fisheries and Aquaculture 2006. Values between 2003 and 2005 world aquaculture production are 42.7, 45.5, and 47.8 MMT respectively. (See note 192)

248 Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006), p 413

249 Ragnar Tveteras, Sigbjorn Tveteras, Elin H. Sissener, "*Modeling Demand for Fishmeal using a Heterogeneous Estimator for Panel Data," Centre for fisheries Economics Discussion paper No. 20* (2002), p 17

250 Albert Tacon, Mohammed Hasan, Rohana P. Subasinghe, "Use of Fishery Resources As Feed Inputs to Aquaculture Development: Trends and Policy Implications," (Rome: Food and Agriculture Organization, 2006), p35 ftp://ftp.fao.org/docrep/fao/009/a0604e/a0604e00.pdf (accessed 13 Feb 2008).

FM elasticity of demand (aux variable) = RANDOM UNIFORM(0.15, 0.95, 0.45)
This auxiliary variable assumes that the elasticity of demand will fluctuate between a minimum of 0.15 and a maximum of 0.85 with a seed of 0.45. The seed is simply the starting number from which the random algorithm will function.

The reason for the assumption of elasticity of demand is that the average value for the elasticity of demand from 1989-2007 was 0.55 (absolute value). Tveteras, Tveteras, and Sissener (2003), corroborate this through their own complex economic footwork, and calculate the average absolute value of fishmeal elasticity of demand for five countries to be 0.66. The historical model that verifies this FM World Price Model has functioned exceptionally to model historical prices with a minimum 0.4 less than the average elasticity of demand and a maximum of +0.3,.

Percent change in price (aux variable) = unsatisfied demand/FM elasticity of demand
Elasticity of demand is found as the (%ΔQ / %ΔP) where Q = quantity and P = price. Therefore, changing the equation to solve for the % Δ in price can be done when one knows the elasticity of demand and the change in quantity. Our elasticity of demand is found using historical production and price data, and verifying these elasticities using the 2003 study by Tveteras, Tveteras, and Sissener.[251] The % Δ Q is the amount of FM that would be produced if supply was not limited—in other words, the unsatisfied demand due to the growth of the aquaculture industry is our change in quantity. Solving using unsatisfied demand as the change in Q gives us the % Δ in P if that quantity existed. Since it does not exist, we have an estimate for the % increase in value of the existing fishmeal as a function of unsatisfied demand.

Rate of change (rate) = Price*(percent change in price/100)
The rate of change uses the 'percent change in price' found above, divides it by 100 to make it a decimal percentage, and multiplies it by the existing price level.

Price (level) = +rate of change
Initial value = 1175
The initial price level of a metric ton of fishmeal is set at USD $1100 in accordance with the average price of 2007.[252] As aquaculture demand for FM increases it increases the 'percentage change in price' as shown above and this percentage increase in price is multiplied by the existing level to find the 'rate of change' in dollars (above). Finally the increase (or decrease) is added to the existing price level driving it up or down.

[251] See Note 216.
[252] See Note 160.

Model 1a: Validating the Model Using Historical Data

Validating Model As Viewed with VENSIM Software

The model shown above is based upon the FM World Price Model, but uses historical data for FM production, adjustable price increase, FM elasticity of demand, and the "% of market" when the data for this latter variable is available. The result is a historical model of FM price for the years 2001-2005.

The changes to the model from the original listed below are the following:

"FM production" (Aux Variable/Lookup) = Time
Lookup = ([(0,0)-(10,10)],(1,5.99),(2,6.2),(3,5.26),(4,6.19),(5,5.87))
The production data comes from an unpublished document by Helga Josupeit, an FAO fishery industry officer.[253] At T=1 production was 5.99 MMT, at T=2 6.2MMT, so on and so forth.

"% of market" (aux variable/lookup) = Time
Lookup = ([(0,0)-(10,10)],(1,0.41),(2,0.34),(3,0.37),(4,0.4))
The percentage of the world production of FM is found using historical data from multiple sources. In 2001, we see that 41% of FM produced was used by aquaculture;[254] in 2002, 34%;[255] in 2003, 37%;[256] and in 2004 no data was available and it is estimated to be 40%

"adjustable percentage increase" (aux variable/lookup) = Time
Lookup = ([(0,0)-(10,10)],(1,0.065),(2,0.056),(3,0.065),(4,0.05))
The percentage increase is found through the simple calculation of the previous year's production of aquaculture divided by the following year's production. This data comes from the FAO report: The State of World Fisheries and Aquaculture 2006.[257]

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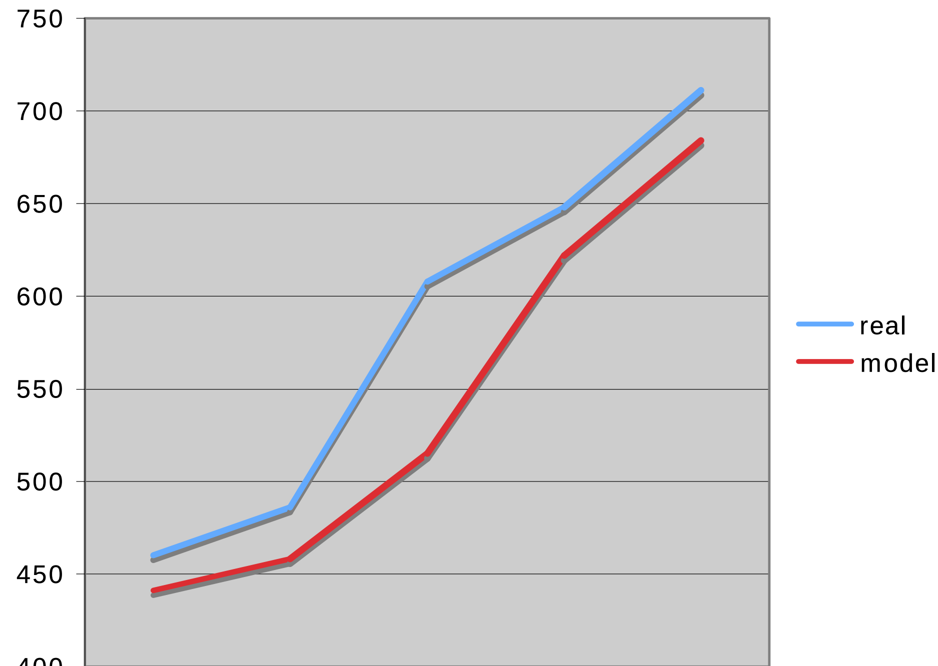
[253] See note 160.
[254] Dadi Kristofersson and James L. Anderson, "Structural breaks in the Fishmeal – Soybean Meal Price Relationship," *Department of Economics and Resource Management, Agricultural University of Norway*, (2004), p 7
[255] See note 178.
[256] Giovanni Serrini, Skretting Italy. "Future Aquaculture" (presentation by Skretting Inc., Duino, Italy, 14-15 Sept 2006).
[257] See note 239.

The initial values changed in the levels are that of "price" which has been changed to 412 USD, the average for 2000;[258] and, the initial value of "aquaculture market size" which has been changed to 37.9 MMT which was the aquaculture industry's size in 2001.[259]

In the verification of the model, we see that the model's prediction of Fishmeal price given the initial data closely represents the actual price between the years of 2001-2005. The table below the graph shows the model price in USD compared to the year's real average price.



	1	2	3	4	5
real	460	486	608	648	711
model	441	458	515	622	684

Underlying Assumptions of the Fishmeal World Price Model

Having validated the model, it is important at this point to clarify the underlying assumptions. One of the primary assumptions is that there are limited substitutes for fishmeal in the aquaculture industry as well as the poultry and pork industry. Due to this fact, the three industries compete for fishmeal in their feeds.

This relationship is mathematically translated into two auxiliary variables, the "FM Elasticity of Demand" which randomly fluctuates between two fairly inelastic boundaries and the auxiliary variable "unsatisfied demand," where the total fishmeal produced is multiplied by 0.6. In this second variable, the 0.6 signifies an assumption that the poultry and pork industries that compete for fishmeal will together maintain at least 40% of the consumption of fishmeal (1-0.6=0.4).

As discussed in the introduction and pre-investigation, while certainly aquaculture and pork and poultry can decrease their use of fishmeal to some extent and use other protein sources, they cannot

[258] See note 160.

[259] See note 160.

replace it entirely. To date there is no equivalent replacement that can totally replace fishmeal without inferior growth, inhibition of growth, higher risk of disease, or some other negative detractor.[260] In a report assessing alternative protein meals for suitable use in aquaculture, Ronald W. Hardy sums up the situation by writing the following,

> "If alternative protein sources were equal or superior in nutritional and economic value to fishmeal, they would already be widely used in aquafeeds. All common protein sources possess characteristics that make them inferior to fishmeal."[261]

This comment leaves no doubt about the current dominancy of fishmeal in animal feeds. However, this assessment made by Hardy does not include larvae-meal. Shortly after writing this paper in 2006, Hardy went on to study and co-author a paper on the use of larvae-meal to feed rainbow trout in 2007. Eventually, insect-based feed will become accepted into the animal feed industry; however, whether it will be accepted as a complete substitute for fishmeal requires additional research. Insect-based feed is slowly undergoing the exhaustive test of time and accompanying research analysis, much as a good book becomes a trusted classic.[262] A discussion of the business principles surrounding this delay in product trust is discussed in the business plan included in this analysis.

Regardless, the purpose of this thesis is the analysis of the profitability of insect based feed production and the design of an industrial process. Because alternative sources that are not complete substitutes to fishmeal have so far not been found, the Fishmeal Management World Price Model uses "phantom market growth" as opposed to what is possible due to the lack of other sources of protein. The term phantom market growth is used to describe the price that would accompany the absolute minimum growth rate in order to maintain food production with population and safeguard current market conditions; not what can be produced by the aquaculture industry given fishmeal supply and the price that would accompany that production.

The model is structured this way because the purpose of the Fishmeal Management World Price Model is to obtain a realistic price by which to determine the profitability of insect-based feed. If this price is to be realistic, it must be assumed that a combination of factors such as the use of other inferior feeds and the quantitative entrance of insect-based feed to the marketplace or some other 'X' factor is permitting the aquaculture industry to grow under "semi-normal market conditions." These normal market conditions can only continue when the aquaculture industry maintains a minimum percentage growth per annum. A greater discussion of the 'X' factor is included in the following section that discusses two scenarios for fishmeal price that were constructed using the model.

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[260] Note: Insect meal has not been qualified in this comment as it has not been produced in significant volume to be considered a replacement, nor has it undergone the exhausting testing required.

[261] Ronald Hardy, "Worldwide Fishmeal Production Outlook and the Use of Alternative Protein Meals for Aquaculture," (Boise: University of Idaho Aquaculture Research Institute, 2006), 413.

[262] Two companies, BioSystems Design which is owned by the author, and its competitor Neptune Industries are in the process of developing insect-based meal on an industrial scale. As of the 11th of June 2008, Neptune Industries had signed a letter of intent to provide 40 metric tons of Ento-Meal™ to Zeigler Bros, Inc. in 2009. (see note 168).

High and Low Price Scenarios For Fishmeal Production

The following analysis uses the Fishmeal Management World Price Model to construct two scenarios. In the first, the underlying assumptions of the model are geared toward producing the lowest foreseeable FM world price. In the second, the assumptions are geared toward a higher fishmeal price. Together the two forecasts form a range which is used in the business plan to build financials based on these best and worst case scenarios.

Scenario 1: Low-End Fishmeal Price Scenario

In the low-end price scenario, we assume that the aquaculture market will experience zero growth over five years. A limitation of the model, it is not designed for negative aquaculture growth because this would require modeling the increased market share that poultry and cattle feeds would begin to consume. This is outside the scope of this analysis. However, it is reasonable to assume that zero growth is a realistic floor. Aquaculture operations that close in the United States[263,264] will permit the Asian aquaculture market to grow slightly. It is presumed that on a macro scale the Asian market wouldn't be able to grow without the fishmeal made available from the aquaculture closures in the US.[265] Therefore the two markets will balance and the "adjustable percentage increase" will equal 0.

In this scenario in order to produce constant results the "FM elasticity of demand variable" is no longer a random uniform command, but is set at the highest acceptable elasticity (0.95) as established by Tveteras in the 2003 study. This is done because FM will become a more and more elastic good as producers assess feed prices and make the decision to transition to corn production.

In order to produce constant results, the fish "recovery constant" variable is set at a conservative constant of 0.5 instead of a random uniform command. This is slightly higher than the lower limit of the range previously used.

Finally, we assume that in an uncertain market where production is transitioning from the US to the already strong Asian market, that no new catch limits or sustainability controls are established other than what exists. Therefore, the "percentage fish destined for FM" variable is unchanged. This results in slow fish population decline each year resulting in a slightly unsatisfied demand which drives FM prices up over small increments each year. The variable changes are thus:

"adjustable percentage increase" = 0
"FM elasticity of demand variable" = 0.95
"recovery constant" = 0.5

In this low-end price scenario, the model predicts the yearly average prices for years one-five are:

Yr. 1: $1207 / MT (an avg. increase of $32 from $1175)
Yr. 2: $1241 / MT (an avg. increase of $34 from Yr 1)
Yr. 3: $1276 / MT (an avg. increase of $35 from Yr 2)
Yr. 4: $1313 / MT (an avg. increase of $37 from Yr 3)
Yr. 5: $1352 / MT (an avg. increase of $39 from Yr 4)

[263] See note 158.
[264] See note 159.
[265] See note 168.

Scenario 2: High-End Price Scenario

In this scenario, we make a conservative estimate that the aquaculture industry continues to grow at a 2% annual growth rate ("Adjustable percentage increase" = 0.02). As discussed, this is not estimated to be enough to keep pace with world population demands, however, it's far lower than the 8-11% annual growth over the last thirty years. The source of the growth assumes that feed producers begin mixing less and less fishmeal with the feeds to stretch supply.[266] What also may occur is the emergence of homemade feeds in Asia as has occurred historically.[267]

Additionally in this scenario, our "recovery constant" variable is again left at 0.4 and we assume that the no new sustainability controls are enacted and that the "percentage fish destined for FM" remains at 0.64, which is a slightly more than sustainable level. The big key in this scenario is the FM elasticity of demand. As this is the high-end price scenario, it will be set at 0.25 which is slightly lower than the lower limit of 0.15 established by the Tveteras study. This relies on the stretching of the fishmeal supply, and assumes that some aquaculture producers may decide to transition or cut feed despite negative effects on yields, and that homemade feeds may relieve some pressure on the FM supply.

Reviewing the changes to the model are:
"Adjustable percentage increase" = 0.02
"recovery constant" = 0.4
"percentage fish destined for FM" = 0.64
"FM elasticity of demand" = 0.25

Under these conditions, the model predicts high-end prices of:

Yr. 1: $1297 / MT (an avg. increase of $122 from $1175)
Yr. 2: $1444 / MT (an avg. increase of $147 from Yr 1)
Yr. 3: $1619 / MT (an avg. increase of $175 from Yr 2)
Yr. 4: $1829 / MT (an avg. increase of $210 from Yr 3)
Yr. 5: $2082 / MT (an avg. increase of $253 from Yr 4)

Conclusion

These scenarios define what in common speech would be defined as best and worst case scenarios. They determine a range in which FM price can be estimated, and therefore determines a year-to-year price in which the larvae-profitability model uses to predict the sale price of larvae-meal.

This modeling is especially important to the business plan because the model additionally informs BioSystems Design's decision on when to enter the market. As will be discussed in the business plan, entering the market after competitors have established legitimacy and before too many US aquaculture companies have shut their doors is a prescient factor in the plan.

[266] See note 162.
[267] See note 168.

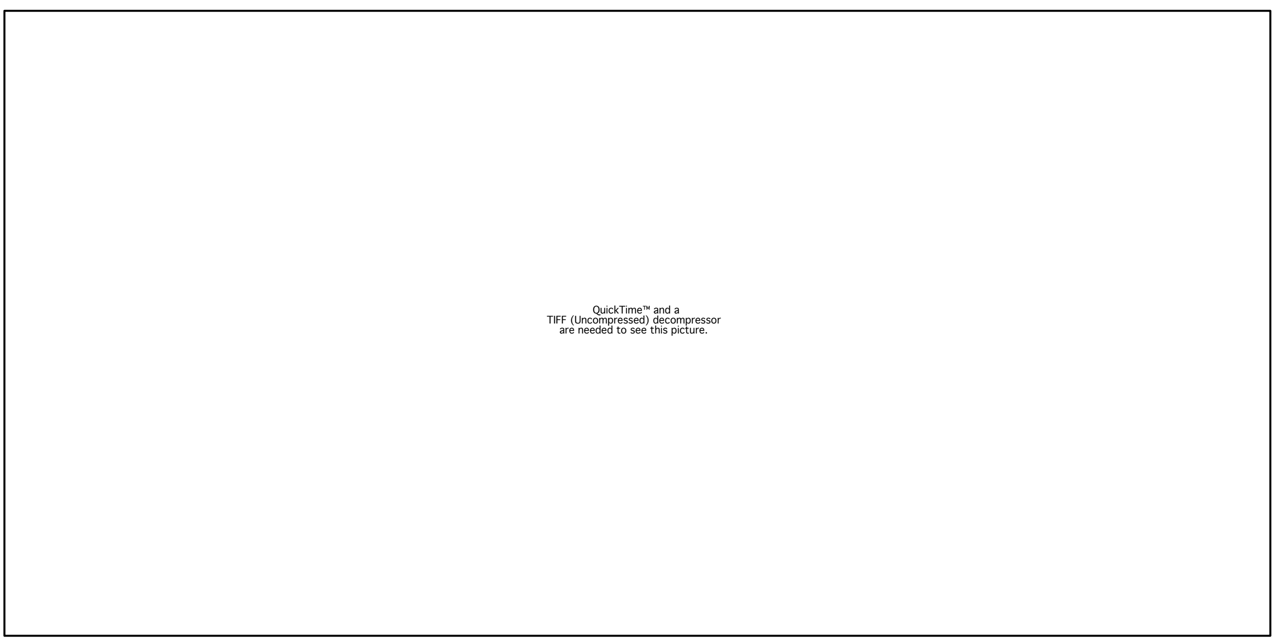
Model 2: Explanation of the Larvae Profitability Model

Using information from the introductions, pre-investigation, lab research, pilot operation and the fishmeal management model, a model of a larvae-meal pilot facility was developed using VENSIM software. This model serves several purposes for process management. The first is that this model predicts profitability. To do this it links with the Fishmeal World Price Model to obtain a price and attach that price to the quantity of larvae-meal profitability. Secondly, this model was designed so that it could easily be adjusted to model different scales of production. This enables the model user to determine the most efficient size of a future operation based upon the variables in the model. As will be discussed in the business plan, the model is capable of modeling factory sizes that are not yet realistic from a design perspective. However, the purpose of this model is not to arrive at the "correct" answer and determine one larvae-meal production and profitability and factory size. Instead, the model was designed to allow variables to be changed and different scenarios to be forecast.

For example, the hourly price of labor in California is $8/hr but if one adjusts the price in the model to be $5.15/hr as it is in the state of Georgia, the profitability of larvae cultivation changes dramatically and a more informed decision on where to locate the first production plant can be made. This same exercise can be done with the rate of tipping fees charged to receive organic waste, the price of larvae-meal, the conversion rate of the bio-pods and the time to load the bio-pods with organic waste to name a few changeable variables.

In the business plan, the financials forecast for BioSystems Design were made using this model and assumptions about where these variables should be. The three most important variables discussed in the business plan were size of the operation (how many bio-pods), tipping fees charged for the receiving of organic waste, and the amount of time and labor required to load the bio-pods with organic waste.

The formulation of the variables that make up the model are explained below and like the first model, they are organized into sub-systems for clearer understanding:



The Larvae-Profitability Model As Viewed in VENSIM Software

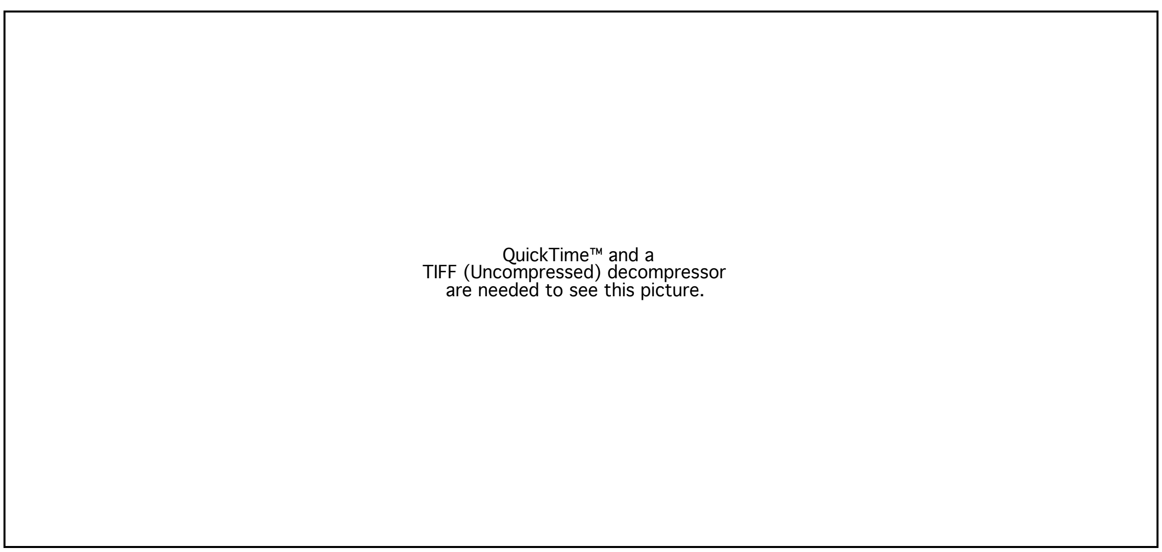
The Larvae Profitability Model Components

Production of Black Soldier Fly for the purpose of creating larvae-meal on an industrial level using food-waste as feed has never been attempted. Therefore, the model above was specifically designed to model the input of organic matter and the output of larvae; the labor costs involved in the feeding, collecting, and cooking of the larvae; and, the operating costs for machines, fuel, electricity etc. After adding up production costs, the revenue from receiving organic waste, known as "tipping fees," is added to the sale of the larvae-meal and is compared to the costs to determine profitability. The price which larvae-meal earns is based upon the price determined in the fishmeal management model.

Unlike the Fishmeal Management and World Price Model, this model was designed for the majority of the variables to be adjustable. The design is intentional. In all cases, the initial value is a suggested value. As the larvae-meal production process becomes more refined, the amount of waste processed will increase, labor times to load and unload ovens will change, oven size may increase, the conversion ratio may increase or decrease etc. Therefore, the benefit of this model is to be able to design scenarios based on assumptions that change models variables. The value is that the model can be adjusted quickly and the cause and effect relationships of the changes can be seen quickly and graphically. This ability is essential to the management of the system, and the results of this model inform the design of an industrial scale larvae-meal production process which is the goal of this study.

The model below can be broken down into three subsystems: the Black Soldier Fly Production subsystem, the labor efficiency indicator subsystem, and the profitability subsystem. Each of these will be broken down into their variables, which will be defined mathematically and explained. After an explanation of each of the subsystems, the model will be used to design two probable production scenarios for the first fiscal year of operation. These scenarios are used in the accompanying business plan.

Subsystem 1: Black Soldier Fly Production



This subsystem models the input and output of the larvae production process. The components of which it is comprised of are defined as:

Waste Available (aux var) = 1000
This is a sliding variable with a beginning value of 1000kg/day. The minimum value is 200, it is set to max out at 5000 kg, the largest facility size envisioned to be developed in fiscal year one (FY1) before the process is mechanized. This mechanization is discussed in the business plan. The slider is set to move at increments of 100kg.

Bio Pods (aux var) = 'waste available'/'conversion each bio pod'
This is a sliding variable, with the number of bio pods equal to the kg of waste available divided by 10 kg which is the conversion rate of each bio pod per day.[268] This equation exists so that there will always be enough bio-pods and never a buildup of waste.

Conversion Each Bio Pod (aux var) = 10
Each bio pod of 4 foot diameter contains a colony of larvae that can consume between 10 and 12 kg of food waste each day. This is a separate variable so that it can be adjusted in the model for different food wastes in which the larvae digest at different speeds. This will be discussed later in the analysis.

Converted Each Day (aux var) = bio pods*conversion each bio pod
The amount of food waste that is converted each day into larvae bio-mass is the amount of bio pods multiplied by the amount of food waste larvae can consume per day,

Kg Food Waste (rate) = IF THEN ELSE(waste available>converted each day, converted each day, waste available)

The conditional in this formula functions like a switch or a cap. If the waste available is greater than the ability of the bio-pods to convert it, the amount of waste entering the "fresh larvae produced" level will be only the maximum possible conversion rate. If it is less than the maximum possible conversion rate, it will be the waste available. This is due to the obvious constraint that the bio-pods cannot be overloaded or the waste will not be consumed. The assumption here is that the factory managers will manage deliveries of waste and avoid excess organic waste buildup.

% Food to Larvae Conversion (aux var) = 0.20
This variable is set at a constant 20%, which is the rate at which *Hermetia Illucens* is believed to convert food waste to larvae body weight.[269]

Fresh Larvae Produced (level) = (Kg Food Waste*"% Food to Larvae Conversion")-Leave to cook/TIME STEP

The amount of waste multiplied by the conversion of waste to larvae equals the production of larvae in the first stage of the process. This larvae accumulates until a large quantity is present and is removed to be cooked in the oven. The model uses a switch, the "binary cook switch" to establish at what quantity the binary cook switch is activated and sends a batch to the oven.

Binary Cook Switch (aux var) = IF THEN ELSE(Fresh Larvae Produced>Cooker Batch Size, 1 , 0)

The Binary Cook Switch is literally a binary switch. If the level, 'Fresh Larvae Produced' hits a quantity above the cooker batch size (determined by the oven size) the binary cook switch equals 1 which allows mathematical operations in the 'leave to cook' to function. If it is less than

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[268] See note 54.
[269] See note 54.

the cooker batch size, it equals 0 and no mathematical operations can commence in the 'leave to cook' function.

Cooker Batch Size (aux var) = 1000
This is the suggested size of the oven. 1000 indicates it can handle 1000kg of wet larvae. Should one use the model and increase the waste received to 50,000kg one should increase the size of the oven. In the case that the waste available increases to an amount larger than could be actually handled by one 1000kg oven in a day (the time step), the model simply acts as though there are an infinite amount of 1000kg ovens that can be loaded and unloaded adding them as necessary. The labor to load and unload the over functions accordingly.

Leave to Cook (rate) = Cooker Batch Size*binary cook switch
If larvae are less than 1000kg (the cooker batch size), the cooking batch will not run. This is because the switch is a binary and if the binary cook switch is zero, mathematically any number times zero equals zero. In this case the leave to cook rate is zero, until the binary cook switch equals 1.

% Wet to Dry Reduction (aux var) = 0.44
There is a 44% reduction of the weight of the larvae in the drying process. Thus, larvae leaving the oven are 44% of the weight of the larvae leaving to cook.[270]

Larvae in Oven (tank) = +Leave to cook*(1-"% Wet to Dry Reduction")-removed larvae
Initial Level = 0
This level models the oven. The larvae that are removed from the bio-pods to be cooked are the quantity of larvae that enter the oven and are reduced in weight by 44% as a consequence of the cooking. They are then removed and another batch is cooked when it is ready.

Removed Larvae (rate) = DELAY FIXED(Leave to cook*(1-"% Wet to Dry Reduction"), cook time in minutes , 0)
The rate's delay command gives a 15 minute delay which was found to be the necessary cook time in minutes. This delay is important because the model simulates hours of labor as well as delayed working which also must be measured.

Cook time in Minutes (aux var) = 0.15
This is a sliding variable that quantifies how much time the larvae are cooked for in minutes. This variable is essential in calculating operating costs and energy consumption. However, at this time 15 minutes is only an unclear estimate.

Larvae Available (level) = removed larvae
This is the final accumulated amount of larvae available for sale.

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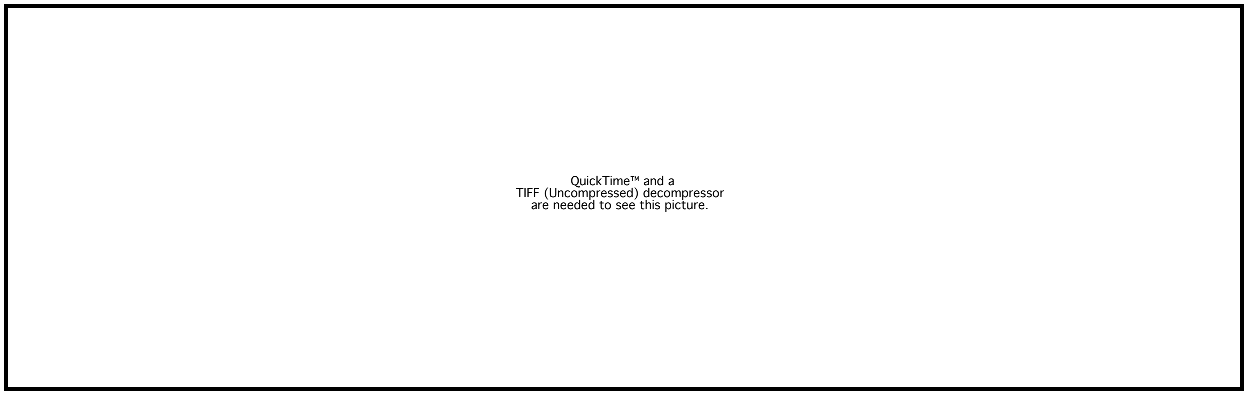
[270] Dr Paul Olivier, e-mail correspondence with the author, 14 April 2007.

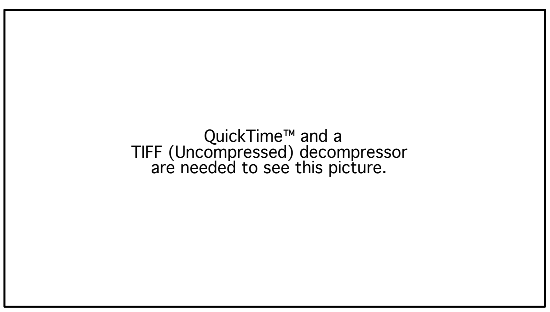
Subsystem 2: The Profitability Subsystem



The profitability subsystem is composed of five levels. Two of these levels are costs that accumulate during the model's run, and two of these levels are revenues that accumulate. The accumulated costs and the revenues are balanced in a fifth and final level, the "profit" level.

Dual Revenue Streams: Tipping Fees & Larvae-meal Production Revenue

This section of the model shows the dual revenue streams from Larvae-meal production and tipping fees for receiving organic waste. The modeling of revenue from the larvae-meal production process is a critical point in the model. It is the node where the FM world price model interacts with the Larvae Profitability model. What occurs is that the "larvae sale price/kg" is held equivalent to the price of FM forecasted by the FM model to determine larvae-meal production revenues.



The second revenue stream is revenue from tipping fees. Tipping fees are where a landfill or composter charge per ton of waste that a hauler deposits at the site. This model is designed for use in the state of California where tipping fees vary from $20-120 per ton depending upon location.[271] A conservative estimate of $40 is used as the suggested start value. It is important to note that this model is designed for use in California because tipping fees for organic waste exist there. In Colombia the situation is the opposite. While landfill tipping fees exist, in Colombia organic waste haulers pay supermarkets for most types of rotten food[272] because it can be resold to farmers as pig feed or composted. The reason that this occurs in Colombia is that the proximity of farming operations to supermarkets makes the purchasing and transport of the food waste profitable. This important distinction between the US and Colombian markets creates a revenue stream for simply receiving the raw material. The revenue streams are defined in the following manner:

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[271] See note 74.

[272] Javier Mauricio Ramirez G. GPAS spa. Composting Group. Personal Correspondence with the Author. February 2008.

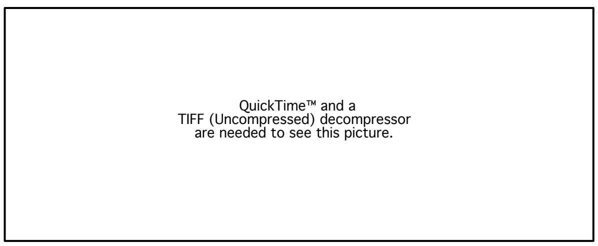
"Tipping Fee Revenue" (level) = (Kg Food Waste/1000)*tipping fee
Initial value = 0

"Tipping Fee" (aux variable) = 40

"Larvae Sale Price/kg" = 1.2
To test the model, a larvae sale price of USD $1.20 per kg is used, which is the price forecasted by the FM world price model for FY1 and FY2 in the low-end price scenario which is described in the business plan.

"Larvae Revenue" (level) = "Removed Larvae"*"Larvae Sale Price/kg"
Initial value = 0
The above simply multiplies the weight of the cooked larvae by the sale price.

Incurred Operation Costs:



At left are the first of two accumulated costs levels. This level shows operating costs, which include permitting, leasing space, & electricity. Costs for machinery and plant construction are considered fixed costs. They are not dynamic and thus are not modeled. The operation costs are found via the following:

"Operation Costs" (level) = Annual Permit Costs/365+(Oven kWh per minute*Price per kWh of electricity*cook time in minutes)+warehouse cost

Operation costs are found by adding several equations together. Electrical costs are found by multiplying the price per kWh of electricity by the kWh used per minute, by the total cooking time. These are the foreseeable estimated electrical expenses. Additional machinery and electrical costs are not foreseeable and are therefore not included.

The annual permit costs are estimated to be $10,000 per year. Therefore the permit costs are divided by 365 to find the cost of the permits per day. Finally, warehouse cost is estimated by multiplying the number of bio-pods, by the square feet they require plus 200% for loading and unloading space, by the price of average industrial space in the San Francisco bay area.

"Price per kWh of Electricity" (aux variable) = 0.13

The price of electricity in the rural areas surrounding San Francisco is roughly around 13 cents per kilowatt-hour.[273]

"Oven kWh per minute" (aux variable) = 5/60

The kWh per minute of an oven suitable for cooking the larvae in small quantities is estimated to be around 5 kWh per hour.[274] Dividing this number by sixty minutes equals the kWh per minute. Warehouse lighting is not considered because it is likely that the facility will be outdoors because the Black Soldier Fly requires sunlight to reproduce. Additional machinery and electrical costs are not foreseeable at this time and are therefore not modeled.

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[273] Tina Montgomery, project manager Sonoma Mountain Village, E-mail correspondence with the author, 20 May 2008.
[274] "Operating Home Appliances," (Public Information Brochure, Modesto County Irrigation District, 2008), p1

"Annual Permit Costs" (aux variable) = 10,000

The permitting process in California to establish a "composting facility" is notoriously difficult and expensive. Unfortunately, this is what a larvae production plant would be under state law. Costs are estimated to be roughly $10,000/yr for the first year to obtain the permits as described by Rich Flammer of Hidden Resources Inc who is a composting consultant.[275]

"squarefeet required" = 2*(bio pods*16)

Four foot diameter Bio-pods require 16 square feet of space each, plus an additional 200% of that space in the factory layout for loading, unloading, storage etc.

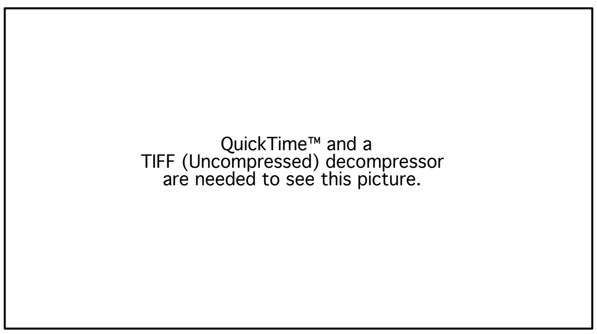
"monthly price per square foot of leased industrial space" = 0.4

The estimated price of leased industrial space is between 40 and 80 cents per square foot in the bay area. This depends upon location and any existing building structure. Because a structure is undesirable, 40 cents is the suggested starting value.

"warehouse cost" = ("monthly price…leased industrial space"/30)*squarefeet required

This variable multiplies the price per square foot of space leased by the square feet required to determine a total cost.

Incurred Labor Costs:



At left is the second level that estimates incurred labor costs. These costs are "raw." They purely show costs per hour of labor and do not take into account the number of hours that legally constitutes a part-time or full time employee, nor health benefits or payroll taxes. For this reason, there is a third subsystem that estimates the efficiency of the employees hired. The components that are used to estimate labor costs are defined in the following manner:

"Labor Costs" (level) = (Price Per Hour Labor*binary cook switch*Hours Per Oven Load and Unload)+(Price Per Hour Labor*(waste available/1000)*Hours per 1000 kg waste)+(Price Per Hour Labor*"Regular Maintenance & Cleaning Hours")

"Price per hour labor" (aux variable) = 8

Current minimum wage in California is $8.00/hour.[276]

"Hours per Oven Load and Unload" (aux variable) = 0.5

One half-hour to load and unload estimates 15 minutes per load and unload. It is an adjustable sliding variable that can be changed while the model is running to account for different models of ovens and increases in process efficiency.

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[275] Rich Flammer, Hidden Resources Inc., Composting permit specialist, e-mail correspondence with the author, 31 July 2008.

[276] California Department of Industrial Relations, "History of the California Minimum Wage," Ca.gov, http://www.dir.ca.gov/Iwc/MinimumWageHistory.htm (accessed 15 Feb 2008).

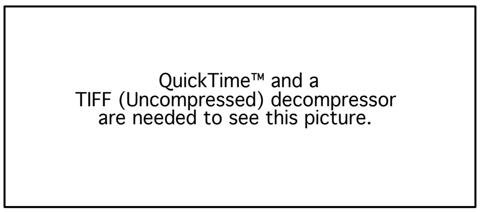
"Hours per 1000 kg waste" (aux variable) = 0.5

One half-hour to load the bio-pods with organic waste is an estimated variable. It is an adjustable sliding variable that can be changed while the model is running to account for different levels of efficiency once plant operations are standardized and streamlined.

"Regular maintenance & Cleaning Hours" (aux variable) = 20/30
20 hours per month / 30 days per month

Twenty hours per month to perform maintenance on the bio-pods and other machines is an estimated variable. It is an adjustable sliding variable that can be changed while the model is running to account for different levels of efficiency once plant operations are standardized and streamlined.

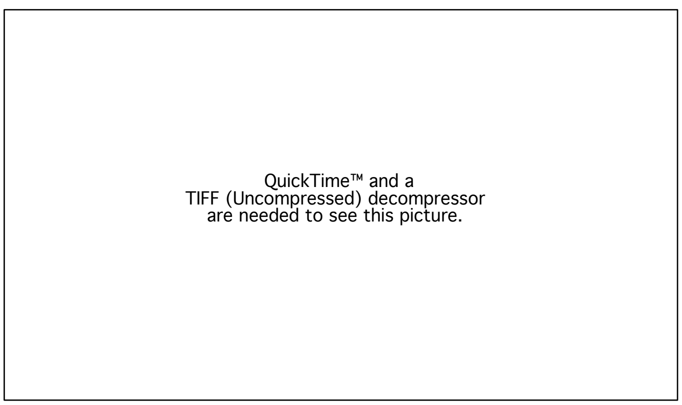
Profitability:



At left is the fifth and final level that very simply adds the two revenue sources, and subtracts the two streams of incurred costs to find profit. The equation for the fifth and final level is the following:

"Profit" (level) = (Larvae Revenue+Tipping Fee Revenue)-(Operation Costs+Labor Costs)
initial value = 0

Subsystem 3: The Labor Efficiency Indicator Subsystem



In the third and final subsystem of the Larvae Profitability Model, the accumulated hours of labor are translated into hired labor efficiency. The reason for this is because, as referred to earlier, hours of labor cannot simply be paid out according to the hours needed. Employees must be hired on a full time (40hrs per week) or part time (20hrs per week) basis. Therefore, the number of labor hours accumulated in a run of the model, will be translated into part-time employees hired to do 20 hrs per week. The efficiency at which employees are being used is calculated simply: if 81 hours of work a week are necessary, four individuals must be hired on a part-time basis. However, 1 of those individuals is now only working 1 hour per week. Legally, the other three individuals cannot do the single extra hour of work because this would result in the need to pay expensive benefits for a full time employee. Thus, the need for the following labor efficiency indicator.

The auxiliary variables in grey were already defined in the Black Soldier Fly Production Subsystem. These are called shadow variables as they allow a variable to be used as many times as necessary without large and complicated arrows crossing the diagram. The formulas of the new components of the subsystem use these shadow variables in the following manner:

"accumulated work hours in total time period" (level) = (Hours Per Oven Load and Unload*binary cook switch)+"Regular Maintenance & Cleaning Hours"+(Hours per 1000 kg waste*(waste available/1000))

initial value = 0

The accumulated total work hours is found by multiplying the hours per oven load and unload by the binary cook switch. Because the binary cook switch flips at different times in the model's run, every time it flips it will multiply by the hours to load and unload the oven. These hours will accumulate in the level. Added to these hours are the maintenance and cleaning hours, plus the hours required to load waste into the bio-pods. All of these hours accumulate in the level over the course of the model's run. These total hours are then used by the other auxiliary variables.

"part time employees hired" (aux variable) = ((Accumulated Work Hours in total Time Period/FINAL TIME)*7)/20

The above divides the total hours of labor necessary by the total time that the model runs to find the hours per day. Because the time step for the model is in days, the hours per day is multiplied by seven to find the hours per week. It is then divided by 20 hours to find the number of part time employee positions that must be offered.

"% employee efficiency" (aux variable) = ((Accumulated Work Hours in total Time Period/FINAL TIME)*7)/(INTEGER((Part Time employees Hired+1)*20))

As alluded to in the introduction of this subsystem, the percent of employee efficiency displays as a percentage, the difference between the number of 20 hours per week employees and the number of actual hours required. This is necessarily done in a very complicated manner, but is conceptually very simple. Conceptually it is simply the number of hours of work actually needed divided by the hours supplied. The hours needed are found by taking the total accumulated hours and dividing by the final time as was done earlier in the "accumulated work hours level." This equals the total hours per day needed due to the model time step. Once multiplied by seven this equals the number of hours per week actually needed. We then divide this number by the hours supplied. The hours supplied is found by rounding the number of part time employees up by 1, taking the integer (which in VENSIM always rounds down), and multiplying by 20 hours. The division of the total hours actually needed divided by the total hours supplied gives a decimal percentage which is the percent efficiency.

V. Introduction to the Business Plan

This business plan, though preliminary, takes the first step in utilizing the data from the innovative logistics models to present the larvae-meal production process to financiers and potential investors. The function of the plan is to utilize the data from these two models to determine the appropriate size and profitability of an industrial scale facility or facilities. The plan must additionally coordinate the data from the models with a financial development strategy and account for competitors and investor needs. The business plan serves as an excellent analysis within this study, revealing how the lab, operations, and second hand research which has been detailed in this study has been put forward to develop a coherent strategy for the development of the technology in the business world.

BUSINESS PLAN – BioSystems Design, LLC. **18 Nov 2008**
www.biosystemsdesign.com

EXECUTIVE SUMMARY

Food supply for the next two decades will be stretched nationally and internationally as population growth and fuel production demands increase. Aquaculture and the production of land based farmed fish is the food industry best positioned to take advantage of the demands on food supplies. The problem for this industry is that at present farmed fish are dependent upon fishmeal as a protein source in their feed and annual production of fishmeal has peaked. This is because the wild stocks which are used to produce fishmeal are at or beyond their sustainable production capacity. More sources of fishmeal to meet rising demand are not likely to be found.

BioSystems Design proposes to create a sustainable alternative to fishmeal to sell to animal feed producers. Black Soldier Fly Larvae (*Hermetia Illucens*) in the form of a dried and pulverized meal has been demonstrated to be a suitable replacement for fishmeal. Larvae cultivation and harvest can be scaled using the Bio-Pod technology pioneered by ESR International however the financials section displays a clear need to mechanize the process to achieve economy of scale.

Black Soldier Fly larvae cultivation is competitive because the larvae feed on organic wastes which include manure, crop residuals, and food waste. These wastes are normally received at landfills and composting centers for a fee. The business model therefore proposes to make money receiving the input, organic wastes, as well as selling the output, the larvae in the form of larvae-meal. This proposal not only makes the process more profitable, but more sustainable and therefore with greater potential for expansion.

COMPETITION

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are needed to see this picture.

The chart above shows the core differences between BioSystems Design and Neptune Industries, its only active competitor in the larvae-meal business. The major difference described in the chart is that despite being a first mover, larvae-meal is not the primary business of Neptune Industries. Their primary focus is on supplying fish fingerlings (baby fish) to aquaculture companies. In addition to this, they already have large non-revenue producing projects underway. They are hoping to sell a vertically integrated aquaculture production system comprised of pumps, tanks, and filters for aquaculture companies to grow the fish they sell. Their core focus right now is closing the fundraising round to build the first pilot system, not on the production of larvae-meal.

Due to these facts, shown above is that Neptune's core business is not larvae-meal. It is fish and fish cultivation technology. Neptune has recurring losses from these other operations. In addition, it has not been made clear if Neptune intends to establish a food waste receiving operation that would permit a double revenue in larvae-meal production, or if they will use onsite treatment of manure as a feed for the larvae. In this chart, it assumes the latter due to the capital intensity needed to establish an entire food waste receiving operation. However, they are described as scaleable because sources working with Neptune have revealed that Neptune is in the process of experimenting with the same Bio-Pod made by ESR international that Biosystems Design uses. These sources indicated that Neptune just recently discovered the bio-pod because they had not yet solved how to reliably cultivate the larvae.

Finally, Neptune Industries will have a slight advantage over BioSystems Design because it has been operating since 1998 and has already developed relations in the aquaculture industry through its other products. However, because aquaculture companies do not formulate their own feeds, this is not a competitive advantage in the feed market.

MARKETING AND SALES

Marketing and Sales to Waste Producers

The receiving of organic waste is a necessary component to the business as it is the feed for the larvae. Additionally, it is a source of revenue. Landfills and composting facilities charge waste haulers per ton dumped at the facility. This will be the same model that BioSystems Design will follow.

Our target market for FY1 and FY2 will be medium size food and agricultural waste producers. Medium is defined as supplying less than 1 ton of food or agricultural waste per day. These include sports arenas, grocery stores, and wholesale food suppliers/transporters with damaged crops. In some cases this may also include farmers whose crops have been attacked by a disease such as *E. Coli*.

These producers are our target market because they are a neglected market niche that is seeking market options. The reason for this is that large industrial processes such as gasification and ethanol production need thousands of tons of waste per month to establish the economy of scale that is profitable. These organic waste processors are not looking to work with medium sized waste producers. However, due to their public images and in some cases third party sustainability certifiers, many of these food waste producers have resorted to paying waste haulers extra to process food waste separate from landfill waste. Our process is flexible and scaleable and can take advantage of this market gap by working directly with these facilities, certifiers and waste haulers.

Our processing strategy will be to develop a small facility in California that handles a little over 1 ton per day and can be scaled as additional waste producer agreements are negotiated. Within the first six months our goal will be to have a facility up and running with a capacity to scale to 50 MT /day. Over two years, our goal will be to establish a mechanized production process allowing for larger scale waste processing and feed output plants to be built. This will allow us to receive waste from a larger number of medium sized food waste clients as well as the option to compete for jumbo sized food waste clients.

Marketing & Sales to Feed Producers

Upon entering the market and establishing our first waste-processing site, we will also be entering the animal feed market. Our strategy will not be to produce larvae-meal as an input for existing animal feed producers, not formulate our own feeds. As the less capitalized of two first movers in larvae-meal production (both started in 2006), our strategy will be to let our better capitalized competitor Neptune spend the majority of the cash to legitimate the product with feed producers while giving the producers time to formulate the larvae-meal from Neptune for different animal feeds. The initial research by academic institutions has already begun, however, the animal feed suppliers will desire to do their own research on formulas. While this is occurring and the market is being developed, our main focus will be on researching and developing the cultivation and processing technology. Our goal will be to mechanize the process to accommodate greater scale.

Due to the large market potential, there should be ample demand and Neptune should not pose a barrier to entry. However, because the feed industry is a relationship business, it will be important to develop a solid reputation during the first two years of process development. While we will allow Neptune to establish the market legitimacy for the product, our goal will be to earn trust and reputation from a small number of key clients by structuring supply contracts to provide small, repetitive amounts, on time, to selected small to medium size feed companies in diverse geographic locations. This latter point of geographic diversity is essential as our goal will be to establish reputation.

The feed industry is a black box industry and input suppliers and prices are considered industry trade secrets. Therefore, when we are ready, price negotiations with larger feed companies will not be affected by our established foundation of smaller clients.

After the first fiscal year and extensive research into process technology, we should be able to mechanize. We should be able to undercut Neptune's price earlier than this because we will receive an additional revenue stream from accepting our input (organic waste). Additionally we will have less overhead because larvae-meal will be our core business. In contrast, Neptune offers a range of aquaculture products that require marketing, production, R & D and employees. Their focus will not be solely on larvae-meal. With a devoted staff, we should be able to develop a superior number of relationships and a larger number of geographically diverse production sites in the first five years. What we may not have at the onset to compete with Neptune is the immediate capitalization.

MANAGEMENT TEAM

Grant Canary – (Principal, CEO)
Ryan Mykita – (Chief Development Officer)
Ryan Cunningham – (External Media Consultant)
Rob Griffith & David L. Canary – (External Legal Counsel, Garvey Schubert and Barer)
Douglas Knights – (External Certified Public Accountant, CPA)

KEY MILESTONES

FY1

- Obtain letters of Intent to purchase Larvae-Meal from 1-3 feed producers
- Establish letters of Intent from 1-3 medium waste producers and their haulers
- Close Series A Investment Round
- Hire Management Team
- Obtain permits for 1 scaleable site
- Build 1 production plant
- Supply a minimum of 60 tons larvae-meal to 1-3 feed producers per quarter for our first year
- Process 4,500 tons of organic waste per quarter for our first year

FY2

- Obtain permits for 2 additional sites
- Close Series B Investment Round
- Construct the additional scaleable sites
- Mechanize all three sites to improve loading time per ton to less than 1/2hr
- Supply 180 tons larvae-meal to 3-9 clients per quarter throughout our second fiscal year
- Process 13,500 tons organic waste per quarter throughout our second fiscal year
- Obtain 1-3 letters of Intent to Purchase Cultivation Bi-Products
- Establish Pre-Processing Technique at the three sites

FINANCIAL PROJECTIONS

In the below financial projections, six scenarios were established. These scenarios show the best and worst case profit margins for three facilities of increasing size. In scenarios 1 & 2, a small processing plant of 1.2 MT / Day was modeled; in Scenarios 3 & 4, a larger plant of 50 MT / Day was modeled. Finally, scenarios 5 & 6 modeled a 200 MT / Day facility. In each of the odd numbered scenarios, low-end fishmeal prices were used, and low-end tipping fees ($40 / MT) were used. Additionally, in all scenarios the forecasting of the second fiscal year anticipates achievement of the key milestone for the second year to develop three production facilities. The second fiscal year also anticipates achievement of a mechanized production process and a drop in time to load each ton of waste to less than one half hour.

Analyzing the profit margins, the three sized facilities vividly show the need to scale. However, the process technology to scale has not yet been developed. This is best demonstrated by the 200 MT / Day facility. At 200 metric tons per day, this is still an extremely small processing capacity when considering that the average processing capacity of a Los Angeles County landfill in 2003 was 2,672 metric tons and that the largest facility in Los Angeles County was processing 10,594 metric tons per day.[277] However, this capacity of only 200 metric tons would require 20,000 bio-pods and

[277] South Coast Air Quality Management District, "Los Angeles County Landfills," 2003 Final AQMP Progam EIR, (sub-chapter 3.5 Solid/Hazardous Waste, table 3.5-3, all standard measured weights converted to metric tons), p 3.5-4 http://www.aqmd.gov/ceqa/documents/2003/aqmd/finalEA/aqmp/11_ch3_waste%20.doc (accessed 1 Nov 2008)

640,000 square feet of space, or roughly 11 American football fields.[278,279] While the space required represents a distinct cost, this problem could be overcome through the use of vertical space. The larger problem is the management and loading of 20,000 discrete units.

Scenarios 1 & 2

Scenarios one and two were established to show the financial forecasts of a 1.2 MT / Day facility. Discussed in the key milestones, BioSystems Design's strategy is to build three of these by the second fiscal year to begin production. While in a best-case scenario the facilities will operate at only a small gain, these facilities will be constructed to scale to the size of the facilities described in scenarios 3-6. However, to do this, the process technology must be developed. While developing this technology, the objective of these facilities will be to establish reputation and relations as discussed in the marketing strategy. Shown below, projections in the second year anticipate mechanization and developing the process technology to reduce the time to load each ton of waste to less than one half hour.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

[278] Glen Elert, "Length of a Football Field (American)," The Physics Factbook, http://hypertextbook.com/facts/2001/NinTam.shtml (accessed 20 Feb 2008).
[279] An American football field is 57,600 square feet including the endzones (see note 231).

Scenarios 3 & 4

Much like scenarios one and two, scenarios three and four show the increased profitability as a result of scaling the technology. Additionally notable is the importance of mechanization in the second year to establish a profitable business in a low-end larvae-meal and tipping fee scenario.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Scenarios 5 & 6

While profitability in the high-end model is quickly achieved at this scale, again the importance of mechanization is demonstrated in the low-end model by observing the second fiscal year in which mechanization is assumed. This is especially true as this capacity facility would require 20,000 bio-pods as noted.

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are needed to see this picture.

PRESENT STATUS

BioSystems Design incorporated in June of 2007 in Oregon. Over the last year and a half, BioSystems Design established a branch in Bogotá, Colombia for research purposes. Since that time it has established a 5-year research contract with the Universidad Nacional. In December of 2007, 24 Bio-Pods from ESR International in Vietnam were imported to Colombia. In May of 2008, a pilot plant at the University was established. Two researchers were hired from the Universidad Nacional and at this time four research studies have been completed on bi-products from the Larvae-Cultivation process. These studies have begun to differentiate which food waste substrates are best for Black Soldier Fly development. Additionally, the studies have indicated that liquids from the process show promise as a potential organic soil amendment that has anti-pathogenic properties. Since its incorporation in 2007, BioSystems Design has maintained itself as an incredibly lean operation whose development has been funded by its sole owner, Grant Canary.

VI. Conclusions From the Study

At the onset of this study, the objective was clearly defined: to design a larvae-meal production process ready to be built, tested, and managed at an industrial scale. An interdisciplinary task, this overarching goal required the development of two systems models. The first of which was an innovative systems model archetype to forecast the price of a maximized eco-system product as a function of its management. This innovative model may serve as an archetype as other eco-systems become maximized and the products they provide prove essential.

The second model continued and further developed the work of Guilno et. al.[280] and linked the fishmeal management model to a process design and management model. This model enabled the design and modeling of a larvae-meal production process at an industrial level. Because of the model's design, the model answers the vital question of how profitable is the process at different economies of scale. Because of the model's connection to the fishmeal management model, profitability can additionally be forecast in different market scenarios. Both of these features are critical to the management decisions surrounding construction of a larvae-meal production process at an industrial level.

These two models and the extensive research in the lab, operating the pilot factory, and doing second hand research are what make up the tangibles of this study. These tangibles are the final product of this study. Listed they are:

1. A model that forecasts a future price for larvae-meal as a function of fishmeal management
2. A model that forecasts the larvae-meal process profitability at different scales
3. Four research studies that inform the process design and a future research trajectory.
4. A pilot factory whose design informs the process design
5. A business plan for the financing and profitable operation of a factory—based upon the models

As the final products of this study, the quality and value of these tangibles is best assessed by analyzing whether producing them for this study achieved the sub-goals outlined at the beginning of this study. Below, these sub-goals are re-listed and in each case an assessment of their achievement is given.

Process Information Sub-Goals

The process development sub-goals were to:

a. Estimate the costs of labor, machinery, and utility operating costs
b. Estimate the time required for each process step based upon the test facility
c. Determine material input and output.
d. Determine the quantity of machines required for varying levels of input and output (scaling)

These goals have been achieved. On page 87 of this study, the larvae-meal profitability model includes a subsystem for the estimation of labor time to load wastes, clean, and load and unload larvae in the oven (pg 88). In the profitability sub-system, estimates of costs associated with labor

[280] See note 238.

are determined. Also included in the profitability subsystem are utility and operating costs estimates (pg 85). As a part of the black soldier fly production subsystem a determination of bio-pods needed for the quantity of waste is calculated and costs for these bio-pods are included in the profitability subsystem (pg 82). This calculation along with the calculation of basic energy consumption and labor allows the model to forecast the results of scaling the process. Accordingly, food waste input and larvae-meal outputs are included as a function of sub-system 1: black soldier fly production (pg 83).

Fishmeal Management Modeling Sub-Goals

The goals outlined for the modeling of fishmeal management were:

a. Answer: Is the aquaculture industry (which requires fishmeal) an essential industry?
b. Construct a model of macro fishmeal production and management without becoming lost in the complexity of the details.
c. Determine production and price history
d. Determine sustainable production limits
e. Estimate realistically the necessary growth of the Aquaculture industry
f. Determine an elasticity of demand for fishmeal

These goals have also been met. In the pre-investigation (pg 18) six distinct claims were assessed and the first of these three assessments convincingly argued that population will grow and jeopardize food supplies, the aquaculture industry is the only industry with the ability to keep food supplies in pace with population growth, and that the industry's growth is constrained by the lack of fishmeal. These arguments are conclusive that the aquaculture industry is an essential industry that cannot be permitted to stagnate.

Sub-goal B is met beginning on page 70 where a systems model is constructed that assesses the price of fishmeal as a function of management practices and demand. This model escapes the trap of detail complexity by defining system boundaries and utilizing historical data to project future data. Historical production and price history used multiple sources including those of the FAO (pg 73,76). Sustainable fishmeal production limits and aquaculture industry growth were determined from multiple sources including the United Nation's sources (pg 73). The elasticity of demand was found using complimentary fishmeal studies and a price for fishmeal was determined as a function of management and demand (pg 75). The model's accuracy was validated using a trial run against historical data (pg 76).

Revenue Modeling Sub-Goals

The goals outlined for the modeling of revenue within this study were:

a. To project a realistic price for fishmeal using a Fishmeal management model
b. To research and estimate tipping fees for the larvae-meal production model
c. To determine the economy of scale required for profitability using the larvae-meal model

Revenue modeling was achieved by linking the two systems models. Sub-goal A was achieved with the discussion of the high and low fishmeal price projection scenarios detailed on pages 79 and 80. Tipping fees were researched and then explained in the introduction to food waste on page 12. Tipping fees range from $20-120 per ton in the state of California depending upon location. Discussion of the most profitable production scale as forecast by the larvae-meal production model is explained in the business plan on pages 95-97.

Test Facility Sub-Goals

The goals outlined for the construction and operation of the test facility were:

a. Construction of a test facility
b. Analysis of the facility's design viability
c. Analysis of potential improvements for the design

The test facility was constructed at the Universidad Nacional in April of 2008 (pg 64). This facility wed Dr. Sheppard and Dr. Tomberlin's rearing methodology and egg collecting methodology with Dr. Paul Olivier's bio-pod technology. This aggregation of the work of three different scientists had never been attempted before. Additionally, the use of a captive population for larval egg replacement as opposed to a wild population was an innovation.

The analysis of the facilities design viability established a procedure for operation (pg 67) and additionally noted that the space required by the bio-pods may become an issue for large operations in suggestion six on page 67. This is additionally noted in the business plan on pages 94-95. Sub-goal C was met with the suggestion of twelve potential improvements for the facility design based on the operation of the pilot facility. These suggestions are listed on pages 68-69 of this study.

Market research Sub-Goals

The goals outlined for the market research were:

a. determine the additional revenue models such as tipping fees that should be pursued
b. determine the waste source clients to target
c. determine the optimal waste source client location: Colombia or the USA

These goals were achieved early in the study with the research presented in the introductions. It was concluded in the introduction to food waste and food waste recycling systems that composters rely on tipping fees in the United States due to a less developed food waste recycling infrastructure (pg 13). Composting in Colombia is a stunted industry due to the depressed tipping fees caused by a developed food recycling infrastructure (pg 12)

Having defined the additional revenue model, it was determined that universities, supermarkets, corporate campuses, and resorts were the best potential waste source clients to target as they are the most willing to pay for treatment to maintain their environmental image (pg16). They additionally have an appropriate amount of waste for preliminary operations and are actively seeking to find alternatives to their current processes (pg 15-16). After defining the revenue model and the waste source clients, it became clear that optimal process profit would occur in the United States due to its less developed food recycling infrastructure and eager clients (pg 16).

Competitive Research Sub-Goals

The goals outlined for the competitor research were:

a. Identify any competitors that may be attempting to produce larvae-meal
b. Develop a business plan and strategy to out-compete any competitors
c. Produce the accompanying financials for the strategy in the business plan

Competitors were identified and a strategy was outlined in the business plan. The competitor identified was Neptune Industries based in the United States which is also developing an ento-meal. A comparison of BioSystems Design with Neptune Industries is on page 91. The strategy for competing with Neptune Industries is outlined on pages 92-93. The financials for the development of larvae-meal production facilities are on pages 95-96 and are based upon the two systems models.

Laboratory Research Sub-Goals

The goals outlined for the laboratory research were:

a. begin studies about substrate and larvae development with a logical research trajectory
b. confirm knowledge of liquid bi-product anti-pathogenic properties
c. confirm process safety procedures

Study one on page 39 began the examination of substrate effect on larvae growth and composition. Additionally, it tested for optimum temperature and determined if single type or mixed substrates were preferable. It was determined that mixed substrates were preferable.

Study two on page 46 developed additional details about specific starch substrates and meat products and their effects on larvae development and composition. It was learned that larvae do not digest meat products and the protein contain very well and mortality rate when they do is high. These two studies began the development of a research trajectory to further analyze substrates.

The anti-pathogenic properties of the leachate from the larvae-meal production process were confirmed in study three on page 53. The anti-bacterial properties of the larvae and safety procedures were confirmed in study four on page 57.

Final Conclusions

Reviewing the achievement of each of the sub-goals, it is clear that this study has been successful in achieving its aims. It has built the informational foundation and supporting structure to construct and operate a larvae-meal production process at the industrial level. The systems models have created a new systems archetype for the logistics field, provided the managerial tools for decision-making, as well as forecasted the financials. The business plan utilized the projections from the models and is an essential synthesis of the academic and business perspectives. In the business plan, the larvae-meal production process is incorporated into both a realistic development strategy that can be financed, as well a strategy to compete with other potential producers. The production of each of these tangibles, with the quality and value indicated by the achievement of each of the sub-goals indicates that the larvae-meal production process is ready for implementation at an industrial level—the purpose of this study.