LIFE CYCLE ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF WOODY POLYCULTURE

BY

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THESIS

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ABSTRACT

Agricultural runoff is the leading contributor to pollution of surface water, causing algal broom and dead zones. A woody polyculture cropping system has several advantages over conventional annual agriculture, including carbon storage, minimal chemical and water use, and developed root systems, which are able to prevent soil erosion and minimize nutrient runoff. This study serves as the environmental component of a larger interdisciplinary initiative with the goal of advancing multifunctional woody polyculture. Specifically, the goal of this study was to determine the relative significance of nursery operations to the environmental impacts of a perennial polyculture system consisting of chestnut trees and pasture. To this end, life cycle assessment (LCA) was used to characterize the relative contribution of each stage of the system's perennial life cycle to the life cycle environmental impacts of the system. It was demonstrated that in comparison to the environmental impacts of transportation, establishment, and production stages of the orchard system, contribution of the nursery stage was insignificant. Further analysis of the nursery stage revealed the components of the nursery that contribute to the environmental impact of the nursery stage the most, which may be helpful in determining significance of the nursery stage in further studies. Significance of the contribution made by transportation from the nursery to the farm is heavily dependent on the distance the rootstock is transported and the fuel use rate during the transport. Contribution made by the production stage was found to be the most significant out of all stages. Volume, economic, and mass allocation methods were evaluated, and it was determined that mass allocation method is the best fit for this system. Using mass allocation method in assigning all environmental impacts to three co-products, it was determined that hay is responsible for contributing more environmental impact than chestnuts or timber in all impact categories, except for in ozone depletion and fossil fuel depletion. In these two impact categories, chestnuts are contributors of a larger portion of environmental impacts than hay or timber. Future studies of this system should include analyses of direct soil emissions to air and water as well as implications of this project's water consumption.

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Table of Contents

1. Introduction 1
2. Background 5
2.1 Life Cycle Assessment 5
2.1.1 Characterizing Environmental Impacts 5
2.1.2 Impact Assessment Methodology: TRACI 7
2.1.3 Perennial Life Cycle 8
2.2 Uncertainty and Sensitivity Analysis 9
2.2.1 Uncertainty 9
2.2.2 Sensitivity 15
2.3 Allocation Procedures 16
2.3.1 Case of Three Co-Products: Chestnuts, Timber, and Hay 17
2.3.2 Case of Two Co-products: Chestnuts and Hay 19
3. Methodology and Data Collection 20
3.1 Stages and Boundary Conditions 20
3.2 Nursery 23
3.2.1 Bare root rootstock 23
3.2.2 Container grown rootstock 25
3.3 Research Site 27
4. Life Cycle Assessment of Woody Polyculture 31
4.1. Introduction 31
4.2. Methods 33
4.2.1 Goal and Scope Definition 33
4.2.2 Life Cycle Inventory (LCI) 34
4.2.3 Life Cycle Impact Assessment (LCIA) 34
4.3. Results and Discussion 35
4.3.1 Environmental Impact of the Nursery Stage 35
4.3.2 Most Significant Components of the Nursery Stage 39
4.3.3 Sensitivity 43
4.3.4 Allocation 47
4.3.5 Mass as a Cut-Off Criteria 54
4.3.6 Water Consumption Impact Assessment 57
4.4. Supporting Information 58
4.4.1 Supporting Information: Environment Impact of the Nursery Stage 58
4.4.2 Supporting Information: Most Significant Components of the Nursery Stage 60
5. Conclusions 70
6. References 73

1. Introduction

Human activities greatly alter the global environment.[1] One of the primary drivers of change which leads to environmental degradation is population growth.[1,2] A rapid increase in global population increases the rate of food consumption, which in turn requires a growth in agricultural production. An increase in agricultural production can be accomplished through either land use change or land cover change.[1] Land use change is a change in management practices such as tillage, chemical application, and irrigation, while land cover change requires alteration of physical nature of the land from one type of land use to another such as conversation of grassland to an annual monoculture crop field.[1]

Currently, the United States agriculture is dominated by annual monoculture systems with the major field crop being corn, soybeans, and wheat.[3,4] These annual monoculture systems, referred to here as conventional agriculture, are often intensive systems focused on short-term optimization of productivity through the practice of high chemical and fossil fuel input.[5] It is projected that the cultivation area of the mentioned annual monoculture crops will decline over the next ten years[3] thus land cover change may not be a viable option for increasing crop production and a change in management practices will have to take place.

Some of the current management practices used in conventional agriculture have unintended effects on the local and global environment. In production of conventional crops soil is disturbed annually through tillage, planting activities, and harvest. The disturbed topsoil is then vulnerable to erosion by water and wind, especially post-harvest when the soil is often left bare. Extensive soil disturbance may also cause the stored nitrogen previously bound to the soil to be released, diminishing fertility of soil.[6] This, as well as some crop's extensive nutrient necessity, requires for additional fertilizer application. Furthermore, rain events, which erode soil, also wash off any excess fertilizer which has been applied to the field. Excess nutrients and soil particles, which get washed off the field, become agricultural runoff and end up in local bodies of surface and ground water making conventional agriculture the primary source of nitrogen and phosphorus delivered to the surface water.[7–10] This has a considerable negative impact on global nitrogen and phosphorus cycles[11] and often leads to eutrophication, a form of water pollution which causes excessive algae growth.[2] When these algae die, bacteria in the water decomposes the

algae while consuming dissolved oxygen in the water. In a severe case of eutrophication, dissolved oxygen in the affected waters may be depleted to a point of hypoxia. A hypoxic zone, sometimes referred to as "dead zone", makes it impossible for some organisms to survive forcing them to flee or die, thus having a significant negative effect on the ecosystem of the affected area.[12,13] Although eutrophication and hypoxia can occur naturally, human activities linked to nutrient induced hypoxia in shallow coastal zones often accelerate the process and make the recurrence persistent.[13,14] It is now estimated that there are now globally over 400 systems which are eutrophication-associated hypoxic zones.[12]

One example of an annually recurring coastal hypoxic zone is in the Northern Gulf of Mexico. It is caused by eutrophication due to nutrients delivered by the Mississippi/Atchafalaya River Basin in combination with temperature- and salinity-induced stratification.[13,15] Nutrients delivered to the Gulf of Mexico come from many sources, including industrial discharge, sewage treatment plant discharge, food and animal agriculture fields, and erosion of soil containing nutrients.[13] However in narrowing down the highest contributor of nutrients, it was estimated that more than 70% of N and P delivered to the Gulf of Mexico come from agricultural sources with corn and soybean being the largest contributors of N.[8] For all these reasons, and many more, conventional agriculture is a dominant driver behind climate change, loss of biodiversity, soil erosion, and degradation of land and freshwater.[11,16]

In an effort to mitigate global environmental impacts of conventional agriculture while keeping in mind the growing population and the limited land availability, it is now widely recognized that food production systems must be sustainable.[17,18] The Environmental Protection Agency Science Advisory Board evaluated the Gulf of Mexico Hypoxia in 2007 and concluded that in order to reduce the hypoxia zone, a significant concurrent reduction in nitrogen and phosphorus riverine flux is required.[13] In order to accomplish this reduction many research topics were proposed, one of which was investigating effects of various agricultural management practices on nutrient loss from agricultural land.[13]

A number of management techniques have been proposed in an effort to make conventional agriculture more sustainable, including conservative tillage practice,[19,20] cover crops[21], and vegetative buffer strips[19,22–25]. However, there are limitations to these

management strategies[19,21–24,26] as they are only incremental improvements and are not enough to substantially decrease environmental impacts of conventional agriculture. In order to alleviate global environmental impacts and achieve a sustainable agriculture system, transformation of agriculture is essential.[11]

In a pursuit of finding a more sustainable alternative to conventional agriculture, perennial crops have been a focus of recent discussion by a number of researchers.[27–31] Increasing biodiversity by mixing plant species through implementing polyculture cropping systems has also been suggested.[32] It is projected that polyculture systems may be a more sustainable alternative to a monoculture system due to potential for nutrient recycling, biodiversity and soil conservation, as well as water quality improvement though soil cover and root presence.[31,32]

However, a transformation from annual to perennial agriculture would require quantitative understanding of economic, social and environmental tradeoffs.[27] In order to define these tradeoffs, a comparative study must be performed where all inputs and outputs for each alternative system are assigned a numerical value, using an accepted matrix, signifying economic, social, or environmental worth of each input and output. These assigned numerical values for inputs and outputs would then be combined for each alternative system to allow for quantitative comparison of the systems. Environmental impact assessment is a commonly used method which allows for comparative assessment of environmental tradeoffs between two systems. To ensure comparability between crops with different life spans, growth patterns, and cultivation methods, the inputs and outputs from the entire life of the crops may have to be considered in performing the environmental impact assessment of the alternative systems. As one of the tools of choice in performing an environmental impact assessment, life cycle assessment (LCA) is often used when evaluating global environmental impacts of the entire life of an agricultural system.[33,34]

Among the perennial agriculture LCA literature, there are LCAs which include all stages of crop's life such as nursery, establishment, production, and destruction[35,36] while some LCAs make a simplifying assumption about the relative importance of nursery, establishment, and destruction stages and focus only on the production stage. LCAs which only focus on one stage are most commonly comparative studies looking at various management practices of a specific crop and only exclude aspects which are the same for

each alternative.[37–39] While excluding certain stages is acceptable in comparative assessments, disregarding inventory of omitted stages in a life cycle environmental assessment of a complex perennial cropping system oversimplifies it. Oversimplification of a perennial crop assessment may cause researchers to leave out a significant amount of environmental impacts associated with the life cycle of a perennial crop. Thus, studies which do not include all stages of a perennial crop's life may not be used to represent the crop's life cycle environmental impacts nor used in comparison to other perennial crop's environmental impacts. To avoid oversimplifying the complexity of a perennial crop, a well performed LCA must capture crop's entire life cycle and encompass environmental impacts over several impact categories.[40]

Very few studies have looked at relative environmental significance of the nursery stage of a perennial crop[35,36,41,42] thus it is unknown what about the perennial crop makes the nursery stage significant or insignificant.

The objective of this work was to determine the relative significance of the nursery stage for a Chinese chestnut tree (*C. mollissima*) relative to the life cycle environmental impacts of a multi-cropping perennial agriculture system comprising of chestnut trees and pasture. To this end, LCA of the orchard system was performed accounting for all stages of the systems' life, including nursery operations, establishment stage, production stage, and destruction. For the nursery and establishment stages, data were collected from existing sites and for production and destruction stages data were estimated. Uncertainty and sensitivity analyses were conducted on all inventory. The resulting impacts of a chestnut tree's nursery stage were compared to the environmental impacts of the systems' establishment, production, and destruction stages thus determining the relative significance of the nursery stage. The nursery stage was then analyzed in an effort to outline the inputs with the largest environmental impacts. The environmental impacts of the system's life cycle were further allocated to three co-products of the system, hay, timber, and chestnuts, using physical relationship allocation and mass allocation methods in order to determine each product's contribution to the environmental impact associated with the system.

2. Background

2.1 Life Cycle Assessment

2.1.1 Characterizing Environmental Impacts

As a result of a sustainability mindset and a concern for the unintended negative impacts produced by conventional agriculture, many assessment methods were developed in order to measure environmental impacts of agriculture.[33] Different assessment methods may deliver different results, thus it is important to choose the right method for the objective of the specific study.[43] Variation in results is often caused by choices made in defining objectives within each of the impact assessments as well as indicators the assessments use in quantifying the environmental issues with which the assessment is concerned.[33,43] Although there are many indicator based impact assessment methods,[33,34] only a few were considered. Some of the most common environmental impact assessment methods used in literature today are the following: carbon footprint method,[44] ecological footprint analysis,[45,46] agro-ecological indicators (AEI),[47] energy flow,[48] and life cycle assessment.[40,49]

Selection of the environmental impact methodology to be used highly depends on the objective of the study. This study's objective was to determine why or why not a certain nursery should or should not be included in the assessment of the life cycle impact of a product. In meeting the objective of this study as well as due to a high variation in management practices among different farms, it was important to be able to get numerical results for environmental impacts per product and per area. It was also important to be able to get a specific numerical value for environmental impact of each inventory input in order to determine which inputs have the highest contribution to the total environmental impact of the system. In avoiding oversimplification and in order to understand global impacts of certain inputs, it was also important to have the results show impacts over several impact categories.[50] Due to all these reasons, and more, a choice was made to use life cycle assessment (LCA) as an environmental impact assessment method for this study.

The study of life cycle environmental impact assessment has been around for over 50 years, developing over time from an energy analysis to the LCA model used today.[51] Many organizations and countries have come forth over the years in support of LCA and adaption of the life cycle philosophy into their practice through creation of programs and networks.[51]

Among these organizations and networks are United Nations Environmental Program (UNEP), European Commission, United States Environmental Protection Agency (USEPA), Australian LCA Network, and Thai network.[51] As LCA became a tool for decision making[52] it became important for studies to be comparable. Lack of a concrete method for conducting an LCA led to creation of different approaches in an effort to standardize LCA[52–54] which led to significant discrepancies in research methods causing quantitative LCA studies, which should be comparable, to be conflicting in results.[51,52] Thus, as LCA gained popularity, the need for standardization of the tool became evident which led to creation of two LCA international standard codes of practice, ISO 14040 and ISO 14044.[51,55,56] Although these codes of practice were developed to guide LCA users, they are very broad and provide very few concrete procedures for performing LCA, section 4.3 of ISO 14040:2006(E) stating that "there is no single method for conducting LCA".[51,55] Furthermore, LCA of agricultural products is a relatively new area that is still being explored[53] and even with the guidance of ISO codes there is still a lot of flexibility in performing LCAs, which causes high uncertainty when comparing them.

Part of the reason for uncertainty when comparing LCAs is variability in objectives of studies. Some examples of objectives include, but are not limited to, reducing greenhouse gas emissions,[57] environmental impact comparison,[41] types of farming methods,[58] and using LCA to study carbon footprint.[59] There are also different types of LCAs which can be performed, including prospective and retrospective LCAs,[60] or consequential and attributional LCAs.[61–66] Another example of flexibility in performing an LCA is choosing impact categories to use. There are two scales, or level of site specificity, of impact categories: global scale and non-global scale. Some studies choose to only focus on non-global impacts[67] while others evaluate a more broad spectrum of impact categories.[36,40,68] Non-global impacts include acidification, eutrophication, smog formation, freshwater ecotoxicity, and human health impacts. Global impact categories include global warming potential, fossil fuel depletion, and ozone depletion.[69]

Regardless of the type of LCA performed, impact categories used, or the objective of the study, a few things are defined in the ISO code to be certain and applicable to all LCA. Section 4.2.1 of ISO 14040:2006(E) code states that there are four main phases of an LCA: goal and scope definition, life cycle inventory, life cycle impact assessment, and

interpretation.[55] ISO 14044:2006(E) code states in section 4.2.3.3 that the system boundary of the study must be clearly defined, listing anything that has been excluded in accordance with defined cut-off criteria. The code further states that the study must clearly define the functional unit that is consistent with the goal and scope definition (section 4.2.3.2 of ISO 14044:2006(E)), the data used in the study must be referenced for the purpose of transparency and reproducibility (sections 4.2.3.6 and 4.3.2 of ISO 14044:2006(E)), and that uncertainty analysis and sensitivity check must be performed (section 4.5.3 of ISO 14044:2006(E)).[56] All LCA studies are expected to follow the guidelines set by the ISO code.

2.1.2 Impact Assessment Methodology: TRACI

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is an impact assessment methodology developed by the United States Environmental Protection Agency (USEPA) designed for conducting impact assessments.[69,70] TRACI (2.1 V1.02, US-Canada 2008) was chosen as the assessment tool used in assessing all inventory for this study.

Due to a lack of universal consensus regarding impact category inclusion, impact categories considered by TRACI were carefully selected for consistency and in accordance with current regulations, policies, and values.[70] Table 1 presents a list of impact categories use by TRACI 2.1. Impact categories such as odor, noise, radiation, waste heat, land use, and water use were excluded by the tool due to various reasons such as unavailability of data or difficulty of prediction.[69,70] However, land use and water use are expected to be added as impact categories in the near future.[70]

Table 1: Impact categories used by TRACI 2.1[69,70]

Impact Category	Scale	Unit	Media
Ozone depletion	global	kg CFC-11 eq	Air
Global warming potential	global	kg CO^2 eq	Air
Photochemical oxidation (smog)	non-global (U.S.)	kg O^3 eq	Air
Acidification	non-global (U.S.)	kg SO^2 eq	Air
Eutrophication	non-global (U.S.)	kg N eq	Air, water
Human health: carcinogenics	non-global (U.S.)	CTUh	Air, water, soil
Human health: non carcinogenics	non-global (U.S.)	CTUh	Air, water, soil
Human health: respiratory effects	non-global (U.S.)	kg PM2.5 eq	Air
Ecotoxicity	non-global (U.S.)	CTUe	Air, water, soil
Fossil fuel depletion	global	MJ surplus	

The database within TRACI is a compilation of inventory data from suppliers and other databases.[70] The source of the data is discussed upon selection of each inventory item separately within the database.

2.1.3 Perennial Life Cycle

Perennial crops differ from annual crops in a significant way. Unlike annuals, perennials live for multiple years after planting, thus the life cycles of the two types of crops differ. As an example, when cultivating an annual crop, such as corn, the life cycle of the crop would include production of the seed, cultivation of the seed, harvesting of the crop, and clearing the field for the following year. An estimate of the whole life cycle of an annual crop would be one to two years depending of the time requirement for seed production. However, stages of a perennial cycle are often defined as follows: (stage 1) nursery, (stage 2) establishment of the orchard, (stage 3) low yield production, (stage 4) high yield production, (stage 5) end of life low yield production, and (stage 6) orchard removal or destruction.[41,45,71] Thus, when cultivating a perennial crop, such as a chestnut tree, the life cycle of this crop would include all the years of nursery production, establishing an orchard, production with variable yield, and finally destruction of the orchard. An estimate of the whole life cycle of a perennial crop would be between three to 80 years, or more, depending on the crop and management practices of the farm.[40,72] Thus, if an LCA of a perennial crop was to be performed, an extensive amount of data would need to be collected in order to consider the entire perennial cycle. In an effort of simplifying implementation of a perennial crop's LCA a number of studies were conducted aiming to determine the importance of considering the entire life cycle of a perennial crop.

In an effort to determine significance of each of the life cycle stages of a perennial crop, several studies were published. Some researchers looked at non-productive stages of perennial crop's life, such as establishment stage, low yield production stage, and end of life low yield production stage. It was found that the non-productive years of a perennial crop have an effect on the overall environmental impact of the crop, thus not capturing these stages may produce misleading results.[72,73] Therefore, for crops with varied yield during the production stage data must be gathered in a way that is representative of the entire production.[73] Discussion has also taken place regarding inclusion of the nursery stage when

performing an LCA of a perennial crop. While some studies concluded that the nursery stage is insignificant,[36,42] others argue that the nursery stage should be included as it may be associated with significant environmental impacts for some crops,[34,46,72,74–76] such as those which need extra care.[72] Furthermore, it is suggested that even if the relative contribution is negligible, the nursery stage should be included for comparability between different crops.[40] Another study supports this point by stating that quality of a seedling, resulting from the nursery's management practices is one of the factors which may play a role in determining productivity of a crop.[42]

For all the previously listed reasons, inclusion of all stages of a perennial crop is suggested. Even so, a large number of LCA studies of perennial crops did not integrate the entire perennial cropping cycle into their study[40] mostly due to them being comparative studies between two similar crops with a goal of comparing management practices.[37–39] These comparative studies usually focus on one or several years of the production stage and only exclude aspects which are assumed to be the same for each alternative. Whether this assumption is valid is debatable. Other studies that do wish to include all stages of the life cycle point out that lack of data, especially for the nursery stage, often makes this difficult.[41] It is the intent of this thesis to provide researches with data for the nursery stage of a Chinese chestnut tree, which they may not have access to otherwise.

2.2 Uncertainty and Sensitivity Analysis

2.2.1 Uncertainty

Uncertainty and variability, here referred to as uncertainty, arise due to lack of knowledge regarding the true value of a data point. There are many sources of uncertainty including spatial and temporal variability, difference in management practices, data gaps, lack of data accuracy or low data quality, and use of site-generic characteristic factors, just to name a few. [40,41,77,78] Uncertainty leads to misrepresentation of product's environmental impacts and in turn to misleading results. To ensure that our results are not misrepresenting the system and are inclusive of the system's spatial and temporal variance, as well as possible difference of management practice, an uncertainty analysis was performed.

Monte Carlo with Latin Hypercube Sampling (LHS; 10,000 runs) was used to propagate uncertainty for input parameters listed in Table 2 through Table 8 to quantify life cycle

environmental impacts for all stages of the studied system. For each input parameter presented in Table 2 through Table 8, a range of values based on gathered data, literature, and conservative estimation was assigned avoiding use of single precise values commonly seen in LCA papers.[35,36,38,42,68] This data presentation format has previously been used in a life cycle management study and aims to account for variability of input quantities due to inconsistency in management practice spatially and temporally.[78] In order to account for the fact that management practices may vary significantly between farms, "Yes/No" distribution was used in cases where an alternative option is as likely as the management practices we encountered, in order to account for both cases.

Table 2: Parameters varied during Monte Carlo simulation for the bare root rootstock nursery stage. Probability density functions were characterized by: minimum and maximum values (uniform); minimum, most probable, and maximum values (triangular). [a] Value was assumed. [b] Equal probability of getting either choice. [c] Raw data gathered from the nursery with estimated range of values. [d] Value provided by the nursery with the range of values from the chemical label

Parameter: Bare root nursery stage	Units	Distribution	Values	Citation
Is harvester used in seed harvesting	N/A	Yes/No	yes, no	b
Harvester speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Harvester fuel use	gal hr^{-1}	Triangular	3, 3.3, 4	79
Is shaker used in seed harvest	N/A	Yes/No	yes, no	b
Shaker speed	trees hr^{-1}	Triangular	50, 60, 70	79
Shaker fuel use	gal hr^{-1}	Triangular	3, 3.5, 4	79
Is sweeper used for seed harvest	N/A	Yes/No	yes, no	b
Sweeper speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Sweeper fuel use	gal hr^{-1}	Triangular	1.5, 2, 2.5	79
Yield of the farm delivering seeds	lbs $acre^{-1}$	Triangular	1000, 2500, 3500	80–82
Weight of chestnut seeds delivered	nuts lb^{-1}	Uniform	34-38	83
Seed transportation	mi round trip	Triangular	100, 500, 1000	c
Seed transportation: vehicle fuel use	mpg	Triangular	15, 20, 40	a
Seed transportation: amount of seeds	seeds $trip^{-1}$	Triangular	1e4, 1.7e4, 2e4	75
Material transportation	mi round trip	Triangular	10, 100, 500	a
Material transportation fuel use	mpg	Triangular	5, 20, 40	a
Seeds to be serviced w/ these material	seeds	Triangular	1e4, 1.7e4, 2e4	c
Material transportation: number of trips	trips	Triangular	0.5, 1, 2	a
Survival rate of seed to rootstock	%	Triangular	40, 50, 85	c,75
Number of years growing in the nursery	years	Triangular	1, 2, 3	c
Pump, irrigation: useful life	years	Triangular	4, 8, 20	a
Pump: weight	kg	Triangular	100, 148, 300	84
Pump: number of plants serviced	plants $year^{-1}$	Triangular	1e4, 6e4, 7e5	c
Pump: fuel type	N/A	Yes/No	diesel, electricity	b
Pump: fuel rate	L m^{-3}	Custom	0.008-0.087	85
Pipe, irrigation: material	N/A	Yes/No	cast iron, PVC	b
Pipe: useful life	years	Triangular	30, 40, 100	86,87
Pipe: nominal size along ground	in	Custom	1.5, 2, 3, 4, 5, 6, 8	88,89
Pipe: nominal size of irrigating head	in	Custom	1.5, 2, 3, 4, 5, 6, 8	88,89
Pipe: distance b/w irrigating heads	ft	Triangular	10, 30, 50	c
Pipe: height of irrigating head	ft	Triangular	1, 3, 4	c
Pipe: coverage width of irrigating head	ft	Triangular	5, 20, 30	c
Seed planting density	seeds ft^{-2}	Triangular	6, 8, 10	c

Table 2 (cont.)

Parameter: Bare root nursery stage	Units	Distribution	Values	Citation
Is mulch applied on the field	N/A	Yes/No	yes, no	b
Mulch application depth	in	Triangular	0.5, 1, 1.5	c
Mulch density	kg m^{-3}	Triangular	200, 335, 561	90
Pesticide, Valor total	kg ai $acre^{-1}$	Triangular	0, 0.173, 0.347	d
Pesticide, Fusilade total	kg ai $acre^{-1}$	Triangular	0, 0.227, 0.34	d
Pesticide, Gramoxone total	kg ai $acre^{-1}$	Triangular	0, 0.54, 1.814	d
Number of pesticide applications	applications	Triangular	2, 4, 8	d
Total volume of water used for irrigation	m^3 $plant^{-1}$	Triangular	0.035, 0.073, 0.15	c
Rootstock harvesting rate	ft^2 hr^{-1}	Triangular	1000, 1600, 3000	c
Tractor fuel use during harvesting	gal hr^{-1}	Triangular	4, 5, 6	91
Distance from field to cool storage	mi	Triangular	0.5, 2, 5	c
Transportation to storage fuel use	mgp	Triangular	15, 20, 40	a
Transportation to storage	plants $load^{-1}$	Triangular	500, 2000, 3000	c
Amount of time spent in the cool storage	days	Triangular	120, 150, 200	c
Number of fans used to cool storage	fans	Triangular	6, 8, 10	c
Cooling fans running rate	hours day^{-1}	Triangular	0, 5, 10	c
Fungicide per application in storage	kg ai $plant^{-1}$	Triangular	3e-8, 6.1e-8, 1.2e-7	d
Fungicide applications in cool storage	applications	Triangular	3, 6, 12	d

Table 3: Parameters varied during Monte Carlo simulation for bare root transportation from the nursery to the farm. For parameters with triangular distribution, values shown are minimum, most probable, and maximum values
[a] Value was assumed.. [c] Raw data gathered from the nursery with estimated range of values

Parameter: Bare root transportation from the nursery to the farm	Units	Distribution	Values	Citations
Cardboard for packaging	plants box^{-1}	Triangular	500, 1000, 1200	c
Fuel use rate	mpg	Triangular	5, 20, 40	a
Travel distance one way	mi	Triangular	50, 210, 1000	c

Table 4: Parameters varied during Monte Carlo simulation for the container grown nursery stage. Probability density functions were characterized by: minimum and maximum values (uniform); minimum, most probable, and maximum values (triangular). [a] Value was assumed. [b] Equal probability of getting either choice. [c] Raw data gathered from the nursery with estimated range of values. [d] Value provided by the nursery with the range values from the chemical label

Parameter: Container nursery stage	Units	Distribution	Values	Citation
Is harvester used in seed harvesting	N/A	Yes/No	yes, no	b
Harvester speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Harvester fuel use	gal hr^{-1}	Triangular	3, 3.3, 4	79
Is shaker used in seed harvest	N/A	Yes/No	yes, no	b
Shaker speed	trees hr^{-1}	Triangular	50, 60, 70	79
Shaker fuel use	gal hr^{-1}	Triangular	3, 3.5, 4	79
Is sweeper used for seed harvest	N/A	Yes/No	yes, no	b
Sweeper speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Sweeper fuel use	gal hr^{-1}	Triangular	1.5, 2, 2.5	79
Yield of the farm delivering seeds	lbs $acre^{-1}$	Triangular	1000, 2500, 3500	80–82
Weight of chestnut seeds delivered	nuts lb^{-1}	Uniform	34-38	83
Seed transportation	mi round trip	Triangular	100, 500, 1000	c
Seed transportation: vehicle fuel use	mpg	Triangular	15, 20, 40	a
Seed transportation: amount of seeds	seeds $trip^{-1}$	Triangular	1e4, 1.7e4, 2e4	75
Material transportation	mi round trip	Triangular	10, 100, 500	a
Material transportation fuel use	mpg	Triangular	5, 20, 40	a

Table 4 (cont.)

Parameter: Container nursery stage	Units	Distribution	Values	Citation
Seeds to be serviced w/ these material	seeds	Triangular	1e4, 1.7e4, 2e4	c
Material transportation: number of trips	trips	Triangular	0.5, 1, 2	a
Survival rate of seed to rootstock	%	Triangular	40, 50, 85	c,75
Pump, irrigation: useful life	years	Triangular	4, 8, 20	a
Pump: weight	kg	Triangular	100, 148, 300	84
Pump: number of plants serviced	plants year^{-1}	Triangular	1e4, 6e4, 7e5	c
Pump: fuel type	N/A	Yes/No	diesel, electricity	b
Pump: fuel rate	L m^{-3}	Custom	0.008-0.087	85
Pipe, irrigation: material	N/A	Yes/No	cast iron, PVC	b
Pipe: useful life	years	Triangular	30, 40, 100	86,87
Pipe: nominal size along ground	in	Custom	1.5, 2, 3, 4, 5, 6, 8	88,89
Pipe: nominal size of irrigating head	in	Custom	1.5, 2, 3, 4, 5, 6, 8	88,89
Pipe: distance b/w irrigating heads	ft	Triangular	10, 30, 50	c
Pipe: height of irrigating head	ft	Triangular	1, 3, 4	c
Pipe: coverage width of irrigating head	ft	Triangular	5, 20, 30	c
Plastic trays: step 1: volume	in^3 tray^{-1}	Triangular	300, 578, 800	92
Plastic trays: step 1: depth	in	Triangular	1.5. 2, 2.5	92
Plastic trays: step 1: density	kg tray^{-1}	Triangular	0.05, 0.11, 0.2	92
Plastic trays: step 1: life	years	Triangular	4, 5, 6	c
Plastic trays: step 1: seeds per tray	seeds tray^{-1}	Triangular	50, 60, 70	c
Type of mixer used for media	N/A	Custom	types of mixers	93
% of trays/pots filled with media	%	Triangular	80, 90, 100	c
Media item 1: Pine bark, density	kg m^{-3}	Triangular	481, 561, 657	94
Media item 1: Pine bark, % of media	%	Triangular	35, 40, 45	c
Media item 2: Pine wood, density	kg m^{-3}	Triangular	350, 420, 510	95
Media item 2: Pine wood, % of media	%	Triangular	5, 10, 15	c
Media item 3: Reclaimed, % of media	%	Triangular	25, 30, 35	c
Media item 4: Sand, density	kg m^{-3}	Triangular	1282, 1602, 1922	96
Media item 4: Sand, % of media	%	Triangular	15, 20, 25	c
Fertilizer added to media: 22-3-8	kg m^{-3}	Triangular	2.4, 4.2, 5.9	d
Pesticide rate per application, small pots	fl oz ft^{-2}	Triangular	0.001, 0.002, 0.003	d
Pesticide applications (step 2)	applications	Triangular	0, 3, 4	d
Amount of time spent in cool storage	days	Triangular	90, 100, 120	c
Cool storage fan detail	kW fan^{-1}	Triangular	0.12, 0.13, 0.14	97
Cool storage, number of fans	fans	Triangular	6, 8, 10	c
Cool storage, fans are on	hours day^{-1}	Triangular	0, 5, 10	c
Travel distance to cool storage	mi	Triangular	0.5, 1, 2	c
Trays per load, transport to storage	trays load^{-1}	Triangular	2000, 2500, 3000	c
Vehicle fuel use within nursery	mpg	Triangular	15, 20, 40	a
Distance from storage to greenhouse	miles	Triangular	0.5, 1, 2	c
Time spent in the greenhouse	days	Triangular	0, 100, 150	c
Greenhouse life expectancy	years	Triangular	15, 20, 25	c
Greenhouse heating: propane	gal GH^{-1} yr^{-1}	Triangular	0, 90, 150	c
Number of small pots per greenhouse	pots GH^{-1}	Triangular	2e4, 2.5e4, 3e4	c
Greenhouse: plastic roof liner density	lbs ft^{-2}	Triangular	0.225, 0.34, 0.45	98
Greenhouse: mesh roof liner density	lbs ft^{-2}	Triangular	0.0083, 0.020, 0.0367	99,100
Greenhouse: floor liner, density	lbs ft^{-2}	Triangular	0.021, 0.038, 0.049	101,102
Greenhouse: floor liner expected life	years	Triangular	8, 10, 12	102

Table 4 (cont.)

Parameter: Container nursery stage	Units	Distribution	Values	Citation
Greenhouse: wood trim, wood width	in	Triangular	3, 4, 5	c
Greenhouse: wood trim, wood thickness	in	Triangular	1.5, 2, 2.5	c
Greenhouse: distance between hoops	ft	Triangular	4, 5, 6	c
Greenhouse: hoops, dimensions	pipe size	Custom	0.75, 1, 1.25, 1.5, 2, 2.5, 3, 3.5, 4	103
Plastic pots (step 2): expected life	years	Triangular	4, 5, 6	c
Plastic pots (step 2): volume	in^3	Custom	8, 15, 24, 37	104–107
Plastic trays (step 2): expected life	years	Triangular	4, 5, 6	c
Plastic trays (step 2): density	kg $tray^{-1}$	Triangular	0.18, 0.2, 0.23	108,109
Plastic pots (step 3): depth	in	Custom	9, 11	110–112
Herbicide in media (step 3)	kg ai pot^{-1}	Triangular	0, 3.7e-7, 5e-5	d
Time spend outside	days	Triangular	270, 310, 350	c
Travel distance to outside growing area	mi	Triangular	0.5, 1, 2	c
Number of pesticide applications while outside	applications	Triangular	7, 9, 11	d
Pesticide rate per application, Ortho Sevin	kg ai $plant^{-1}$	Triangular	0, 4.8e-6, 1e-5	d
Pesticide rate per application, Orthene	kg ai $plant^{-1}$	Triangular	0, 1.3e-6, 3e-6	d
Pesticide rate per application, Dursban	kg ai $plant^{-1}$	Triangular	0, 5.2e-6, 1e-5	d
Pesticide rate per application, Ovation	kg ai $plant^{-1}$	Triangular	0, 1.6e-7, 3e-7	d
Plastic liner below plants, density	kg ft^{-2}	Triangular	0.015, 0.016, 0.017	101,102
Plastic liner below plants, expected life	years	Triangular	8, 10, 12	102
Plant protective cover cloth, density	kg ft^{-2}	Triangular	1.5e-3,1.7e-3,4.7e-3	113
Plant protective cover cloth, expected life	years	Triangular	1, 3, 5	c

Table 5: Parameters varied during Monte Carlo simulation for container grown root stock transportation from the nursery to the farm. For parameters with triangular distribution, values shown are minimum, most probable, and maximum values
[a] Value was assumed.. [c] Raw data gathered from the nursery with estimated range of values

Parameter: Container grown rootstock transportation from the nursery to the farm	Units	Distribution	Values	Citations
Fuel use rate	mpg	Triangular	5, 20, 40	a
Travel distance round trip	mi	Triangular	50, 420, 2000	c

Table 6: Parameters varied during Monte Carlo simulation for the establishment stage. Probability density functions were characterized by: minimum and maximum values (uniform); minimum, most probable, and maximum values (triangular).
[a] Value was assumed. [b] Equal probability of getting either choice. [c] Raw data gathered from the research farm with estimated range of values. [d] Raw data gathered from the research farm with the range values from the chemical label

Parameter: Establishment stage	Units	Distribution	Values	Citation
Tree planting density	trees $acre^{-1}$	Triangular	36, 49, 70	80–82
Distance material is transported	mi round trip	Triangular	10, 50, 500	a
Plants to be serviced w/ these material	plants	Triangular	50, 200, 15000	c
Material transportation fuel use	mpg	Triangular	5, 20, 40	a
Time spent in the cooler	days	Triangular	0, 14, 60	c
Cooler electricity use rate	kWh day^{-1}	Triangular	18, 22, 38	114
Total plants stored in the cooler	plants	Triangular	50, 200, 15000	c
DAP (18-46-0) total during year 1	kg $plant^{-1}$	Triangular	0, 1.4, 2.8	c
Potash (0-0-60) total during year 1	kg $plant^{-1}$	Triangular	0, 0.69, 1.4	c

Table 6 (cont.)

Parameter: Establishment stage	Units	Distribution	Values	Citation
Was the field tilled prior to planting	N/A	Yes/No	yes, no	c
Pasture seed transportation distance	mi round trip	Triangular	40, 100, 400	a
Pasture seed transportation fuel rate	mpg	Triangular	5, 20, 40	a
Is pasture sowed using a tractor	N/A	Yes/No	yes, no	c
Pasture grass seeding rate	lbs $acre^{-1}$	Triangular	0, 15, 40	115
Pasture clover seeding rate	lbs $acre^{-1}$	Triangular	0, 4, 35	115
Root Dip: Diehard, before storage	oz $tree^{-1}$	Triangular	0, 5e-3, 1e-2	d
Root Dip: Horta sorb, before storage	lbs $tree^{-1}$	Triangular	0, 1e-4, 2e-4	d
Diehard, before transport to farm	oz $tree^{-1}$	Triangular	0, 5e-3, 1e-2	d
Horta sorb, before transport to farm	lbs $tree^{-1}$	Triangular	0, 1e-4, 2e-4	d
Diehard, before planting	oz $tree^{-1}$	Triangular	0, 5e-3, 1e-2	d
Horta sorb, before planting	lbs $tree^{-1}$	Triangular	0, 1e-4, 2e-4	d
Diehard, in planter	oz $tree^{-1}$	Triangular	0, 5e-3, 1e-2	d
Horta sorb, in planter	lbs $tree^{-1}$	Triangular	0, 1e-4, 2e-4	d
Distance from storage to farm	mi	Triangular	0, 10, 50	c
Storage to farm fuel rate	mpg	Triangular	15, 27.5, 40	a
Total number of plants planted	plants	Triangular	50, 200, 15000	c
Was a planter used for planting	N/A	Yes/No	yes, no	c, b
Planting by auger petrol use	gal $tree^{-1}$	Triangular	1e-3, 5e-3, 1e-2	116
ATV: distance from farm to field	mi	Triangular	0, 1, 5	c
ATV fuel use	mpg	Triangular	20, 35, 50	117
Irrigation by truck: fuel use rate	mpg	Triangular	15, 22, 30	118
Plastic tubes for tree protection density	Kg $tube^{-1}$	Triangular	5e-3, 9e-3, 1e-2	119
Pesticide to tree row, year 1	applications	Triangular	1, 2, 3	c
Total Surflan to tree row, year 1	kg ai $acre^{-1}$	Triangular	0, 2.31, 3.5	d
Total Poast to tree row, year 1	kg ai $acre^{-1}$	Triangular	0, 0.51, 1	d
Total crop oil a to tree row, year 1	kg $acre^{-1}$	Triangular	0, 1, 2	c
Distance from tree for tree row pesticide application, year 1	ft	Triangular	1, 2, 3	c
Total Surflan to tree row, yrs 2 and 3	kg ai $acre^{-1}$	Triangular	0, 4.6, 7	d
Pesticide to tree row, yrs 2 and 3	applications	Triangular	2, 4, 6	c
Pesticide between rows, yrs 2 and 3	applications	Triangular	2, 4, 6	c
Total Pendulum between rows, yrs 2 and 3	kg ai $acre^{-1}$	Triangular	0, 1.72, 3.5	d
Total Glyphosate between rows, yrs 2 and 3	kg ai $acre^{-1}$	Triangular	0, 0.90, 2	d
Total crop oil between rows, yrs 2 and 3	kg ai $acre^{-1}$	Triangular	0, 1.76, 4	d
Distance from tree for tree row pesticide application, yrs 2-3	ft	Triangular	1, 2, 3	c
Survival rate of rootstock to tree	%	Triangular	90, 95, 100	c, 120
Mowing pasture	times $year^{-1}$	Triangular	3, 3.5, 4	c
Pasture, years growing before killed by shade	years	Triangular	15, 20, 25	c
Urea (46%N) application during year 2	kg $tree^{-1}$	Triangular	0, 0.23, 0.3	121
Urea (46%N) application during year 3	kg $tree^{-1}$	Triangular	0, 0.37, 0.4	121

Table 7: Parameters varied during Monte Carlo simulation for the production stage. Probability density functions were characterized by: minimum and maximum values (uniform); minimum, most probable, and maximum values (triangular). [a] Value was assumed. [b] Equal probability of getting either choice. [c] Raw data gathered from the research farm with estimated range of values. [d] Raw data gathered from the research farm with the range values from the chemical label

Parameter: Production stage	Units	Distribution	Values	Citation
Years of orchard life post grafting	years	Triangular	45, 50, 55	80
Years before machinery harvest	years	Triangular	9, 10, 12	c, 80
Is harvester used in chestnut harvest	N/A	Yes/No	yes, no	c, b
Harvester speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Harvester fuel use	gal hr^{-1}	Triangular	3, 3.3, 4	79
Is shaker used in chestnut harvest	N/A	Yes/No	yes, no	c, b
Shaker speed	trees hr^{-1}	Triangular	50, 60, 70	79
Shaker fuel use rate	gal hr^{-1}	Triangular	3, 3.5, 4	79
Is sweeper used in chestnut harvest	N/A	Yes/No	yes, no	c, b
Sweeper speed	acres hr^{-1}	Triangular	1, 1.2, 1.5	79
Sweeper fuel use rate	hr^{-1}	Triangular	1.5, 2, 2.5	79
Pesticide rate per application, tree row	kg ai $acre^{-1}$	Triangular	0, 1.4, 3	d
Tree row pesticide applications total	applications	Triangular	25, 50, 100	d
Pesticide application by wand vs broadcaster	N/A	Yes/No	wand, broadcaster	c, b
Mowing per year	times $year^{-1}$	Triangular	3, 3.5, 4	c
Grass yield	ton $acre^{-1}$	Triangular	6, 7, 8	c
Seeding rate: grass	lbs $acre^{-1}$	Triangular	0, 15, 40	115
Seeding rate: clover	lbs $acre^{-1}$	Triangular	0, 4, 35	115
Is pasture resowed	N/A	Yes/No	yes, no	c, b
Is the pasture resowed using a tractor?	N/A	Yes/No	yes, no	c, b
Fertilizer, kg Urea (46%N) in year 4	kg $tree^{-1}$	Triangular	0, 0.51, 0.6	121
Fertilizer, kg Urea (46%N) in year 5	kg $tree^{-1}$	Triangular	0, 0.74, 0.8	121

Table 8: Parameter varied during Monte Carlo simulation for the destruction stage. The triangular distribution values shown are minimum, most probable, and maximum values

Parameter: Destruction stage	Units	Distribution	Values	Citation
Rate of cutting trees	min $tree^{-1}$	Triangular	1, 2, 3	122

2.2.2 Sensitivity

Sensitivity analysis is performed for the purpose of identifying the input parameters associated with the highest variance of the environmental impact values so that these input parameters can be evaluated and modified in an effort to decrease uncertainty. Oracle Crystal Ball was used in performing the sensitivity analysis of all results.

The sensitivity of each result, such as environmental impact, or the forecast value, is determined through running a simulation which computes rank correlation coefficients between every input parameter and the forecast value.[123] Simulations were run using Latin Hypercube sampling method with 10,000 trials in an effort to increase accuracy per the

suggestion of the Crystal Ball's Reference and Examples Guide.[124] During the simulation, the program uses Spearman's rank correlation in order to measures the strength of association between the input values and the forecast value, or the degree to which the input parameter and the forecast value change together.[124] In a case that the input parameter and the forecast value have a high correlation, it is concluded that the input parameter has a significant impact on the variance of the forecast value. The program then ranks the input parameters in accordance with their correlation to the variance of the forecast value and produces sensitivity charts which show relative contribution each significant input parameter has on the variance of the forest value.[125]

2.3 Allocation Procedures

In a multi-cropping system such as this, the total environmental impact over the system's lifetime must be attributed to each co-product in accordance with a selected allocation method. In selection of an allocation method, ISO 14044:2006(E) was consulted. Section 4.3.4.2 of the ISO 14044:2006E document states that allocation should be avoided whenever possible through expanding the boundary of the system and dividing the system processes into sub-processes, which would then be assigned to the corresponding co-products.[56] When allocation cannot be avoided, physical relationship allocation method must be used through dividing inputs between co-products in a way that reflects the physical relationship between the inputs and the co-products. In a case that physical relationship method is not enough to fully separate all the inputs between co-products, other relationship allocation methods must be used such as economic value allocation method where inputs are allocated to co-products based on their proportion of economic value.[56]

A number of allocation methods have been used in past LCA studies including mass allocation,[36,42] economic allocation,[36] volume allocation,[76] and product allocation where all emissions are allocated to the main product.[126] The choice of allocation method may have a significant influence on each co-product's relative contribution to the environmental impact of the system, thus it is advisable to use several allocation methods in order to illustrate sensitivity.[36,126]

The multi-cropping system studied is a system of pasture and chestnut trees which may either produce two or three co-products depending on whether wood is sold during the

destruction stage. If wood is sold during the destruction stage, then it is assumed to be a co-product of the system. If wood is not sold, then it is assumed not to be a co-product. Following are two cases, one describing allocation method for the case of assuming timber to be a co-product and other describing allocation method for the case of assuming timber not to be a co-product.

2.3.1 Case of Three Co-Products: Chestnuts, Timber, and Hay

In a case of assuming that during the destruction stage wood is sold for timber, the system has three co-products: chestnuts, timber, and hay. This assumption was made for this project and was used in allocation of environmental impacts of the system to co-products. Several allocation methods had to be used in input allocation between co-products. Hay is grown as a separate entity from chestnuts and timber and requires separate treatment techniques, thus physical relationship method was used in assigning inputs to hay, avoiding further allocation. However, chestnuts and timber are co-products of one entity, or are both products of one tree requiring inputs most of which cannot be divided between chestnuts and timber using physical relationship, thus a different allocation method must be used. The choice of allocation method may affect the environmental impact assigned to each co-product, thus in order to illustrate sensitivity of results with respect to the chosen allocation method, impact of chestnut and timber co-products were measured using three allocation methods: economic, mass, and volume.[126]

Furthermore, each stage produces a different set of products, thus each stage requires a separate set of allocation methods. Figure 1 presents methods used in allocation of inputs to each co-product within each stage as well as inputs associated with each co-product in physical relationship allocation method. The input allocation methods shown in Figure 1 are coded in accordance with the method used: solid lines represent physical relationship allocation method which was used in allocation of inputs between chestnuts/timber and hay, and dashed lines represent mass/economic/volume allocation methods used in allocation of most inputs between chestnuts and timber.

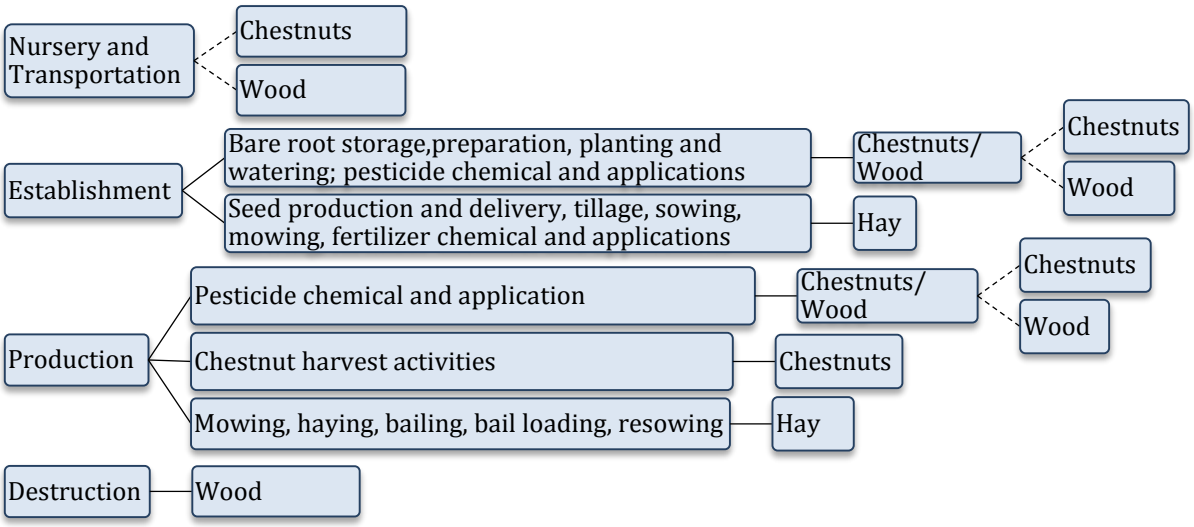


Figure 1: Allocation methods used in each stage of the perennial cycle. Dashed lines represent mass/economic/volume allocation methods and solid lines represent physical relationship allocation

For mass, economic, and volume allocation methods separate units were chosen: lbs for mass allocation, dollar amount for economic allocation, and ft^3 for volume allocation. For all three methods, a functional unit of one chestnut tree over the life time of the orhcard was used in order to account for fluctuation of chestnut yield and the fact that each co-product is gathered at a different stage of orchard life.[36] Because life span of an orchard varies and is an uncertainty, it was decided to leave the phrase "life time of the orchard" as part of the functional unit instead of specifying the numerical value for the life of the orchard, and vary the range of values for the orchard life during uncertainty analysis. Thus, allocation considers both the uncertainty of orchard life years and the uncertainty of tree planting density. Data used in calculating mass, volume, and dollar amount for each of the co-products are listed in Table 9. Nut yield fluctuation over the life time of a chestnut tree was taken into account using "Grower Decision Support Tool for Conversion to a Chestnut Orchard System" model developed by Michigan State University Extension.[80] It was assumed that year zero is year of grafting and the total yield over orchard life time was calculated using the full production values listed in Table 9.

Table 9: Parameters varied during Monte Carlo simulation of allocation methods uncertainty. For parameters with triangular distribution, values shown are minimum, most probable, and maximum values

Parameter	Units	Distribution	Values	Citations
Years of orchard life post grafting	years	Triangular	45, 50, 55	80
Tree planting density	trees $acre^{-1}$	Triangular	36, 49, 70	80–82
Timber density	lbs ft^{-3}	Triangular	28, 29, 30	95,127
Timber length for lumber	ft	Triangular	7, 10, 13	80
Tree diameter at breast height	in	Triangular	4, 6, 10	128
Timber selling price	\$ $(board\ ft)^{-1}$	Triangular	3, 5.5, 8	129,130
Chestnut yield at full production	lbs $acre^{-1}$	Triangular	1000, 2500, 3500	80–82
Chestnut selling price	\$ lb^{-1}	Triangular	2.45, 3.1, 3.5	80,82
Chestnut weight	nuts lb^{-1}	Triangular	34, 36, 38	83
Chestnut diameter	in	Triangular	1, 1.12, 1.25	131

2.3.2 Case of Two Co-products: Chestnuts and Hay

The other case is assuming that during the destruction stage wood is not sold for timber, but instead is considered a waste, meaning its economic value is less than zero,[132] thus the system has two co-products: chestnuts and hay. Chestnuts and hay are produced separately, requiring separate inputs and care, thus it is possible to divide the system's inputs among chestnuts and hay using a physical relationship method without requiring additional allocation. Figure 2 shows co-products collected from each stage and inputs allocated to each co-product using physical relationship allocation method.

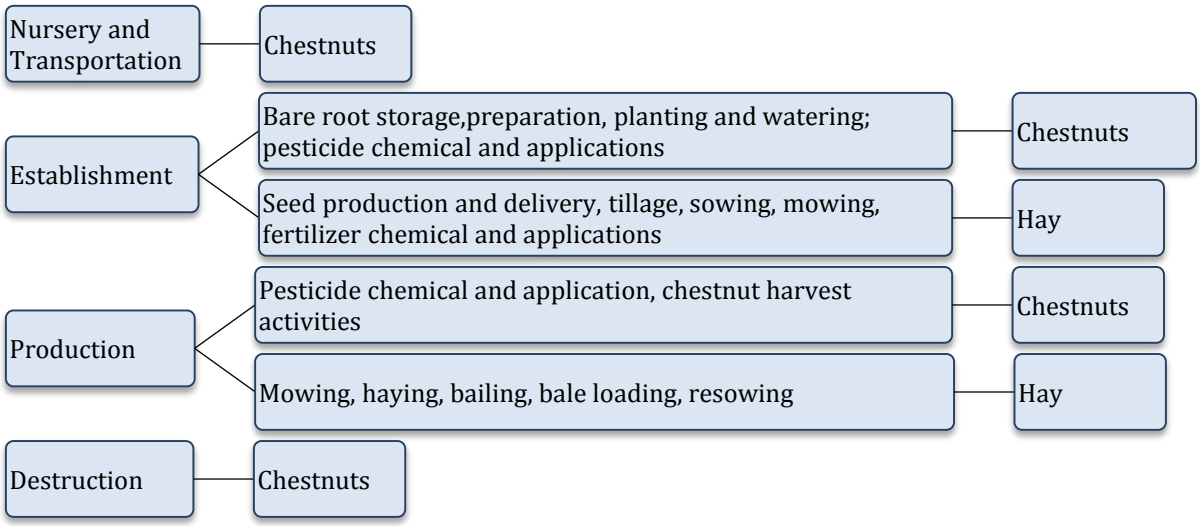


Figure 2: Co-products of each stage and inputs allocated to each co-product using physical relationship allocation method

3. Methodology and Data Collection

3.1 Stages and Boundary Conditions

For reasons listed in section 2.1.3, it was decided to assess life cycle of a chestnut tree according to six perennial crop's life cycle stages: nursery, establishment of the orchard, low yield production, full production, end of life low production, and orchard destruction. Furthermore, two different rootstock types were considered in this study: bare root and container grown. Separate boundary conditions had to be considered for each rootstock type, because of the considerable difference in management practices during the nursery stage. Boundary conditions for both rootstocks may be viewed in Figure 3 and Figure 4. For both rootstocks it was assumed that grafting took place at the farm, thus it was excluded from the nursery operations.

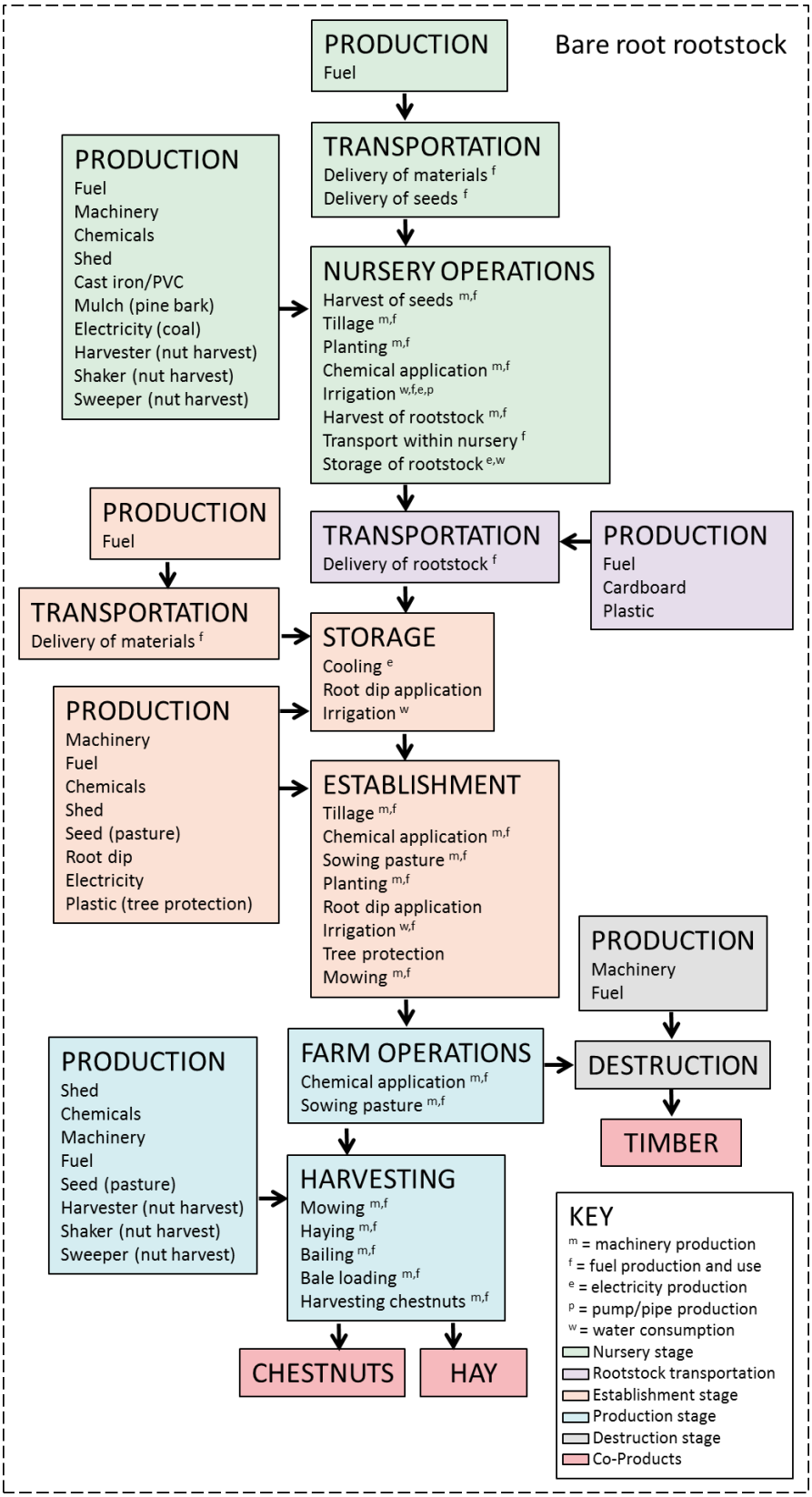


Figure 3: Boundary conditions for the inputs included in assessment of an orchard consisting of chestnut trees grown from bare root rootstock and pasture. Each color represents a different stage into which the inputs were included

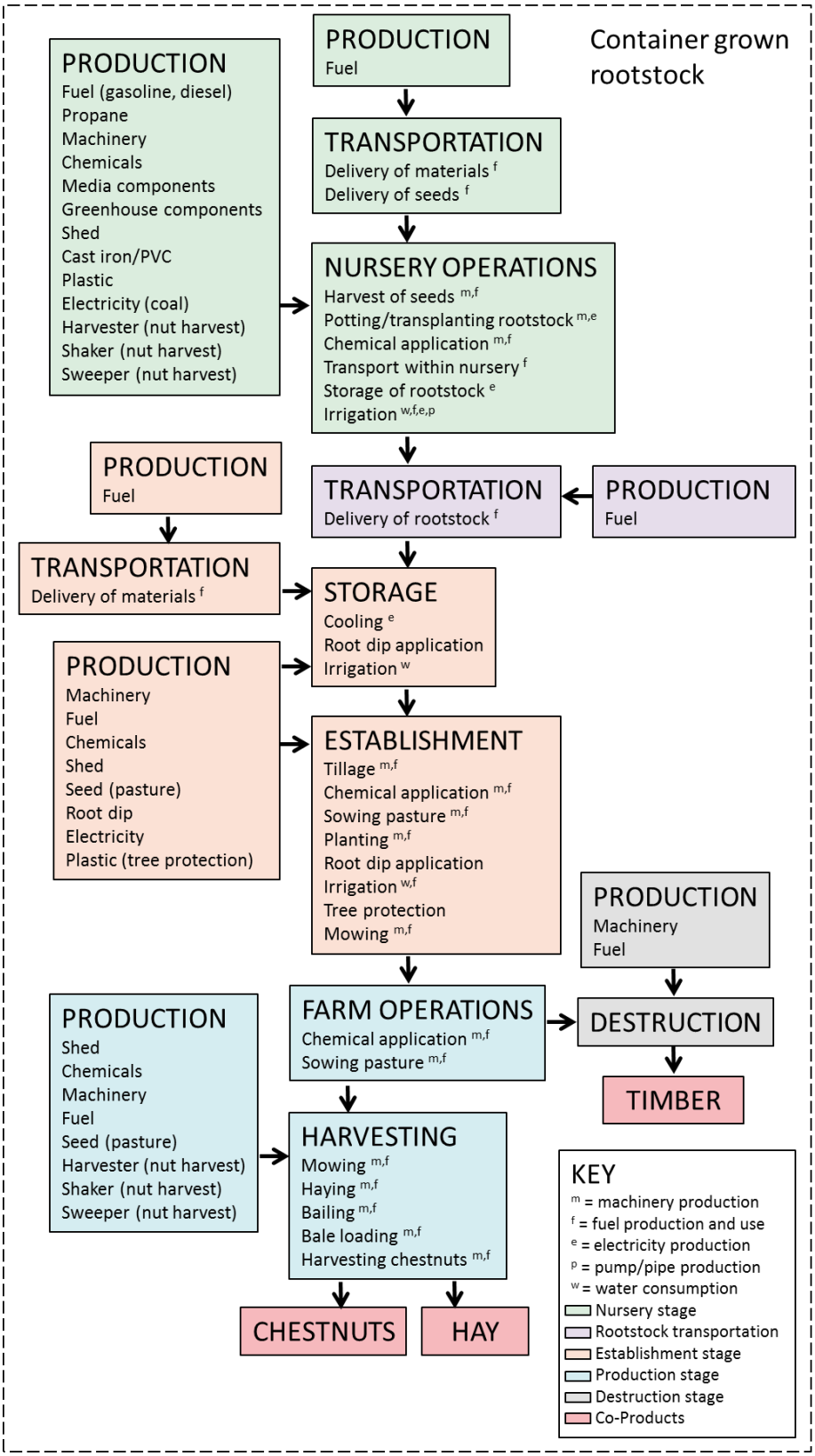


Figure 4: Boundary conditions for the inputs included in assessment of an orchard consisting of chestnut trees grown from container grown rootstock and pasture. Each color represents a different stage into which the inputs were included

Data listed within boundary conditions of Figure 3 and Figure 4 were collected from two field sites. Data for the nursery, transportation to the nursery, and transportation from the nursery to the farm were collected from a nursery in the Midwestern United States. Data for storage and establishment stage were collected from a Multifunction Woody Polyculture (MWP) research project field established in May 2015 on University of Illinois at Urbana-Champaign (UIUC) farm land. Before being cultivated with perennial agriculture in May 2015, the land was used for research purposes of conventional agriculture, specifically corn-soybean rotation.

3.2 Nursery

The visit to a nursery in the Midwestern United States took place in September of 2015. Upon arrival, I met with the owner of the nursery and the managers of the chestnut rootstock. After a short meeting discussing the MWP project, my role in the project, and what I was hoping to get out of the visit, the managers took me on a greenhouse and field tour. During the tour they described the process of growing rootstock from seed and answered my questions regarding the inputs required for growing a successful rootstock.



Figure 5: An example of a bare root rootstock (left) and a container grown rootstock (right). Upon being sold, the root mass of the two types of rootstocks is significantly different, with the container grown rootstock root mass being considerably larger

There are two types of Chinese chestnut rootstock available for purchase at this nursery: bare root and container grown. An example of each type of rootstock is shown in Figure 5. Both types of rootstock are grown from seeds collected from the same orchard, however they differ greatly in their size and root mass. These significant differences between the two types of rootstock are results of different management practices during growth. Following is the description of management practices used for each rootstock.

3.2.1 Bare root rootstock

Bare root is the type of rootstock purchased for the field study of the MWP research project. A bare root is the cheaper of the

two rootstock options, however it may have a lower survival rate post transplanting than a container grown rootstock. This type of rootstock also grows slower post transplanting and may require a longer time period before it is able to produce chestnuts.

Bare root rootstock is grown from seed in the field, as shown in Figure 6. Before the ground is ready for seeding, it must be tilled using a bedding plow and an 80-90 horsepower tractor. The tractor wheels are set 6 feet center to center. The beds where seeds are grown are made to be 400 foot long, four feet wide, and 4-6 inches high. No fertilizer is applied to the field prior or post planting. The seeds are received in the late fall, between October and early December, and are planted within a few days. The field is seeded using an 80-90 horsepower tractor and a two-person seeder. Roughly five 400-foot beds are seeded in one hour. Four seeds are planted in each row, with approximate density of 6-10 seeds per square foot. The depth of placing the seed into the ground is twice the diameter of the seed. Once the seed has been placed into to the ground, bark mulch is placed on the top of the seeded ground to keep it moist. The seeds are grown for two years.

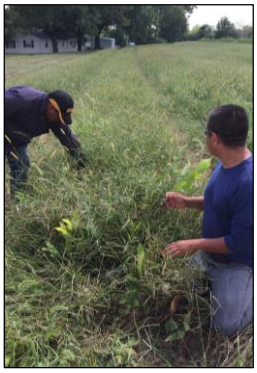


Figure 6: One of the beds in the field where bare root rootstock is grown during the nursery stage



Figure 7: Tractor used for pesticide application onto bare root rootstock field

During the two-year growth, overhead irrigation is practiced using water pumped from a lake. From beginning of May until end of June, the field is irrigated three times a week at 0.5 inches water depth. Between end of June and beginning of September, the field is irrigated every day at one inch water depth, and from the beginning of September until beginning of October the field is irrigated three times per week at 0.5 inches. The field is not irrigated between October and May. Pesticides Valor, Fusilade, and Gramoxon are sprayed separately using a tractor, similar to the one shown in Figure 7, between the months of March and June during both years of growth.



Figure 8: Digger used for harvesting bare root roostock

Two years after planting, an 18-inch seedling is ready to be harvested in October. A digger, pictured in Figure 8, pulled by an 80-90 horsepower tractor is able to harvest bare root seedlings at a rate of one 400-foot long bed per hour. Survival rate of seedlings from the time of planting to harvesting is roughly 50 percent. Upon harvest, seedlings are placed in a cooler over winder at 38 degrees Fahrenheit for storage until the following spring, at which time they are sold. While in cooler, it is important to keep the roots wet at all times thus water is sprinkled on the roots every day. Once a month water which is sprinkled on the roots is mixed with fungicide to prevent mold from growing on roots. In the spring following harvest the rootstock is wrapped into plastic, placed into a cardboard box, and shipped to buyer.

3.2.2 Container grown rootstock

Container grown is another type rootstock available for purchase from this nursery. This type of rootstock has a much larger root mass and is believed to have a higher survival rate post transplanting compared to bare root rootstock. Container grown rootstock is more expensive than bare root rootstock, however it is often a preferred option for orchard managers with little chestnut growing experience.

Container grown rootstock goes through three stages of growth. The seeds are first received in late fall, same as with bare root rootstock. During the first stage the seed is planted into a plastic container filled with media consisting of 40 percent pine bark, 10 percent pine wood, 30 percent reclaimed media, 20 percent sand, and 22-3-8 slow release fertilizer. Roughly 60 seeds are planted per tray, with the tray being reusable for five years. The trays are set onto pallets, watered, and sent to a cool storage facility for stratification. Trays stay in cool storage for 90-120 days with temperature set at 35-40 degrees Fahrenheit. Most years no electricity is required to keep the storage facility temperature low due to low temperatures outside. The soil in trays is kept moist through watering 3-4 times per week.



Figure 9: An example of a greenhouse where container grown rootstock is kept

After 90-120 days the trays are taken out of storage and placed into a temperature controlled greenhouse, pictured in Figure 9. The temperature inside the greenhouse is kept at 40 degrees Fahrenheit using propane fueled heaters. Here, the rootstock goes through the germination process. The rootstocks are kept in the stage one trays in the greenhouse from March until April.



Figure 10: Rootstock in stage one trays (left) and stage two pots (right)

In April, each seedling is transferred from stage one seedling trays to their own stage two small pot, pictured in Figure 10. Only about 40 percent of seedlings are transplanted and the rest are discarded. The growth media in stage two small pots is the same as in stage one, including the fertilizer. The slow release fertilizer in the media will last until stage three, thus no additional fertilizer will be added while in stage two. While in greenhouse, fungicide is sprayed on stage two rootstock every 30 days until stage three and the pots are watered at 0.5 inches of water every other day while the temperature outside is low and every day during the summer when the temperature is high.



Figure 11: Stage three rootstock is placed outside for the remainder of its time at the nursery

The seedlings are kept in small pots until June, at which time stage three begins with the transfer of seedlings from stage two small pots to stage three large, 3-gallon pots and placing the pots outside on a plastic liner, pictured in Figure 11. In the large pots, the same growth media is used with the same fertilizer addition. This is the only fertilizer addition to the large pots. In large pots only, Marengo pre-emergent herbicide is also added to the media at a rate listed on the label. While in large pots, the seedlings are watered every day using overhead irrigation, every pot getting roughly one inch of water per day during hot summer days and 0.5 inches during cooler days until middle of October when irrigation stops. Pesticide is sprayed every month, or as needed depending on the type of

pest to be killed. All four pesticides, Ortho Sevin, Orthene, Dursban, and Ovation, are mixed in a large tank in accordance with the product labels. Over winter the plants are covered with a cloth, which keeps them from freezing. The plants are sold the following spring and are delivered to the customer using a van.

3.3 Research Site

The research site is located on the UIUC research designated field in Urbana, Illinois. The site is 37 acres devoted to research of MWP established in May 2015. The goal of this research project is to determine the tradeoffs of converting a conventional agriculture field, such as corn-soybean rotation, to a multifunctional woody polyculture field.

The site is divided into 24 equal size plots, shown in Figure 12, measured 240 feet by 240 feet. Each plot is planted as one of the seven treatments. Each treatment is repeated four times, thus each plot represents one of the four repetitions of the seven treatments. Treatments one and two are combined in one plot with treatment one being a corn-soybean rotation treatment and treatment two made up of monoculture plots of chestnuts, apples, hazels, and currants. Treatment three is a plot on which chestnuts and hazelnuts are combined, planted in alternating rows with chestnuts planted at 30 feet apart and hazelnuts at 18 feet apart. Treatment four is the same as treatment three except that currants are planted in rows between all trees. Treatment five is the same as treatment four except that chestnuts and hazels are planted at double density, thus chestnuts are planted at 18 feet apart and hazels at nine feet apart. Treatment six is similar to treatment four in that it has chestnuts planted at 30 feet apart and hazelnuts 18 feet apart in alternating rows with

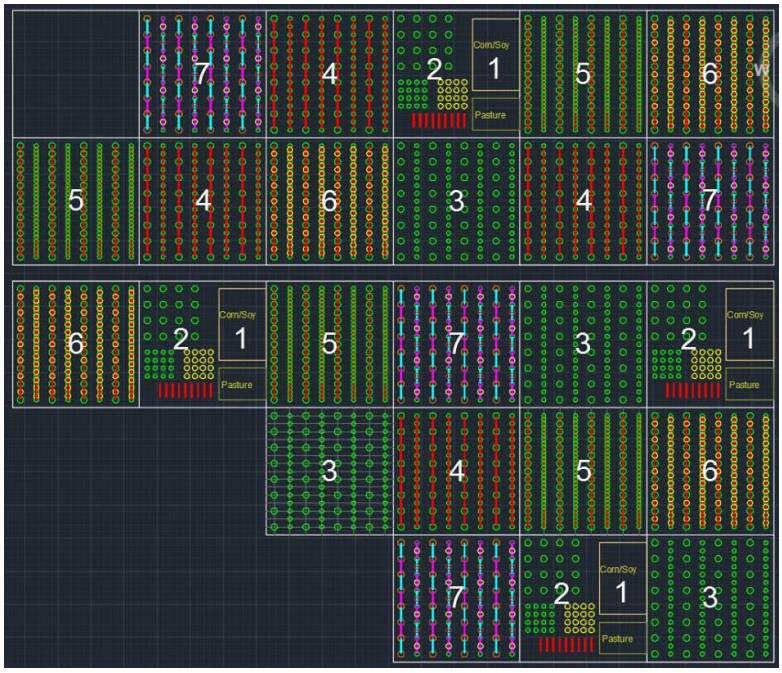


Figure 12: 24 equal size plots into which the research field was divided. Each plot represents one of the four repetitions of the seven different treatments planted

currants planted in tree rows between all trees. In addition to that, treatment six also has apples planted in rows between all trees as 30 feet apart in chestnut rows and 18 feet apart in hazel rows. Treatment seven is a native restoration plot with the same structure as treatment six except more diverse focusing on native species such as pawpaw, Saskatoon serviceberry, American hazelnut, elderberry, chokeberry and many more. In all of the treatments, pasture is grown in the 30 foot alleys between the tree rows.

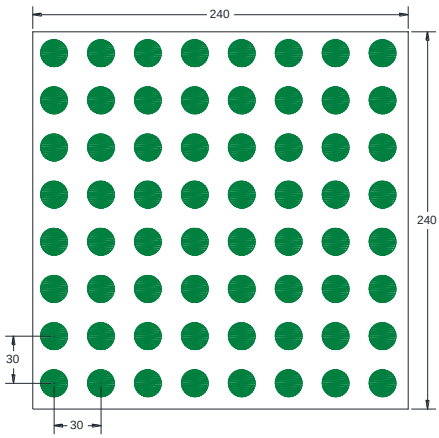


Figure 13: 240 foot by 240 foot plot representing an orchard consisting of chestnuts trees planted 30 feet apart

It is the goal of this research project to perform an LCA of all crops planted on this research field, however it was decided to first focus on chestnuts, because of the relatively easy access to the nursery data. Therefore, for the purpose of this thesis, data collection was focused on chestnuts within treatment three and the data reported here is relevant to chestnuts only. It was assumed that treatment three was planted with chestnuts at 30 feet apart with a density of 64 trees per treatment, as shown in Figure 13.

The establishment of the orchard stage begins with the field preparation, which involved tillage and fertilizer application. Pasture mixture was also sowed on the entire field prior to planting trees. The chestnut bare root rootstocks were delivered to the storage cooler near the research site in March 2015. Upon receiving the rootstock, the roots were dipped in a root dip solution and placed into a plastic container in which they were stored until planting. The containers were placed into the cooler, pictured in Figure 14, with temperature set to 60 degrees Fahrenheit. While in storage, the rootstocks were watered 3-4 times per week in order to avoid drying out the roots.



Figure 14: Cooler in which all rootstock was kept at the farm prior to being taken to the field

On the day of planting, which took place at the begging of May 2015, the plants were taken out of the cooler, roots were dipped into a root dip solution, and transported to the farm for planting. Once at the farm, the plants were placed into the root dip solution until they were ready to be planted, as pictured in Figure 15.



Figure 15: Rootstock was kept in a root dip solution at the farm prior to being planted

Two options were considered for planting. One option was using a hand held auger, and the other option was using a planter, pictured in Figure 16. In both scenarios, an ATV is used to transport the rootstock to the area of planting. In a case that a planter is used, the plants are kept in a root dip mixture inside the planter, which is not the case when an auger is used.



Figure 16: By planter is one of the ways which a farmer may choose to plant their orchard. The other option is using a handheld auger

After planting is complete, all plants are watered at a rate of one gallon of water per plant using a water tank and a truck, pictured in Figure 17. Once the pasture was ready to be mowed, equipment pictured in Figure 18 was used for mowing. The establishment stage is assumed to last through the end of the year of grafting, which will take place in May 2017. Thus, the establishment stage is assumed to last three years. During this stage no additional irrigation is considered. Pesticides are applied using a tractor, and fertilizer is assumed to be applied to each tree manually.



Figure 17: Truck and tank apparatus used for watering trees post planting

After the establishment stage is complete, low production stage begins, which is the year post the year of grafting, or year four. This stage is expected to last 9-12 years post the year of grafting. During this stage, if chestnuts are collected it is assumed that they would be collected by hand. The pasture is assumed to be mowed four time per year and begging with this stage haying, bailing, and bale loading is assumed to also take place.



Figure 18: Tructor and mower used for mowing pasture during the establishment and production stages

After 9-12 years of low production, full production stage begins at which time it is assumed that chestnuts will begin to be collected using nut harvesting equipment, including a harvester, shaker, and sweeper. During this stage mowing also takes place four times per year and hay is collected though haying, bailing, and bale loading. It is also assumed that once the trees grown large enough to produce a considerable amount of shade, the pasture will not be able to survive under the shade and will have to be re-sowed using a more shade tolerant mixture. Full production stage is expected to last for approximately 33-44 years. The yield was approximated using "Grower Decision Support Tool for Conversion to a Chestnut Orchard System" model developed by Michigan State University Extension.[80]

It is assumed that once the chestnuts decrease in yield that the trees will be cut down and the field will be replanted, thus end of life low production stage was not considered. During the destruction stage the trees are cut down using a forestry harvester and are assumed to be sold for timber.

4. Life Cycle Assessment of Woody Polyculture

4.1. Introduction

Conventional agriculture - by way of agricultural runoff - is the primary source of nitrogen and phosphorus delivered to the surface water[7–10] leading to nutrient enrichment of surface water and persistent recurrence of Gulf of Mexico hypoxia.[10,15] In particular, nutrient release from soil results from annual disturbance of land during preparation and harvest as well as post-harvest exposure of bare soil to wind and water erosion.[6] The common practice of fertilizer application onto agricultural fields increases the amount of nutrient released, especially when the fertilizer is applied far in advance of planting as the nutrients are not being used by plants and are more likely to runoff.[6]

In an effort to mitigate soil erosion, nutrient release, and ultimately global environmental impacts of conventional annual agriculture, a number of management techniques have been studied including conservative tillage practice,[19,20] cover crops,[21] and vegetative buffer strips.[19,22–24] However, there are limitations to these management strategies[19,21–24,26] as they are only incremental improvements and are not enough to substantially decrease environmental impacts of conventional agriculture. In order to alleviate global environmental impacts, transformation of agriculture is essential.[11]

In a pursuit of a more sustainable alternative to conventional agriculture, perennial crops have been a focus of recent discussion by a number of researchers.[27–30] However, a transformation from annual to perennial agriculture would require quantitative understanding of economic, social and environmental tradeoffs.[27] In order to define these tradeoffs, a comparative study must be performed where all inputs and outputs for each alternative system are assigned a numerical value, using an accepted matrix, signifying economic, social, or environmental worth of each input and output. These assigned numerical values for inputs and outputs are then combined for each alternative system to allow for quantitative comparison of the systems. Environmental impact assessment is a commonly used method which allows for comparative assessment of environmental tradeoffs between two systems. To ensure comparability between crops with different life spans, growth patterns, and cultivation methods, the inputs and outputs from the entire life of the crops may have to be considered in performing the environmental impact assessment

of the alternative systems. As one of the tools of choice in performing an environmental impact assessment, life cycle assessment (LCA) is often used when evaluating global environmental impacts of the entire life of an agricultural system.[33,34]

Among the perennial agriculture LCA literature, there are LCAs which include all stages of crop's life such as nursery, establishment, production, and destruction[35,36] while some LCAs make a simplifying assumption about the relative importance of nursery, establishment, and destruction stages and focus only on production stage. LCAs which only focus on one stage are most commonly comparative studies looking at various management practices of a specific crop and only exclude aspects which are the same for each alternative.[38,39,78] While excluding certain stages is acceptable in comparative assessments,[133] disregarding inventory of omitted stages in a life cycle environmental assessment of a complex perennial cropping system oversimplifies it. Oversimplification of a perennial crop assessment may cause researchers to leave out a significant amount of environmental impacts associated with the life cycle of a perennial crop. Thus, studies which do not include all stages of a perennial crop's life may not be used to represent the crop's life cycle environmental impacts nor used in comparison to other crop's environmental impacts. To avoid oversimplifying the complexity of a perennial crop, a well performed LCA must capture crop's entire life cycle and encompass environmental impacts over several impact categories.[40]

Very few studies have looked at relative environmental significance of the nursery stage of a perennial crop,[35,36,41,42] thus it is unknown what about the perennial crop makes the nursery stage significant or insignificant.

The objective of this work was to determine the relative significance of the nursery stage for a Chinese chestnut tree (*C. mollissima*) relative to the life cycle environmental impacts of a multi-cropping perennial agriculture system comprising of chestnut trees and pasture. To this end, LCA of the orchard system was performed accounting for all stages of the systems' life, including nursery operations, establishment stage, production stage, and destruction. For the nursery and establishment stages, data were collected from existing sites and for production and destruction stages data were estimated. Uncertainty and sensitivity analyses were conducted on all inventory. The resulting impacts of a chestnut tree's nursery stage were compared to the environmental impacts of the systems'

establishment, production, and destruction stages thus determining the relative significance of the nursery stage. The nursery stage was then analyzed in an effort to outline the inputs with the largest environmental impacts. The environmental impacts of the system's life cycle were further allocated to three co-products of the system, hay, timber, and chestnuts, using physical relationship allocation and mass allocation methods in order to determine each product's contribution to the environmental impact associated with the system.

4.2. Methods

4.2.1 Goal and Scope Definition

LCA is widely used in evaluating environmental impacts of agricultural decisions[36–39,78,126] and was used here as an assessment tool in determining significance of chestnut tree's nursery stage relative to the life cycle environmental impact of a multi-cropping orchard system consisting of chestnut trees and pasture.

One target outcome of this work is to provide a sound basis for other researchers' decision-making for the inclusion or exclusion of the nursery stage as a whole or partially in future LCA studies of similar crops. LCA was carried out according to the methodology of ISO 14040/14044.[55,56] The functional unit for this study was 1 chestnut tree over the life time of the orchard. The exact life time of the chestnut orchard was varied during the uncertainty analysis. Inputs to pasture were divided per tree according to the density of planted trees, thus the functional unit for pasture inputs was also 1 chestnut tree over the life time of the orchard. The system was assumed to have three co-products: chestnuts, timber, and hay. The system boundary was set from cradle-to-gate, beginning with production of all inventory inputs and ending with harvested products at farm gate. All stages of the system's life were included, encompassing nursery, establishment, low production, full production, low production near the end of life, and destruction of the orchard. For all stages, the following inputs were considered: irrigation equipment production, tillage, all chemical application including chemical production and the application itself, all direct machinery use, planting, harvesting, energy used for cooling and heating, production and use of all fuel, mowing of pasture, and production of mulch. The inventory for gathering of seeds to be planted at the nursery was also included. The use of shed for storing machinery was included as well as production of materials used for building a greenhouse; however, all other infrastructure

was excluded. All transportation to the nursery and the farm was considered as well as transportation within the nursery and the farm, including fuel production and use. Transportation from the nursery to the farm was also considered, including fuel production and use as well as bare root packaging material.

4.2.2 Life Cycle Inventory (LCI)

Separate input inventory was collected for each stage of the system's life. Primary source of inventory data for the nursery stage was a nursery in the Midwestern United States with data being collected in the fall of 2015. Data was compiled through a combination of a site visit and electronic data requests. At the time of the visit, owners, managers, and laborers were interviewed. Detailed data received from the nursery includes irrigation rates, pesticide application rates, fertilizer use rates, mulch use rates, as well as tillage, planting, and harvesting practice specifics. Where the nursery was not able to provide inventory values, secondary data sources were utilized. Fuel use in delivering seeds and materials to the nursery, transportation within the nursery, and fueling the irrigation pump as well as electricity use for the cooler was estimated using literature. Data regarding transportation from the nursery to the farm were collected from the nursery.

Inventory data for the establishment stage were gathered from a multifunctional woody polyculture research site in Urbana, Illinois, property of University of Illinois at Urbana-Champaign. Establishment stage was assumed to last three years, from the time rootstock is planted to the time it is grafted. Raw data was gathered for the first two years and estimated for the third year with the help of researches and staff in charge of the farm. Inventory for production and destruction stages was conservatively estimated based on researchers' plans and literature. High uncertainty was placed around all estimated values.

Uncertainty and sensitivity analyses were performed using Monte Carlo with Latin Hypercube Sampling (LHS; 10,000 runs) to propagate uncertainty for all input parameters and quantify life cycle environmental impacts for the studied system. Physical relationship and mass based allocation methods were used for input allocation between co-products.

4.2.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) was conducted using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2.1 V1.02,

US-Canada 2008), which classifies and characterizes the impact for each raw material and emission across ten categories: stratospheric ozone depletion, global warming potential (GWP), photochemical oxidation (smog), acidification, eutrophication, human health: carcinogenic, human health: non carcinogenic, human health: respiratory effects, ecotoxicity, and fossil fuel depletion. No normalization, weighting, or aggregation beyond TRACI was performed. Water consumption impact was assessed separately using Available WAter REmaining (AWARE) method developed by Water Use in LCA group (WULCA).

4.3. Results and Discussion

4.3.1 Environmental Impact of the Nursery Stage

The environmental impact for each stage of the orchard system consisting of chestnut trees and pasture was calculated. Stages considered are nursery, establishment, production, and destruction. Yield fluctuation during the production stage was considered. Transportation from the nursery to the farm was also considered. Uncertainty and sensitivity analyses were performed for each stage. Results for each stage's contribution to the total environmental impact of the system within each environmental impact category is presented in Figure 19 for chestnut trees grown from bare root rootstock and in Figure 20 for chestnut trees grown from container grown rootstock. Box and whisker plots represent the results of the uncertainty analysis, showing 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of each stages' possible contribution. Values from which the percentages were calculated are included in Section 3.4.1 of Supporting Information.

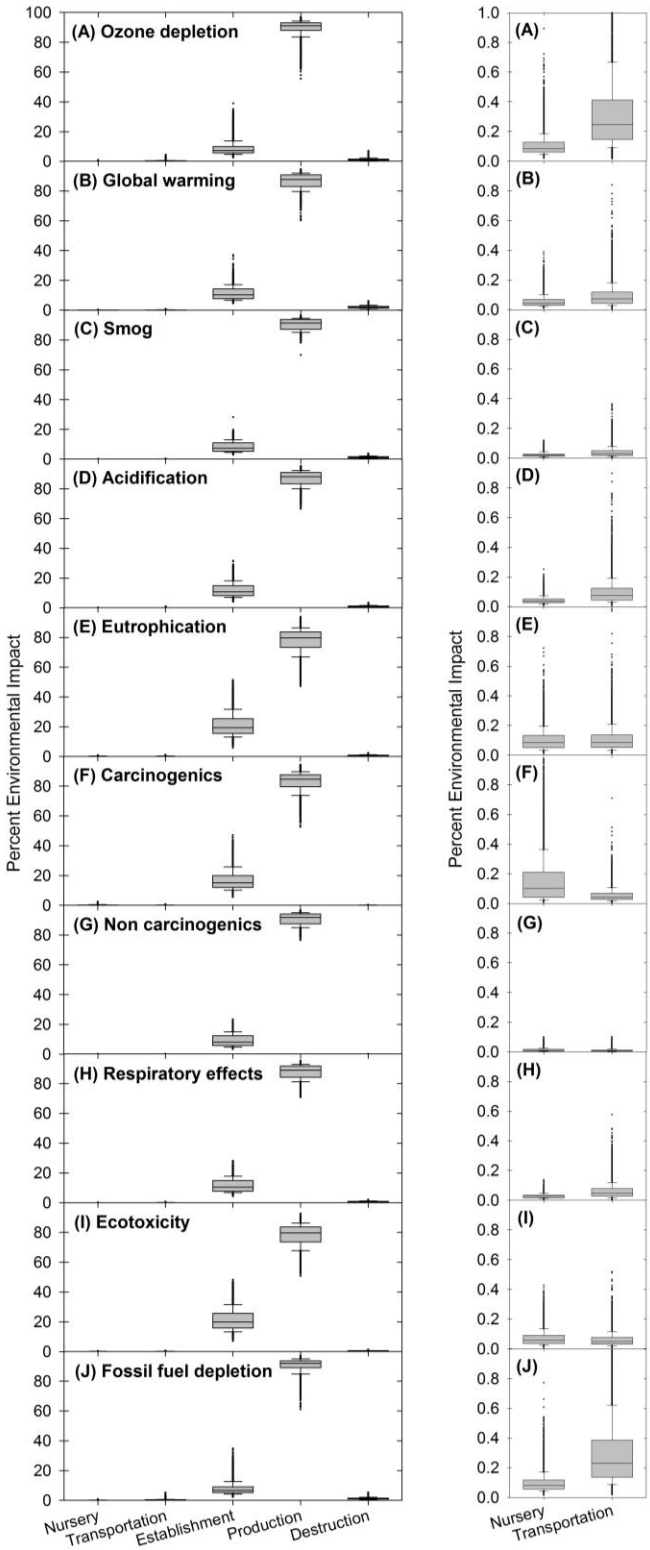


Figure 19: Significance of each stage across all considered environmental impact categories of the orchard system consisting of chestnut trees grown from bare root rootstock and pasture. Box and whisker plots represent 10th, 25th, 50th, 75th, and 90th percentiles of possible percentage each stage contributes to the total environmental impact of the system. The nursery stage of this system was determined to be insignificant in all impact categories, bearing less than 1% of the total environmental impact of the entire life cycle of the system. Transportation of rootstock from nursery to the orchard was demonstrated to be insignificant

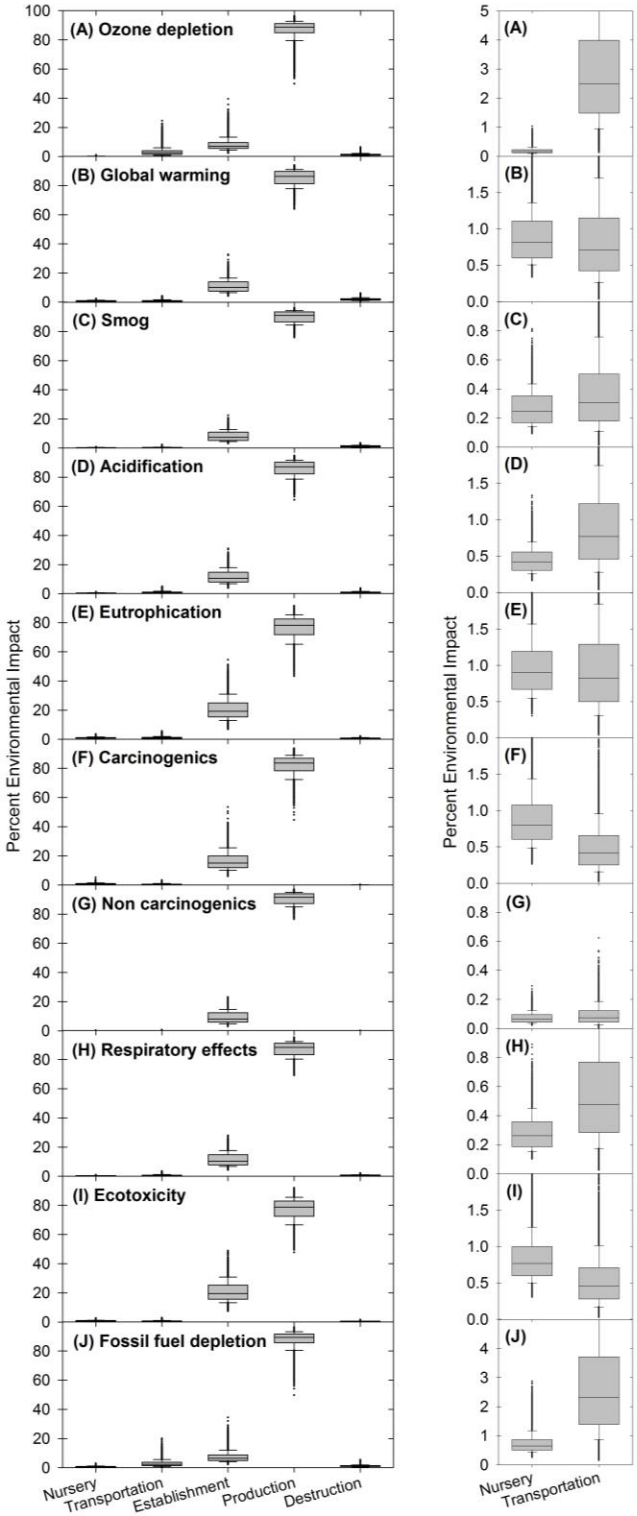


Figure 20: Significance of each stage across all environmental impact categories of the orchard system consisting of chestnut trees grown from container grown rootstock and pasture. Box and whisker plots represent 10th, 25th, 50th, 75th, and 90th percentiles of possible percentage each stage contributes to the total environmental impact of the system. The nursery stage of this system was determined to be insignificant, bearing less than 2% of the total environmental impact of the entire life cycle of the system in all impact categories

Using the environmental significance cut-off criteria, described in section 4.2.3.3 of ISO 14044:2006(E), it was determined that any stage with 75th percentile equating to less than two percent contribution to the life cycle environmental impact of the orchard system is insignificant. However, if the stage is considered significant in one impact category, then it is determined to be significant in all impact categories. From results presented in Figure 19 for the bare root rootstock and Figure 20 for the container grown rootstock, it can be concluded that the nursery stage in both cases has an insignificant contribution to the environmental impact of the system's life cycle in all impact categories. It can also be concluded that transportation of the bare root rootstock from the nursery to the farm is insignificant, however transportation of the container grown rootstock has a significant contribution to the system's life cycle environmental impact in two impact categories: ozone depletion and fossil fuel depletion. Significance of transportation of rootstock from the nursery to the farm is highly dependent on the transportation distance and fuel use. Bare root rootstock, being smaller than container grown rootstock, can be transported with other items, thus fuel use allocated to the bare root rootstock is significantly less than fuel allocated to the container grown rootstock. Further examining the figures, production stage has the largest contribution to the system's life cycle environmental impact in all impact categories. Within the production stage, production and use of machinery as well as production and use of fuel during the harvesting activities of chestnuts and pasture are the most significant inputs. This is consistent with other studies which found machinery and fuel use to be significant.[39,126]

It must be recognized that significance of one stage is highly dependent on inputs within another stage. For instance, if during the production stage the pasture was not mowed, but grazed by animals, and chestnuts were harvested by hand, then the contribution of the production stage to the total environmental impact of the system would decrease significantly. Significant decrease in the contribution of the production stage to the total environmental impact of the system may potentially make the nursery stage a significant contributor.

4.3.2 Most Significant Components of the Nursery Stage

Although it was concluded that in the case of the system studied the nursery stage contributes insignificantly to the total environmental impact of the system, this may not be the case with all studies. Significance of the nursery is highly dependent on the management practice and the inputs which are used in rootstock cultivation, and although many management scenarios were considered during the uncertainty analysis, some management practices may have been missed. Therefore, for the most accurate results, each nursery must be reviewed separately in order to determine whether its contribution to the life cycle environmental impact would be significant. In order to potentially be able to quickly determine whether the nursery stage may be significant without performing a full LCA, it may be helpful to know which inputs typically contribute the most to the environmental impact of the nursery and then evaluate the nursery based on its use of these inputs.

In order to determine which inputs contributed the most to the total environmental impact of the nursery stage, all inputs of the nursery stage were analyzed for their individual impacts and uncertainty. Figure 21 presents the results for inputs of the bare root rootstock in the ozone depletion impact category. Figures for container grown rootstock and the rest of the bare root rootstock impact categories may be found in section 3.4.2 of Supporting Information. For each input in Figure 21 box and whisker plots represent the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of each input's contribution to the total environmental impact of the nursery stage.

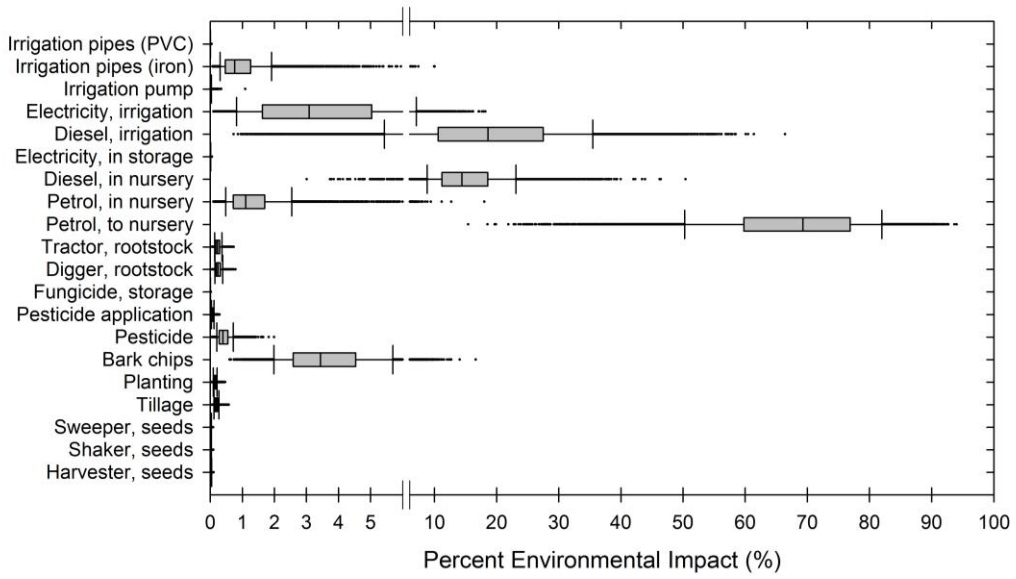


Figure 21: Percent environmental impact for which each input is responsible in the ozone depletion impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage. The figure shows which inputs significantly impact the total environmental impact of the bare root nursery stage

In determining the inputs that had a significant contribution to the total environmental impact of the nursery stage, environmental significance cut-off criteria was used considering inputs with 75th percentile greater than or equal to five percent of the total environmental impact of the nursery stage to have a significant contribution to the total environmental impact of the nursery. The results of this analysis can be viewed in Table 10 for the bare root rootstock nursery and in Table 11 for the container grown rootstock nursery.

Table 10: Relative significance of the bare root rootstock nursery inputs. Inputs marked with an "x" were determined to have a significant contribution to the total environmental impact of the bare root nursery in the impact categories under which the mark is located. Significance is measured as input's 75th percentile being equal to or greater than five percent of the total environmental impact of the bare root nursery in any impact category. Irrigation pipes: either PVC or iron pipes are used, analyses for both cases were performed. Fuel for irrigation: either electricity of diesel is used, analyses for both cases were performed. Diesel and petrol: both production and distribution to end user are considered. Electricity was assumed to be produced from coal

Input	Includes	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Irrigation pipe (PVC)	production of pipe material (PVC)		x				x				
Irrigation pipe (iron)	production of pipe material (cast iron)		x	x	x	x	x	x	x	x	
Irrigation pump	production of pump material (cast iron)						x				
Electricity, irrigation	electricity is used to fuel irrigation pump		x	x	x	x	x	x	x	x	
Diesel, irrigation	diesel is used to fuel irrigation pump	x	x	x	x	x	x	x	x	x	x
Electricity, storage	production of electricity used in storage										
Diesel	diesel use in harvesting seed and rootstock	x	x	x	x	x			x		x
Petrol, in nursery	gasoline use in nursery										
Petrol, to nursery	delivering seed and materials to nursery	x	x	x	x	x	x	x	x	x	x
Tractor, rootstock	production of tractor used during harvest										
Digger, rootstock	production of digger used during harvest						x				
Fungicide, storage	production of chemicals applied in storage										
Pesticide application	production and use of machinery and diesel										
Pesticide	production of pesticides applied to field										
Bark chips	production of bark chips for mulch		x	x	x	x	x	x	x	x	
Planting	production and use of tractor, planter, diesel							x			
Tillage	production and use of tractor, plough, diesel										
Sweeper, seeds	production of machinery for seed harvesting										
Shaker, seeds	production of machinery for seed harvesting										
Harvester, seeds	production of machinery for seed harvesting										

Table 11: Relative significance of the container grown rootstock nursery inputs. Inputs marked with an "x" were determined to have a significant contribution to the total environmental impact of the container grown rootstock nursery in the impact categories under which the mark is located. Significance is measured as input's 75th percentile being equal to or greater than five percent of the total environmental impact of the bare root nursery in any impact category. Irrigation pipes: either PVC or iron pipes are used, analyses for both cases were performed. Fuel for irrigation: either electricity of diesel is used, analyses for both cases were performed. Diesel and petrol: both production and distribution to end user are considered. Electricity was assumed to be produced from coal

Input	Includes	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Cover cloth	production of plant protective cover cloth										
Plastic liner	production of ground liner for field										
Irrigation pipe (PVC)	production of pipe material (PVC)										
Irrigation pipe (iron)	production of pipe material (cast iron)						x	x		x	
Electricity, irrigation	electricity is used to fuel irrigation pump			x		x	x	x		x	
Diesel, irrigation	diesel is used to fuel irrigation pump	x									
Irrigation pump	production of pump material (cast iron)										
Aluminum, GH	production and extrusion of aluminum for greenhouse						x			x	
Wooden trim, GH	production of wood for greenhouse structure										
Floor liner, GH	production of plastic for greenhouse floor liner										
Mesh for roof, GH	production of mesh for greenhouse roof lining										
Plastic roof liner, GH	production of plastic for greenhouse roof lining										
Door, GH	production of the door used in greenhouse										
Propane, GH	production of propane used for heating greenhouse										
Pesticide application	machinery and diesel use in stage 3 application										
Fungicide, storage	production of chemicals applied in storage										
Pesticide	production of pesticides applied rootstock	x									
Electricity, storage	production of electricity used in storage										
K_2O fertilizer	production of potassium sulfate (50% K_2O)							x			
P_2O_5 fertilizer	production of single superphosphate (21% P_2O_5)										
N fertilizer	production of calcium ammonium nitrate (26% N)	x	x	x	x	x	x	x	x	x	
Sand, media	production of sand used in media										
Pine wood, media	production of pine wood chips used in media					x					
Pine bark, media	production of pine bark chips used in media	x	x	x	x	x	x	x	x	x	x
Electricity, mixer	production of electricity used in media mixer										
Media mixer	production of media mixer						x	x	x	x	
Plastic	production of plastic for pots and trays		x	x	x	x	x	x	x	x	x
Petrol, in nursery	gasoline use in nursery										
Petrol, to nursery	delivering seed and materials to nursery	x							x		x
Diesel, seeds	diesel use in seed harvesting										
Sweeper, seeds	production of machinery for seed harvesting										
Shaker, seeds	production of machinery for seed harvesting										
Harvester, seeds	production of machinery for seed harvesting										

In the bare root rootstock nursery most of the significant contribution was incurred by energy use, including petrol, diesel, and electricity. Other significant contributors are irrigation pipe production, machinery production, and mulch production. In the container grown nursery, some of the significant contribution is due to energy use, including diesel, petrol, and electricity. However, production of fertilizer, plastic, mixer, media, aluminum, and pesticides also had significant contribution to the total environmental impact. Comparing these results to other studies, there is some consensus on fuel and plastic use being significant contributors.[74–76] However, there is a disagreement on significance of chemical production and use.[75]

This leads to question whether these results are generalizable. The inputs listed as significant contributors to the total environmental impact of the nursery are not expected to change from nursery to nursery. However, the amount of these inputs used may change from nursery to nursery due to different management practices, thus how impactful these inputs may change. Therefore, if a study has concluded that an LCA of the nursery stage must be included, it is advisable to collect raw data for the nursery applicable to that study.

4.3.3 Sensitivity

Oracle Crystal Ball was used in performing the sensitivity analyses of all environmental impact results. The program uses Spearman's rank correlation in order to determine which inputs contribute the most to variance of results. Because correlation does not necessarily mean causation, in order to avoid errors, only assumptions that are directly relevant to calculation of the stage being analyzed were selected. For example, when analyzing the results of the nursery stage, only the nursery stage inputs were selected to be analyzed. Since all inputs contribute to the sensitivity of the results in some way due to the uncertainty range around all inputs, only inputs with a contribution to variance of greater than two percent were considered. Inputs with contribution to total variance of less than two percent were combined and considered as "Other." The results of the sensitivity analyses are shown in Figure 22 through Figure 27.

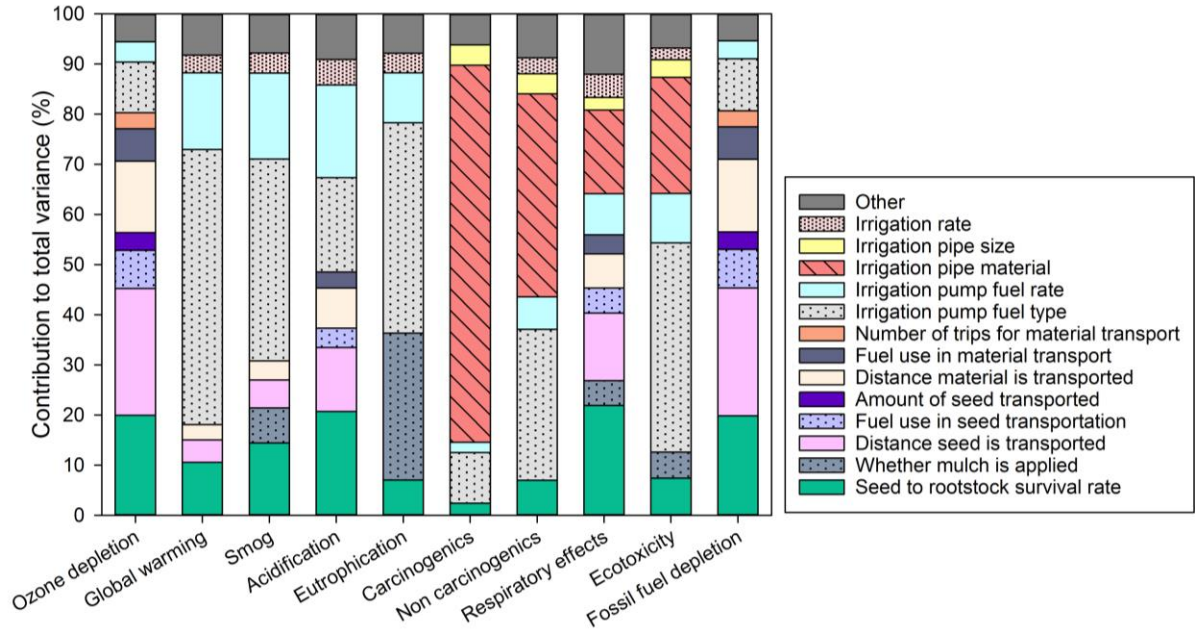


Figure 22: Sensitivity analysis results for the nursery stage of a bare root rootstock. The input parameter of irrigation pump fuel type (diesel vs electricity) contributes significantly to the sensitivity of results in most impact categories. Irrigation pump material (PVC vs cast iron) contributes significantly to the variance in impact categories of carcinogenics and non carcinogenics

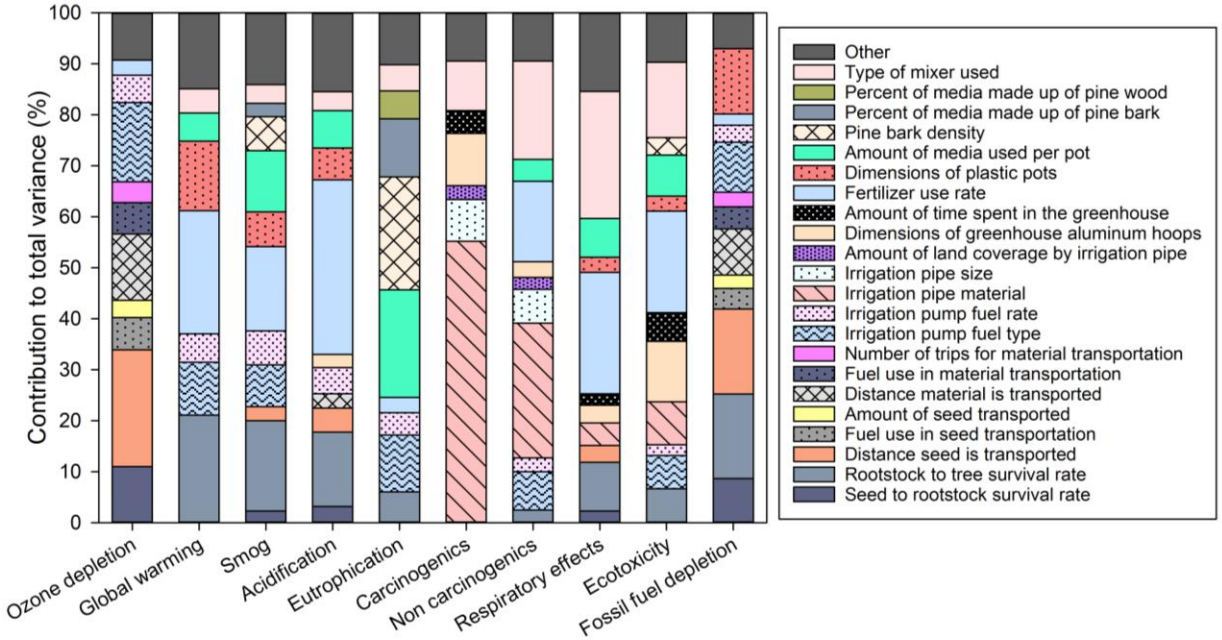


Figure 23: Sensitivity analysis results for the nursery stage of a container grown rootstock. None of the input parameters are the most significant contributors to sensitivity of results in all impact categories. However, some input parameters are more significant than others in some impact categories, such as irrigation pipe material (PVC vs cast iron), type of mixer used, rootstock to tree survival rate, fertilizer use rate, and distance seed is transported

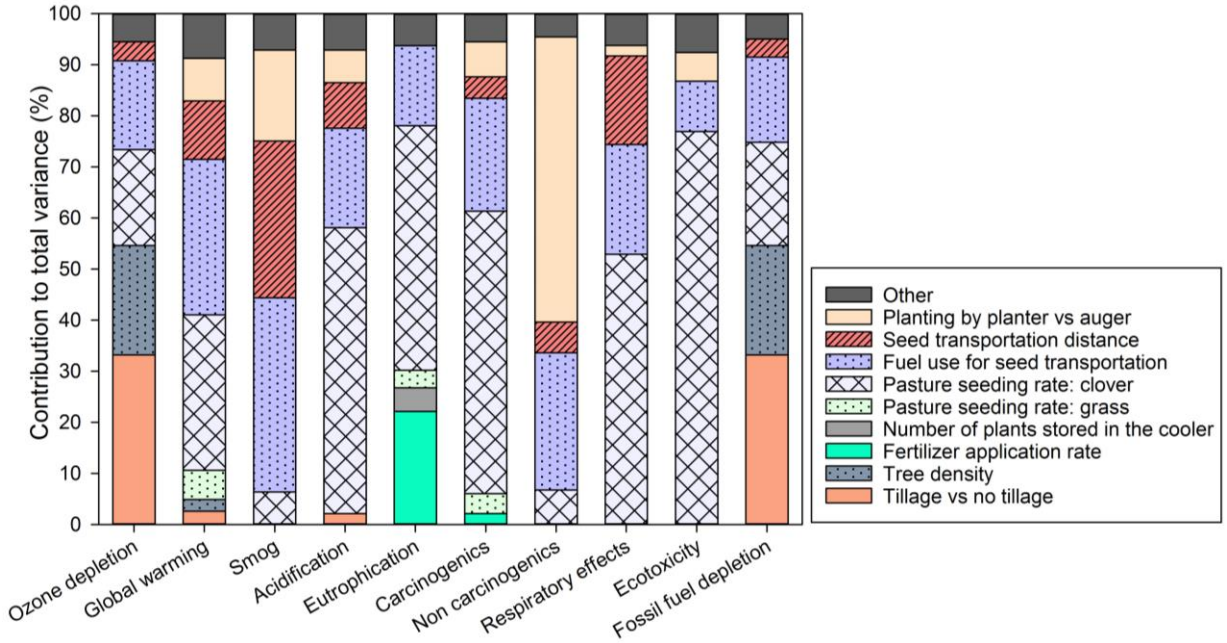


Figure 24: Sensitivity analysis results for the establishment stage of an orchard consisting of chestnut trees and pasture. Some of the most significant contributors to the variance of results include planting technique (planter vs auger), amount of fuel used in seed transportation to the farm, amount of clover used in seeding pasture, and tree planting density

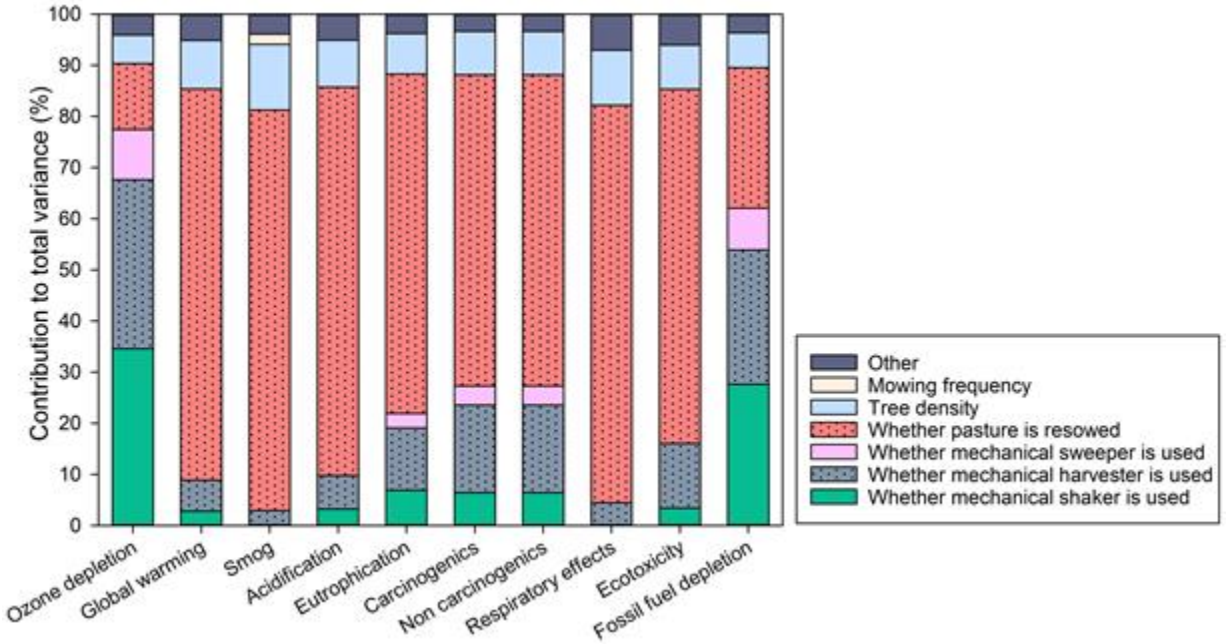


Figure 25: Sensitivity analysis results for the production stage of an orchard consisting of chestnut trees and pasture. The most significant contributor to the variance of environmental impact results is whether the pasture is resowed. This is significant, because if the pasture is not resowed, then pasture harvesting activities would not take place during most of the production stage. However, if the pasture is resowed, then the pasture harvesting activities would take place contributing significantly to the total environmental impact of the system

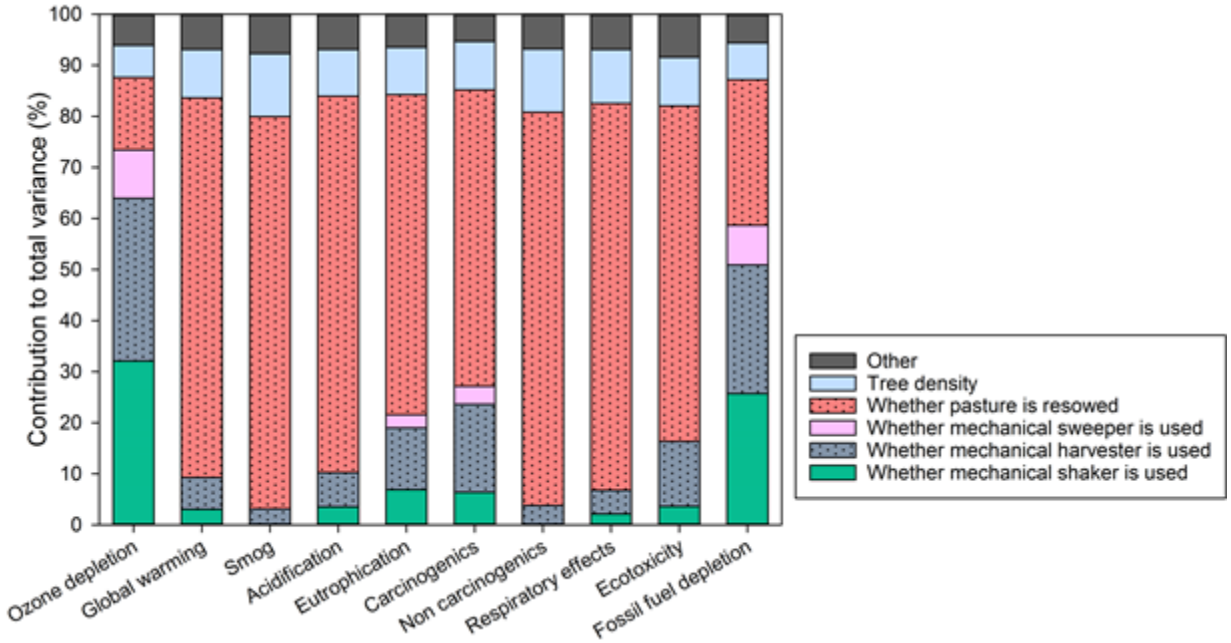


Figure 26: Sensitivity analysis results for the entire life cycle of an orchard consisting of chestnut trees grown from bare root rootstock and pasture. Results presented here are very similar to the results presented in the figure for the production stage of the system. Similar to the production stage, contribution to variance here is also dominated by machinery use

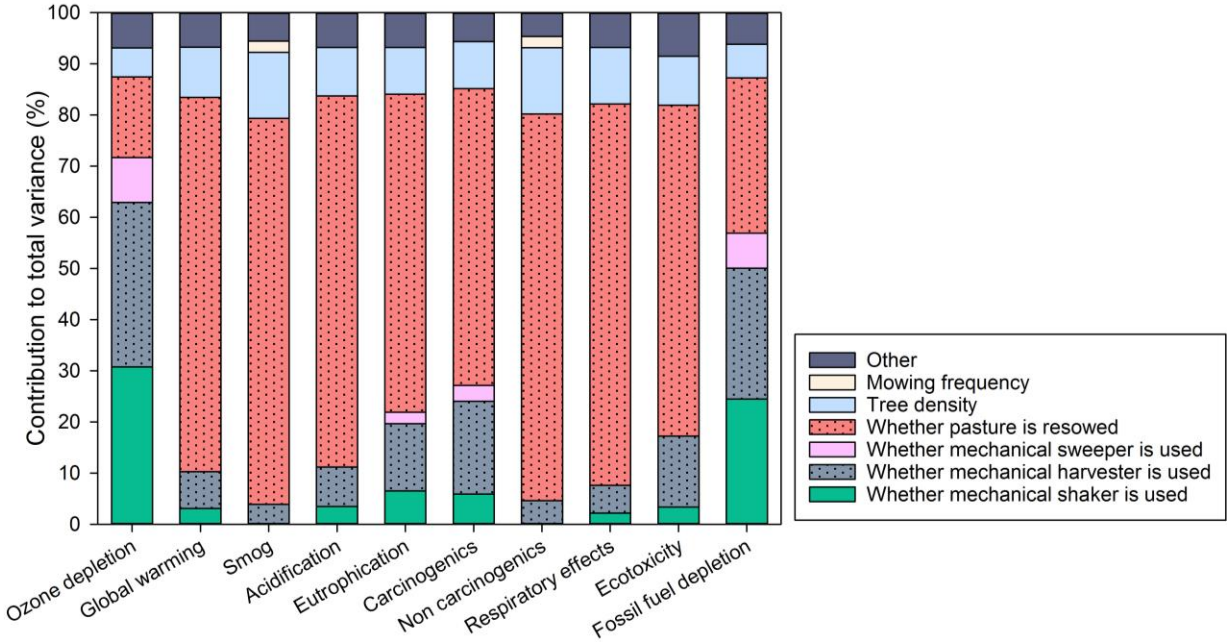


Figure 27: Sensitivity analysis results for the entire life cycle of an orchard consisting of chestnut trees grown from container grown rootstock and pasture. Results presented here are very similar to the results presented in the figure for the production stage of the system. Similar to the production stage, contribution to variance here is also dominated by machinery use

The results of the sensitivity analyses presented in Figure 22 through Figure 27 show that for the nursery stage there is not one input that is the dominant cause of variance. In the establishment stage, a lot of the variance is caused by the seeding rate of clover due to a high uncertainty range placed around clover seeding rate. However, a significant portion of the

variance not caused by the clover seeding rate is caused by inputs related to fuel and machinery use, such as planting technique and fuel use during seed transportation. For the production stage, the majority of variance is caused by whether certain machinery is used, such as whether certain chestnut harvesting equipment is used or whether the pasture is resowed, which would dictate whether mowing takes place for majority of the production stage. Variance of these inputs is linked to variance in machinery use and fuel use during the production stage.

When performing the sensitivity analyses of the entire life cycle of the system, the results shown in Figure 26 and Figure 27 are very similar to results of the production stage shown in Figure 25. This is not surprising as the production stage is the largest contributor to the total environmental impact of the system, thus sensitivity of the production stage in turn affects sensitivity of the entire LCA.

4.3.4 Allocation

In a multi-cropping system such as this, the total environmental impact over the system's lifetime must be attributed to all co-products in accordance with a selected allocation method. Data for pasture was collected separately from chestnuts and timber, thus allocation of inputs between pasture and chestnuts/timber was performed using physical relationship allocation method. However, because chestnuts and timber are co-products of one entity (the tree), most inputs cannot be allocated using the physical relationship method and must be allocated using a volume, economic, or mass allocation method. All three allocation methods were considered. Uncertainty and sensitivity analyses were performed on all three methods using Monte Carlo with Latin Hypercube Sampling (LHS; 10,000 runs) to propagate input uncertainty for 10 parameters (Table 12) and quantify probable percentage of inputs to be allocated to chestnut and timber co-products within each allocation method. Assigned values were based on the literature or were conservatively estimated if data were lacking.

Table 12: Input parameters used in performing uncertainty and sensitivity analyses on all three allocation methods: volume, mass, and economic. Probability functions are characterized by minimum, most probable, and maximum for triangular distribution

Parameter	Units	Distribution	Values	Citations
Years of orchard life post grafting	years	Triangular	45, 50, 55	80
Tree planting density	trees acre^{-1}	Triangular	36, 49, 70	80–82
Timber density	lbs ft^{-3}	Triangular	28, 29, 30	95,127
Timber length for lumber	ft	Triangular	7, 10, 13	80
Tree diameter at breast height	in	Triangular	4, 6, 10	128
Timber selling price	$ (board ft)$^{-1}$	Triangular	3, 5.5, 8	129,130
Chestnut yield at full production	lbs acre^{-1}	Triangular	1000, 2500, 3500	80–82
Chestnut selling price	$ lb^{-1}	Triangular	2.45, 3.1, 3.5	80,82
Chestnut weight	nuts lb^{-1}	Triangular	34, 36, 38	83
Chestnut diameter	in	Triangular	1, 1.12, 1.25	131

Chestnut yield fluctuation over the life time of a chestnut tree was taken into account using "Grower Decision Support Tool for Conversion to a Chestnut Orchard System" model developed by Michigan State University.[80] The tool assumes that no yield is produced during the first five years. During year six 4% of full production yield can be expected and during year seven 8% can be expected. Beginning with year eight, an increase of 10% takes place every year until yield reaches 100%, or full production, at year 16. Chestnut orchard is expected to have full production yield from year 16 through year 45. Starting at year 46, the yield will begin decreasing at a rate of 2.3% every year until year 51, which is the last year predicted by the tool. It was assumed that year zero is the year of grafting, and the total yield over orchard life time was calculated using the full production values listed in Table 12. Chestnut yield prediction over the lifetime of the orchard is presented in Figure 28.

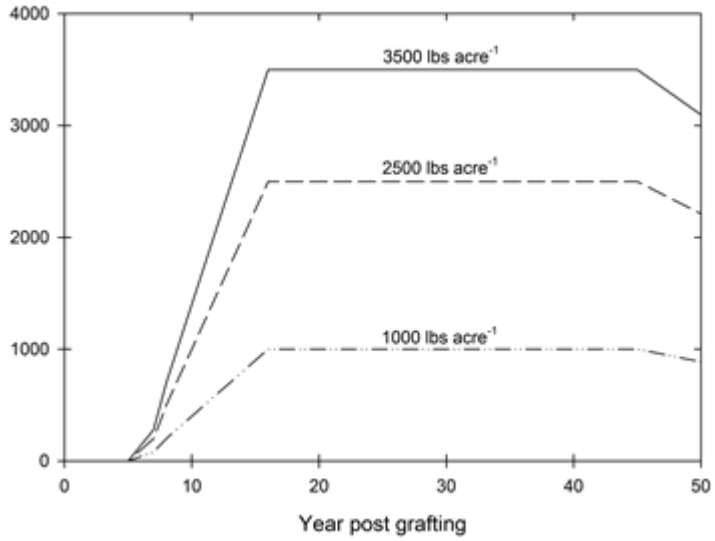


Figure 28: Yield prediction of a chestnut orchard over life time based on data provided by MSU Extension study[80] with estimates of 1000, 2500, and 3500 lbs per acre yield at full production

Uncertainty and sensitivity analyses results for each allocation method are presented in Figure 29 and Figure 30.

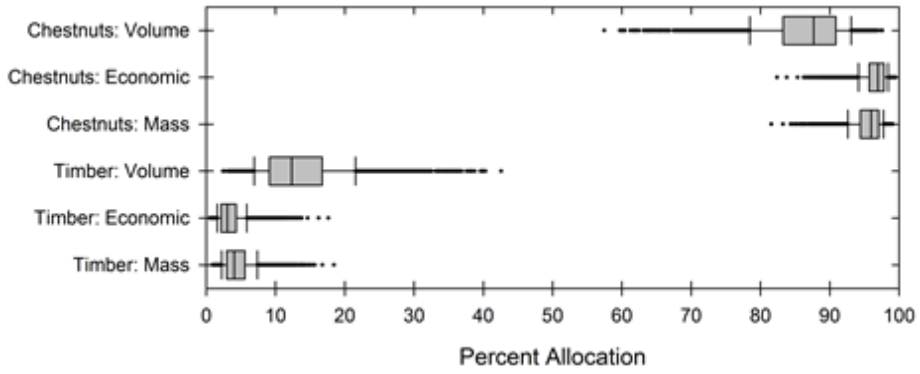


Figure 29: Uncertainty analysis results for each allocation method showing 10th, 25th, 50th, 75th, and 90th percentiles of percent allocation each method would allocated to each co-product. All three allocation methods allocate majority of inputs to chestnut co-product

Analysis of the three allocation methods presented in Figure 29 show that using any of the three allocation methods will yield a significantly larger portion of inputs to be allocated to chestnuts over timber. However, there is a disagreement between allocation methods to the percentage of inputs each co-product should receive. A much larger percentage would be allocated to timber using volume allocation method over economic or mass allocation methods. Economic and mass allocation methods yield similar results, with economic allocation method yielding a bit higher percentage of inputs being assigned to chestnuts than mass allocation method.

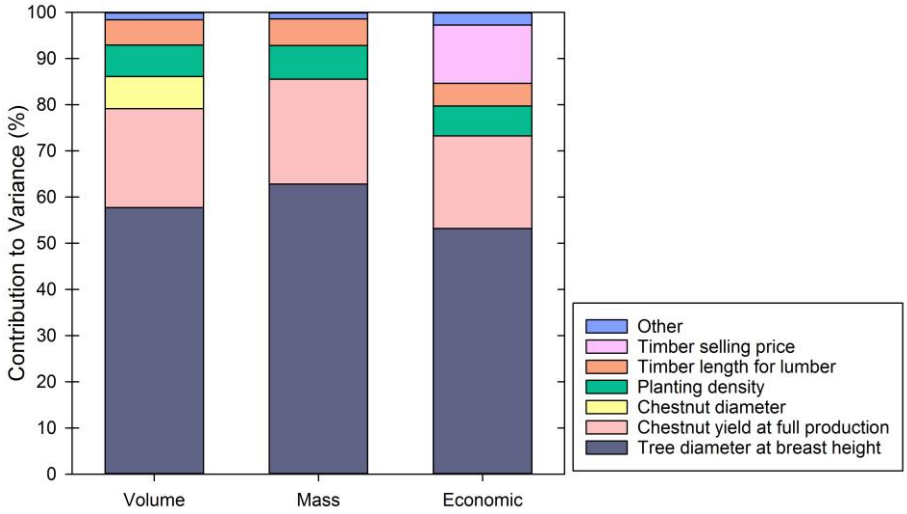


Figure 30: Sensitivity analysis, of results presented in Figure 29 showing contribution to variance each input parameter has on each allocation method. Based on the data, tree diameter at breast height input parameter contributes significantly to the uncertainty of results presented in Figure 29 with chestnut yield at full production being the second largest contributor

From the sensitivity analysis results presented in Figure 30, the input parameter "tree diameter at breast height" contributes significantly to the variation of allocation results presented in Figure 29. Going back to the original assumptions presented in Table 12, more specific data could not be found, thus we were not able to redefine the "tree diameter at breast height" assumption in an effort to have a smaller variance in the results.

In making the decision of allocation method to be used for this project, several aspects were considered. For the volume allocation results shown in Figure 29 allocation percentage values are spread out significantly from minimum of 2% to maximum of 46% in volume allocation to timber and from minimum of 54% to maximum of 98% in volume allocation to chestnuts. This is a result of a very high uncertainty directly associated with high uncertainty inputs used in volume allocation calculations. Comparing the uncertainty of volume allocation to economic and mass allocation uncertainty, uncertainty associated with volume allocation is much greater, thus it was decided that volume allocation method would not be selected as the allocation method for this project. As previous mentioned, allocation percentage to each co-product results for economic and mass allocation methods are similar. In order to make sure that the variance between mass and economic allocation methods is insignificant and is in fact similar to the point of being assumed the same, analysis of variation (ANOVA) was performed comparing the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of each method's allocation percentages for timber and chestnuts. The results of the ANOVA method showed that there is no difference in means between mass and economic allocation methods. However, economic allocation method has an additional uncertainty due to price fluctuation spatially and temporally, and although some temporal price fluctuation was considered, data for spatial fluctuation was not available. Although some have argued that this uncertainty is comparable to uncertainty attached to other allocation methods,[132,135] considering the results of the ANOVA and the additional uncertainty associated with the economic allocation it was decided to continue analysis using mass allocation as we believe mass allocation to be a more predictable and stable method than economic allocation spatially and temporally.

Using physical relationship and mass allocation methods, all inputs over the life cycle of the orchard system consisting of chestnut trees and pasture were allocated to three co-products: timber, hay, and chestnuts. Physical relationship allocation was used in

distribution of inputs between hay and chestnuts/timber. Physical relationship allocation was also used in distribution of some inputs between chestnuts and timber which were directly associated to one or the other co-product. Activities associated with harvesting of chestnuts were allocated to chestnuts and the destruction stage was allocated to timber. Inputs that were applied to the tree as a whole, such as during the nursery and establishment stages, as well as some inputs during production stage, were not able to be distributed between chestnuts and timber using physical relationship allocation, thus mass allocation was used in those cases. Uncertainty analysis was also considered. The resulting life cycle environmental impact to be allocated to each co-product is presented in Figure 31, for chestnuts grown from bare root rootstock, and Figure 32, for chestnuts grown from container grown rootstock, in a form of box and whisker plots due to uncertainty.

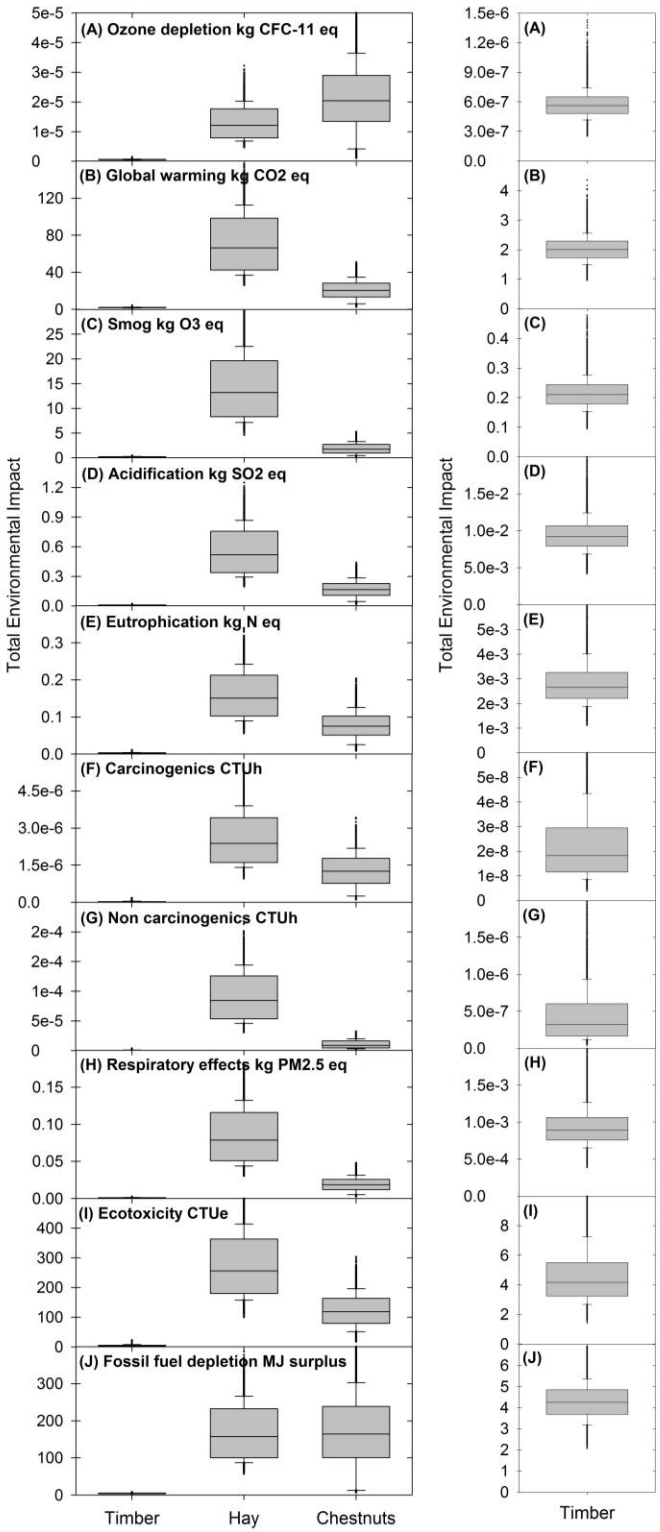


Figure 31: Allocation of inputs between the three co-products over the life cycle of an orchard consisting of chestnut trees grown from bare root rootstock and pasture. Physical allocation and mass allocation methods were used. Out of the tree co-products, hay is the most significant contributor to the total environmental impact in all impact categories except ozone depletion and fossil fuel depletion

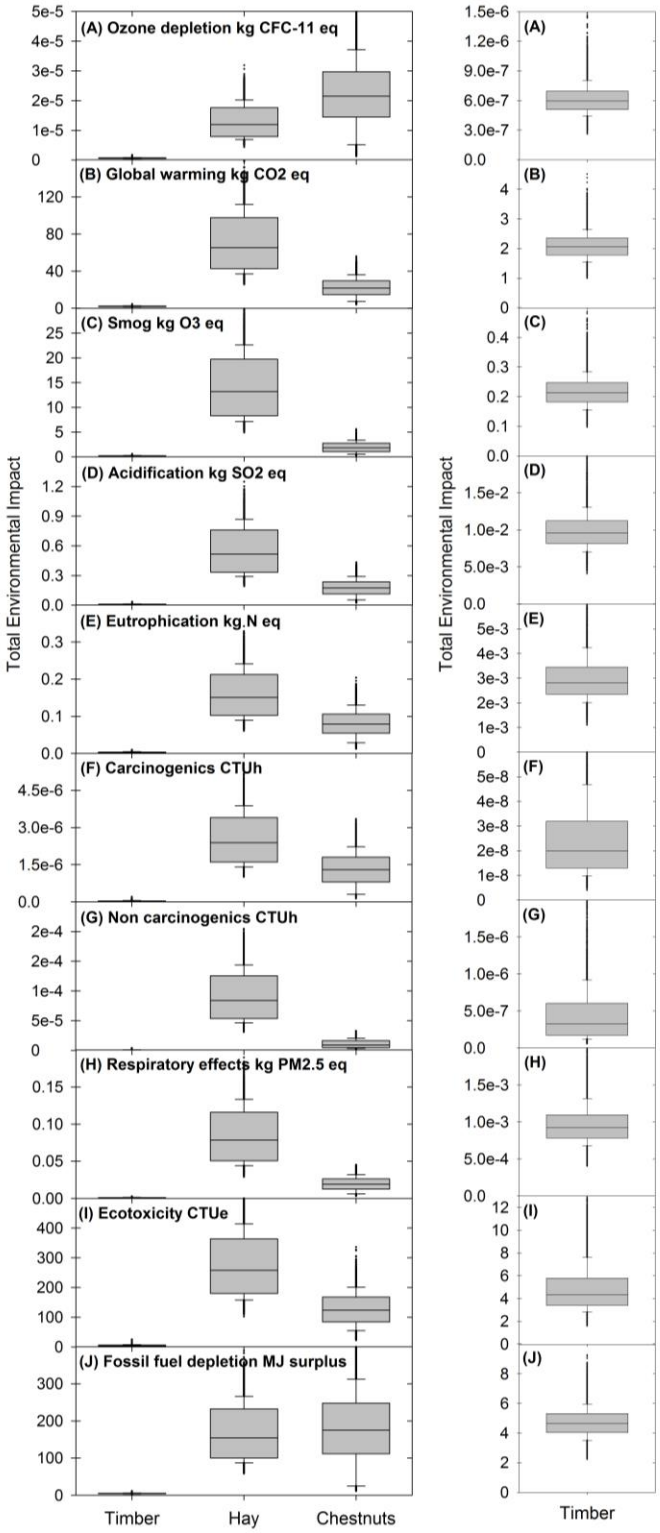


Figure 32: Allocation of inputs between the three co-products over the life cycle of an orchard consisting of chestnut trees grown form container grown rootstock and pasture. Physical relationship allocation and mass allocation methods were used. Out of the tree co-products, hay is the most significant contributor to the total environmental impact in all impact categories except ozone depletion and fossil fuel depletion

Examining the results presented in Figure 31 and Figure 32, it can observed that in most impact categories hay is allocated majority of the environmental impact associated with the orchard system. Chestnuts have been allocated more environmental impact than hay in impact categories of ozone depletion and fossil fuel depletion. It is surprising that hay is allocated significantly more environmental impact than chestnuts, since hay is a secondary co-product, with chestnuts being the primary product of the orchard. However, taking a closer look at the data and the environmental impacts associated with each input during the production stage, which is the stage responsible for majority of the environmental impact associated with this system, mowing activities and diesel use for chestnut harvest are responsible for a large majority of the environmental impact incurred. For the impact categories of ozone depletion and fossil fuel depletion, diesel use for chestnut harvest is responsible for roughly half of the total environmental impact incurred during the production stage, compared to roughly 30 to 40 percent of total environmental impact incurred through mowing, which is the reason for chestnuts being allocated more environmental impact in those impact categories. However, in all other impact categories mowing activities are responsible for anywhere between 60 to 90 percent of the total environmental impact produced during the production stage.

4.3.5 Mass as a Cut-Off Criteria

According to code ISO 14044:2006(E) section 4.2.3.3, exclusion of life cycle stages, inputs, and outputs is only permitted when the omitted piece would not have a significant impact on the overall conclusion of the study. The section goes further to specify the cut-off criteria, which may be used in exclusion of inputs and outputs to be mass, energy, and environmental significance. In order for mass to be considered an acceptable cut-off criteria, it must be true that as cumulative mass of input parameters increases so does cumulative environmental impact, thus the relationship between cumulative mass and cumulative environmental impact must be a strong positive correlation with minimal outliers. In an effort to test whether mass would be an acceptable cut-off criteria when performing an LCA of an orchard with chestnut trees and pasture, all input parameters associated with growing a chestnut tree and pasture from seed to orchard's end of life were converted into kg and compared to the environmental impact associated with those input parameter. The results

for considering the nursery stage only as well as the entire life cycle of the orchard with the chestnut trees grown from bare root rootstock are presented in Figure 33 and the results for considering the container grown rootstock nursery stage only as well as the life cycle of the orchard with the chestnut trees grown from container grown rootstock are presented in Figure 34.

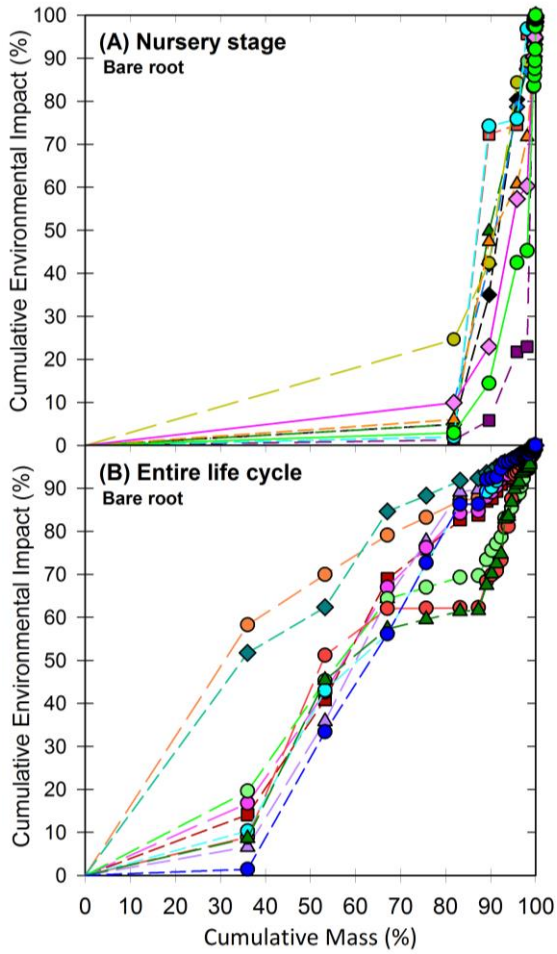


Figure 33: Data presented is for bare root rootstock nursery stage (A) and entire life cycle of the system including pasture (B). The graph compares cumulative mass percentage of all input parameters required for growing a bare root chestnut rootstock from seed (A) and all input parameters required during the system's entire life cycle (B) to the cumulative environmental impact those input parameters have. Each line represents an environmental impact category and each point represents an input parameter. For the nursery stage alone (A), cumulative mass increases much faster than cumulative environmental impact, thus mass would not be an acceptable cut-off criteria in this case. For the entire life cycle (B), cumulative mass and cumulative environmental impact do seem to have a strong linear correlation for all impact categories combined. However, viewing each impact category separately, some impact categories do seem to follow the linear relationship, but some don't.

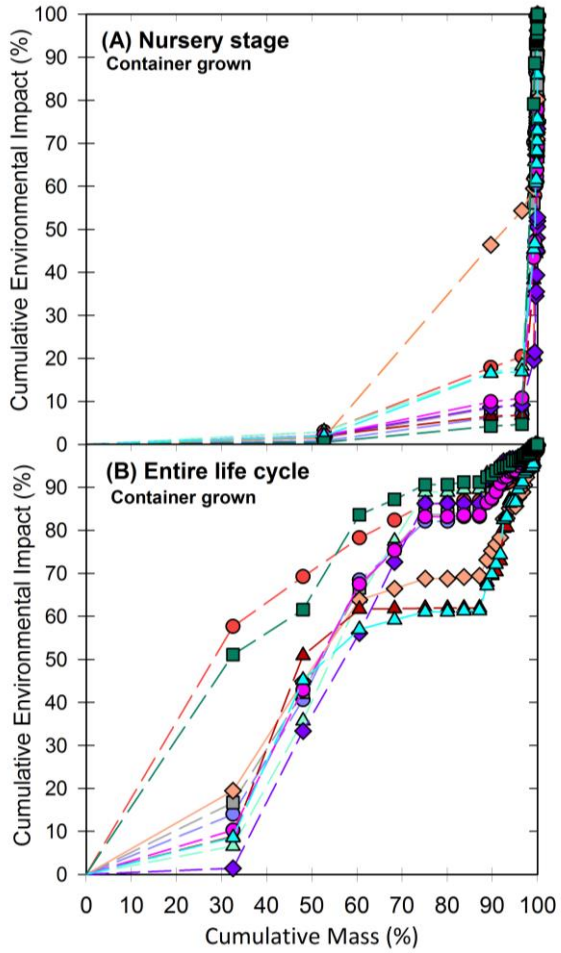


Figure 34: Data presented is for container grown rootstock nursery stage (A) and entire life cycle of the system including pasture (B). The graph compares cumulative mass percentage of all input parameters required for growing a container grown chestnut rootstock from seed (A) and all input parameters required during the system's entire life cycle (B) to the cumulative environmental impact those input parameters have. Each line represents an environmental impact category and each point represents an input parameter. For the nursery stage alone (A), cumulative mass increases much faster than cumulative environmental impact, thus mass would not be as acceptable cut-off criteria in this case. For the entire life cycle (B), cumulative mass and cumulative environmental impact do seem to have a strong linear correlation for all impact categories combined. However, viewing each impact category separately, some impact categories do seem to follow the linear relationship, but some don't.

Uncertainty was not considered in the analysis of results presented in Figure 33 and Figure 34, thus only the raw data gathered for the case of this project is presented. Based on data presented in Figure 33 and Figure 34, mass would not be an appropriate cut-off criteria for assessment of the nursery stage alone. In a case of performing an LCA of a chestnut tree's entire perennial cycle, mass may be used as a cut-off criteria when considering all impact categories in an effort to get a rough estimation of which inputs may or may not be significant. However, mass may not be an acceptable cut-off criteria when considering each impact category separately, or when performing a comparative assessment between crops

or management practices. This area still needs to be further explored through performance of an uncertainty analysis or considering data from several studies.

4.3.6 Water Consumption Impact Assessment

An initial assessment of the direct water consumption by the nursery, establishment, and production stages was performed using the Available WAter REmaining (AWARE) method developed by Water Use in LCA group (WULCA). For the nursery stage a factor of 1.23 was used, and for the establishment and production stages a factor of 0.98 was used.[134] Uncertainty and sensitivity analyses were performed on the raw data collected. The results of the assessment are presented in Figure 35.

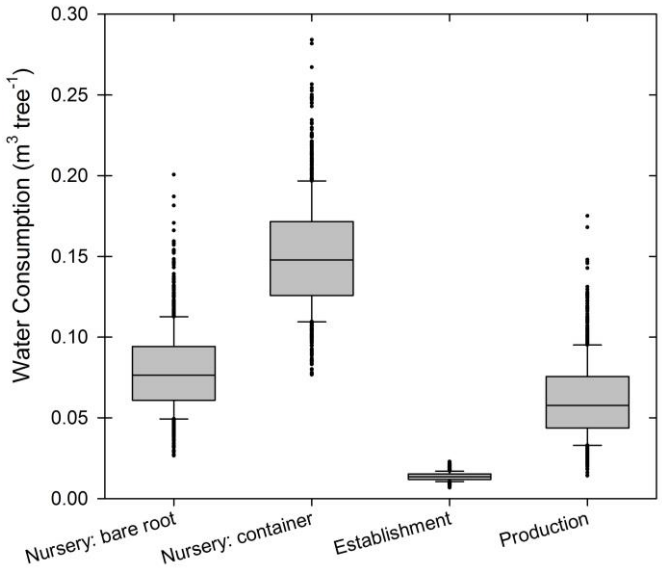


Figure 35: Water scarcity footprint of each stage considering water consumption data collected from nursery, establishment, and production stages as well as the factor provided for the Midwestern US region by the AWARE water assessment method

Implications of this project's water consumption are still not clear and must be evaluated further.

4.4. Supporting Information

4.4.1 Supporting Information: Environment Impact of the Nursery Stage

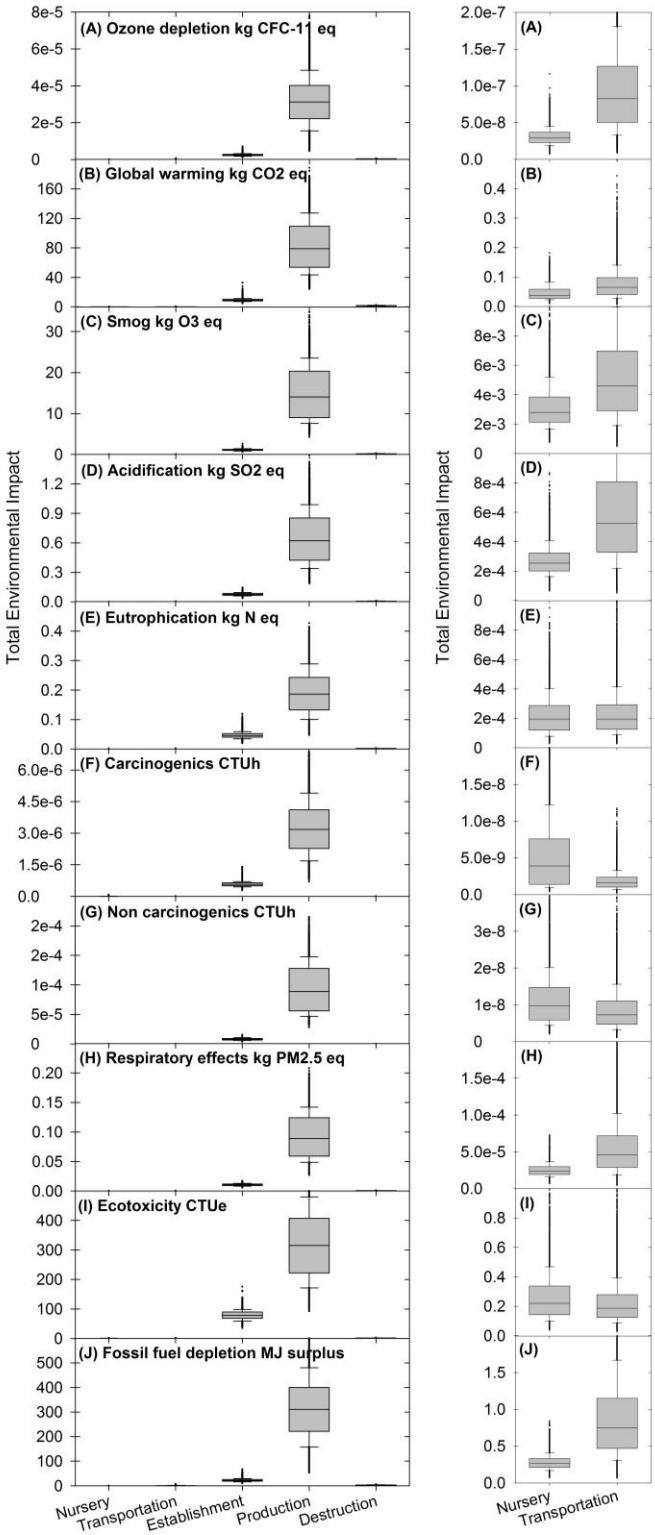


Figure 36: Environmental impact of each stage of the orchard system consisting of chestnut trees grown from bare root rootstock and pasture

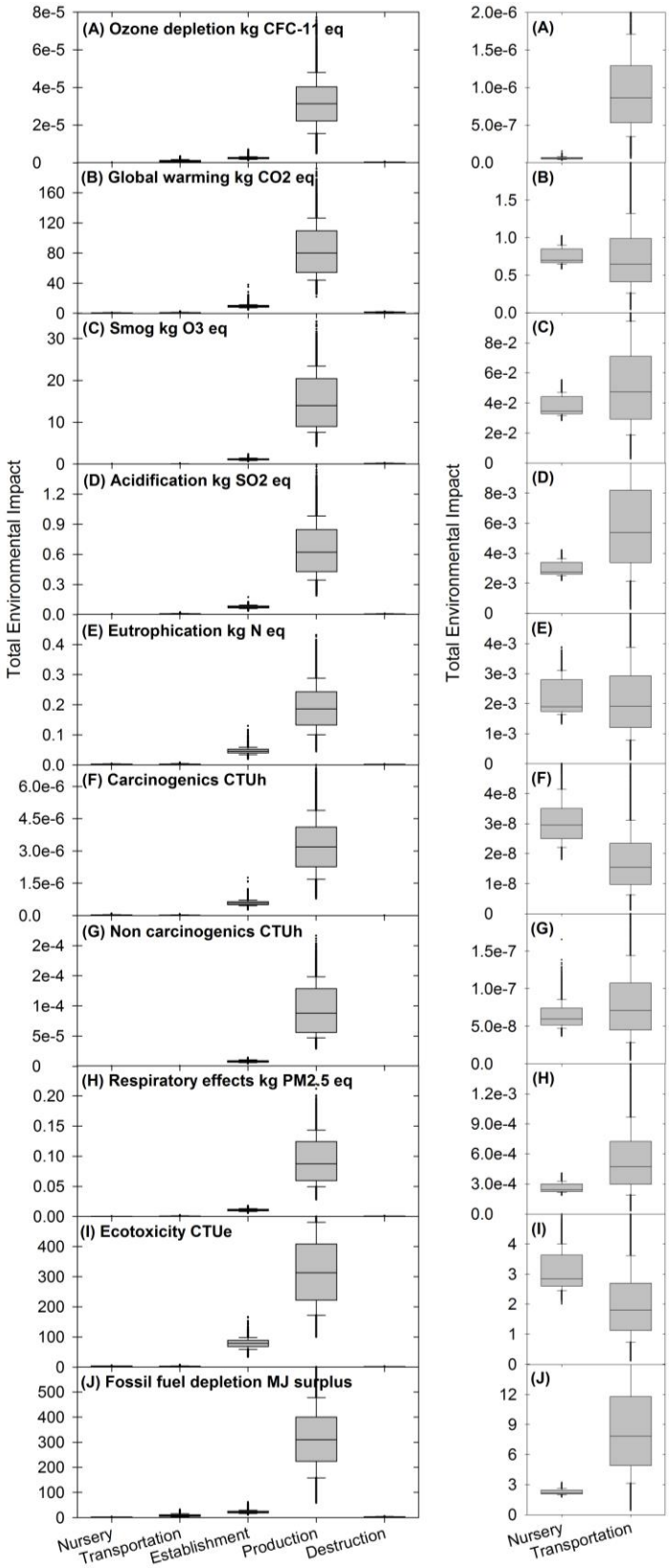


Figure 37: Environmental impact of each stage of the orchard consisting of chestnut tree grown of container grown rootstock and pasture

4.4.2 Supporting Information: Most Significant Components of the Nursery Stage

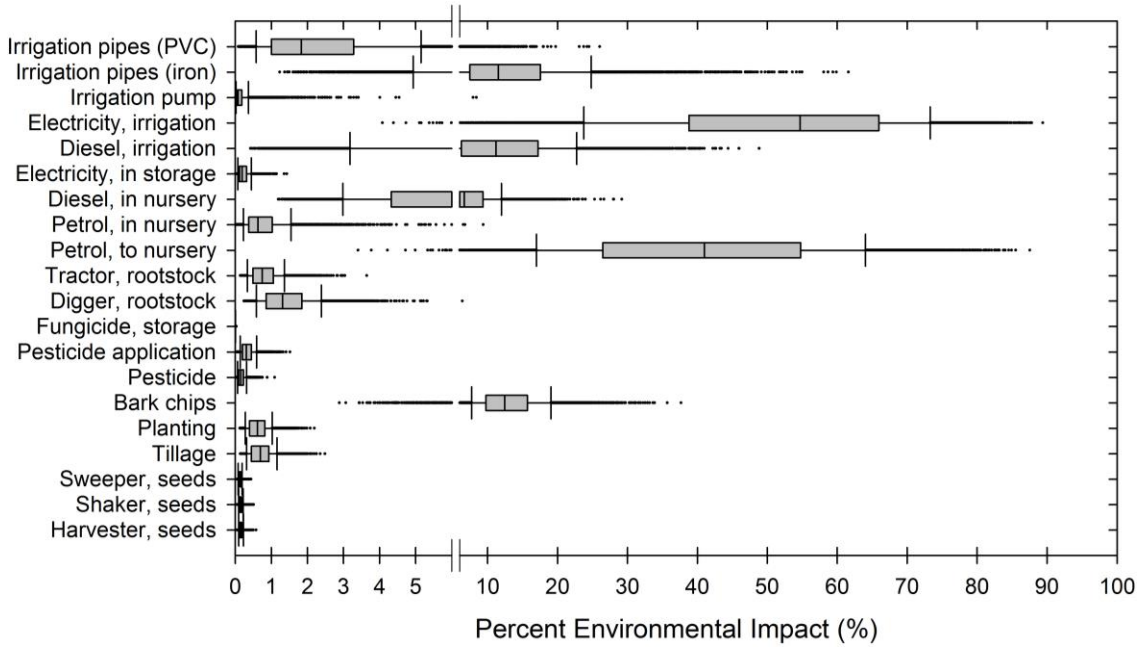


Figure 38: Percent environmental impact for which each input is responsible in the global warming impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

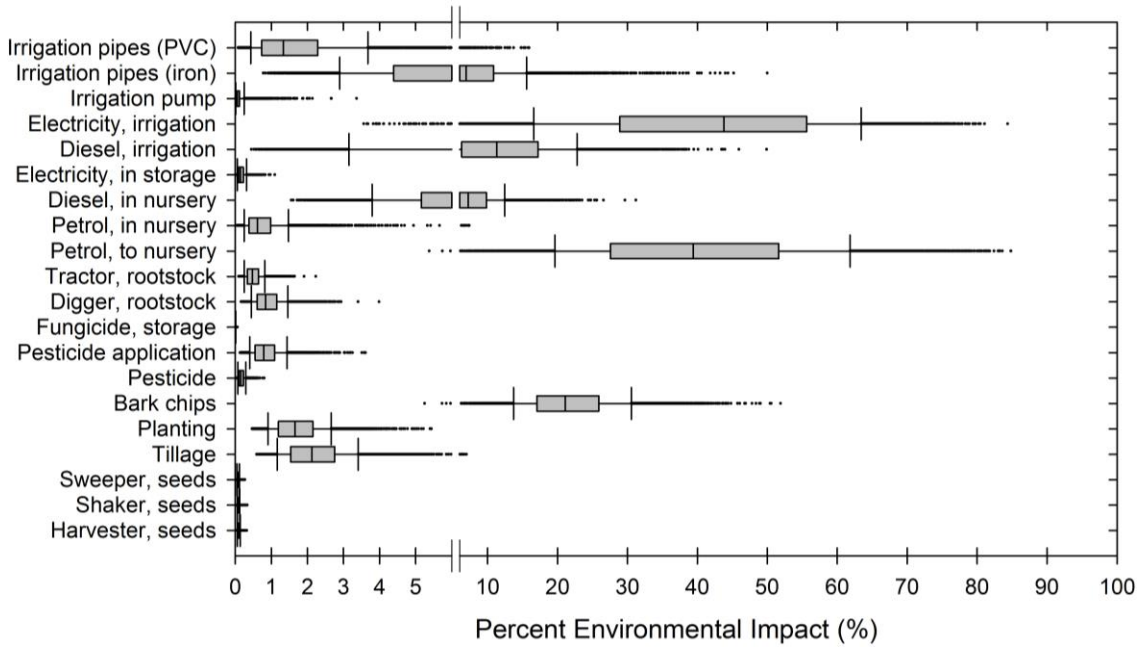


Figure 39: Percent environmental impact for which each input is responsible in the smog impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

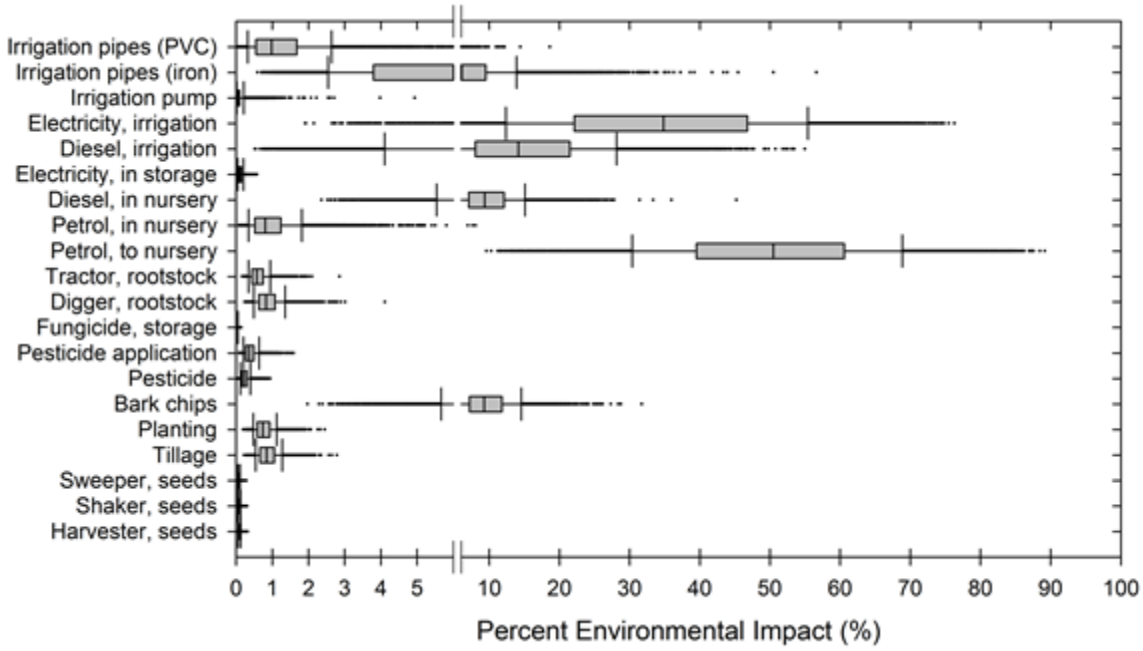


Figure 40: Percent environmental impact for which each input is responsible in the acidification impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

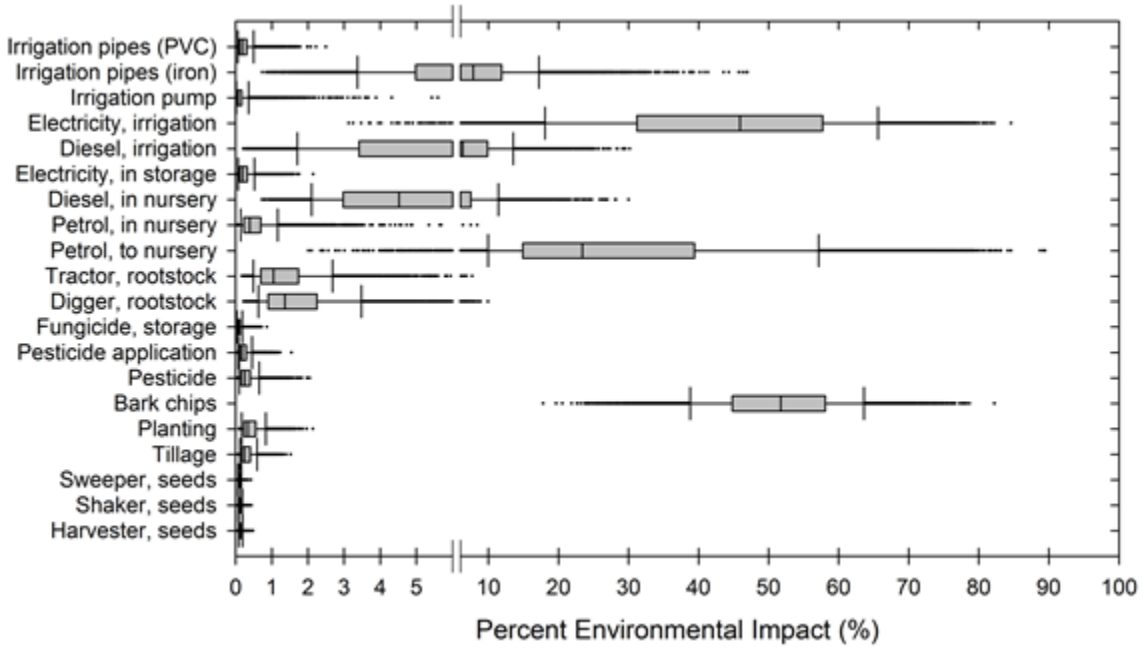


Figure 41: Percent environmental impact for which each input is responsible in the eutrophication impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

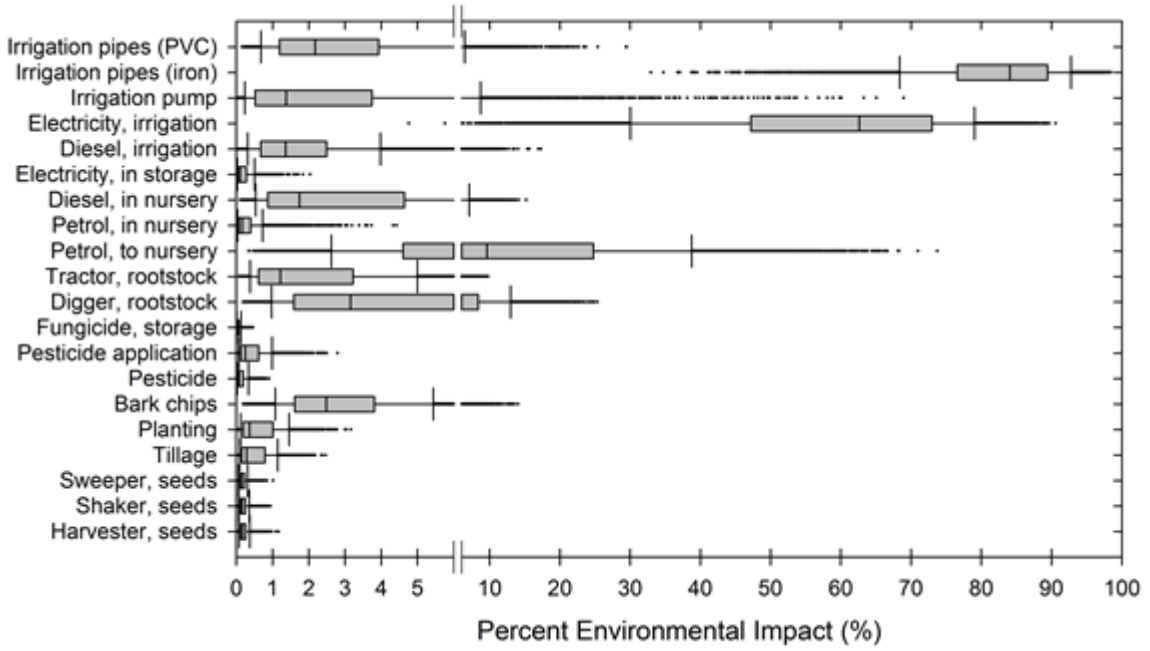


Figure 42: Percent environmental impact for which each input is responsible in the carcinogenics impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

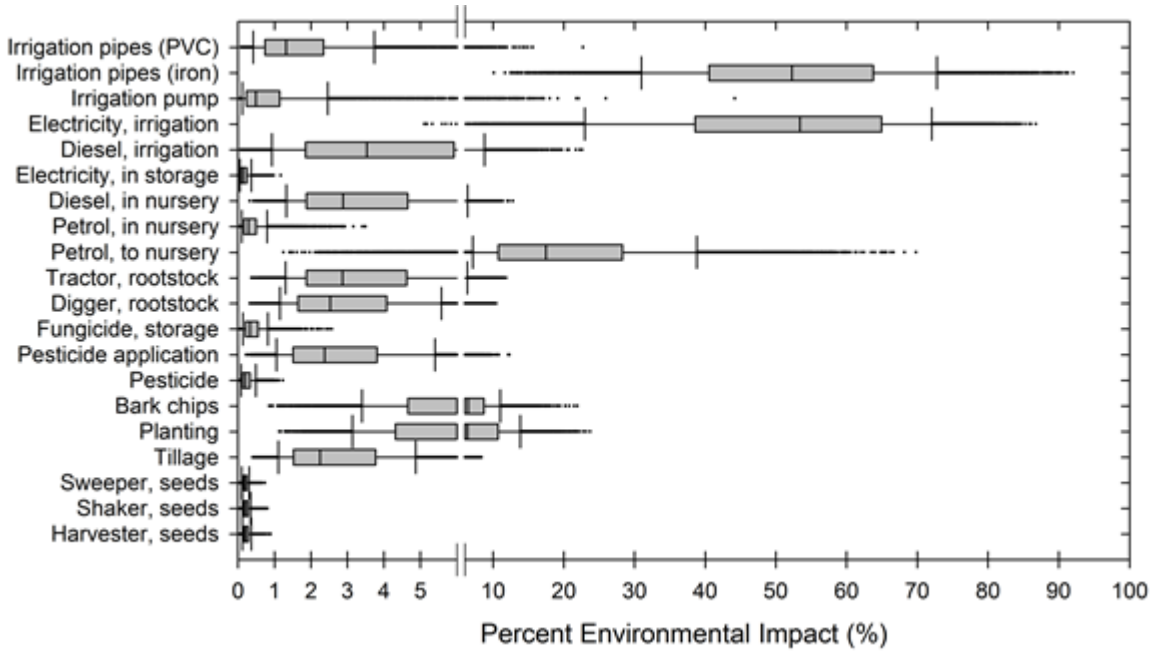


Figure 43: Percent environmental impact for which each input is responsible in the non carcinogenics impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

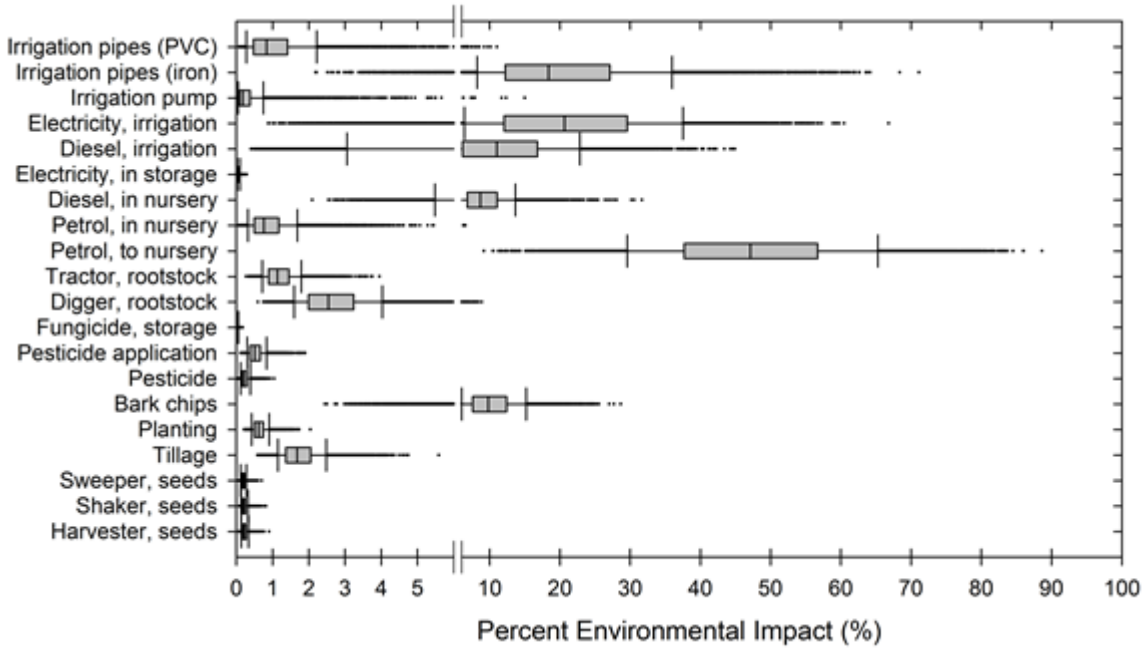


Figure 44: Percent environmental impact for which each input is responsible in the respiratory effects impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

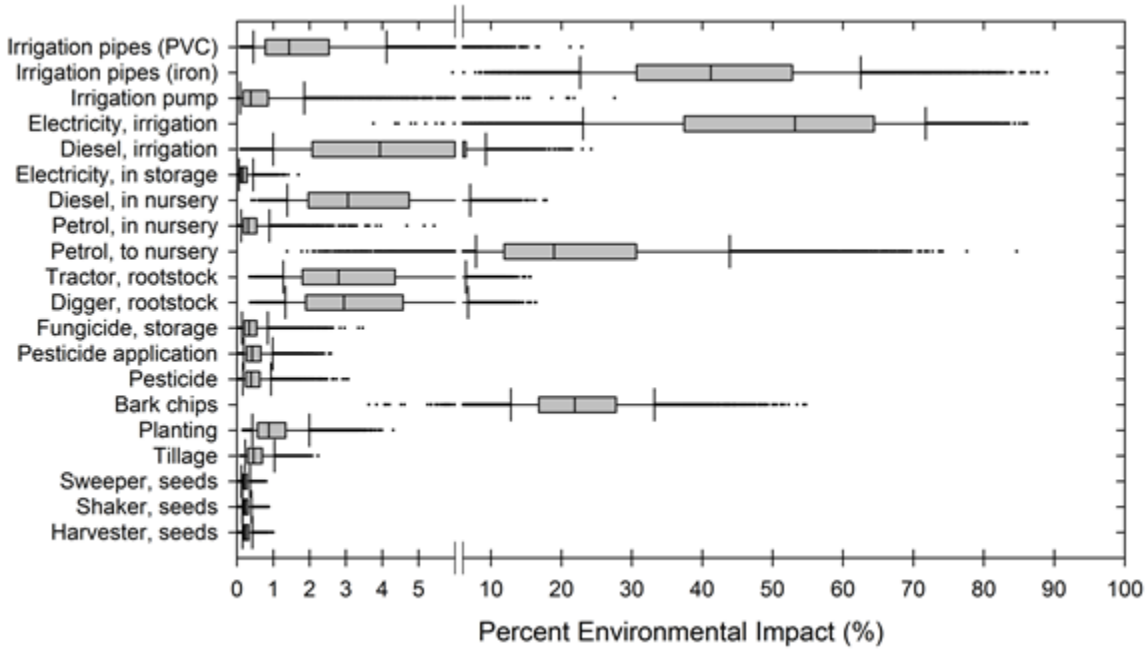


Figure 45: Percent environmental impact for which each input is responsible in the ecotoxicity impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

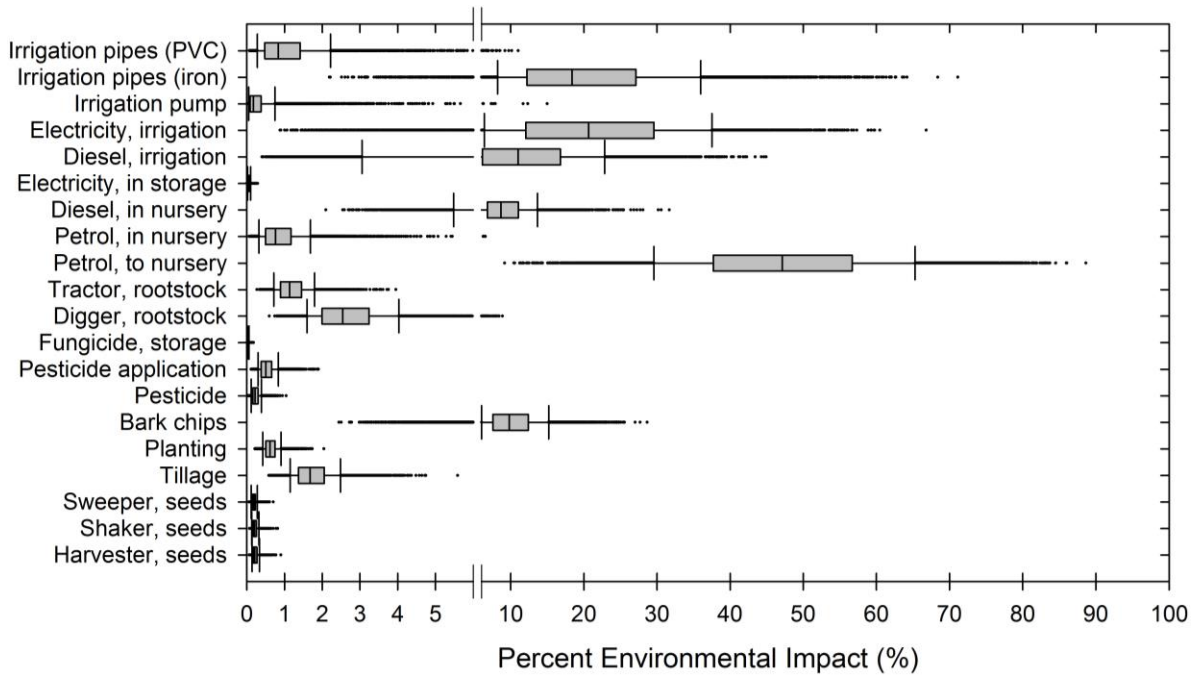


Figure 46: Percent environmental impact for which each input is responsible in the fossil fuel depletion impact category of the bare root nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the bare root nursery stage

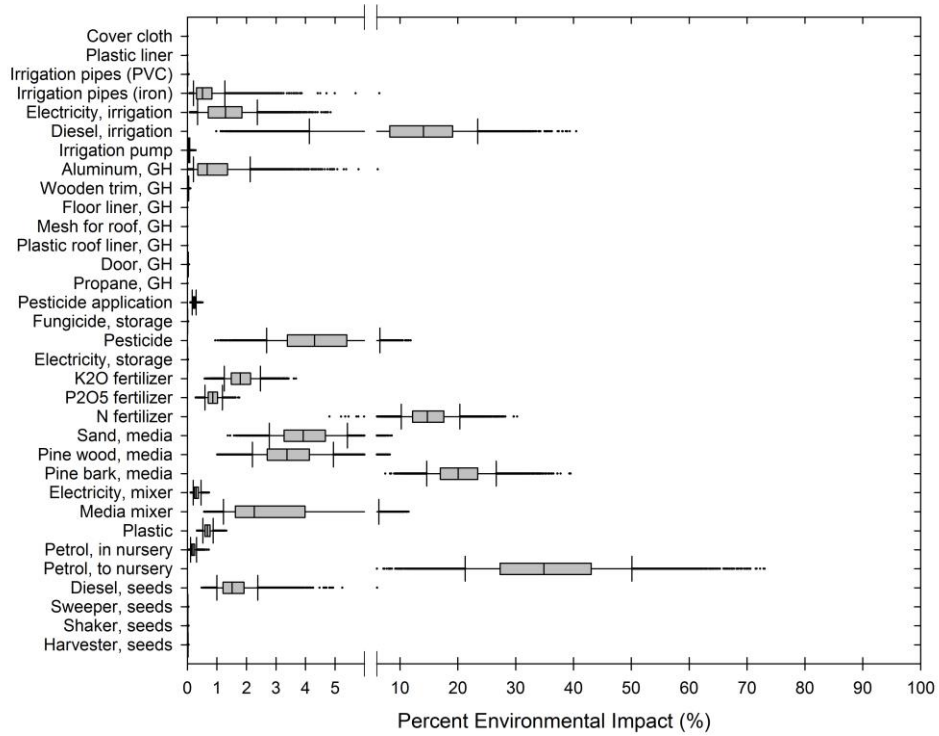


Figure 47: Percent environmental impact for which each input is responsible in the ozone depletion impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

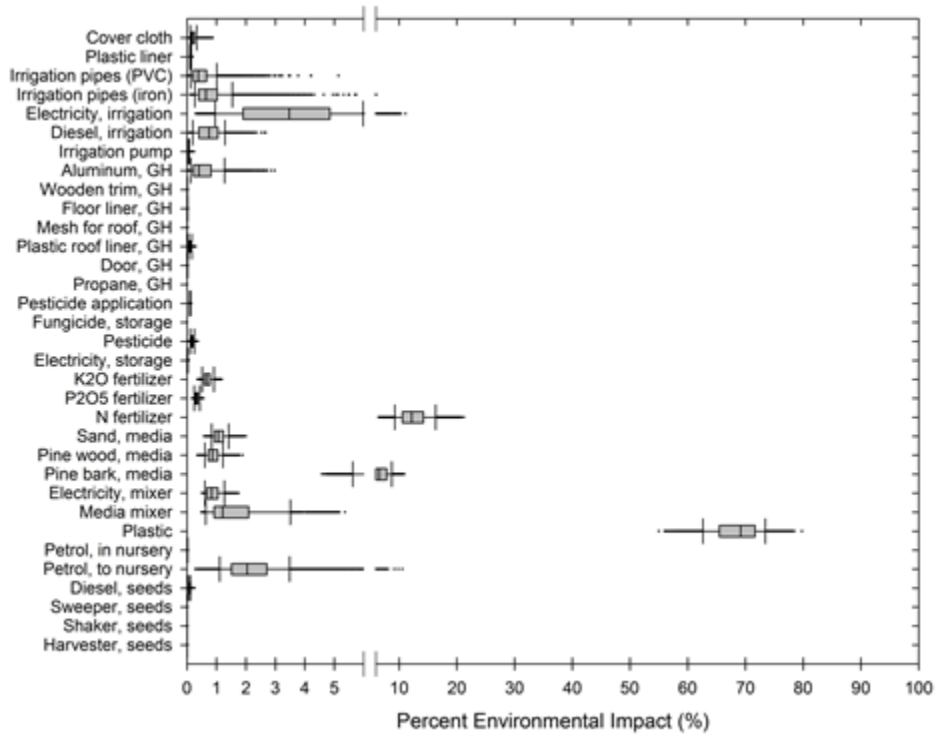


Figure 48: Percent environmental impact for which each input is responsible in the global warming impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

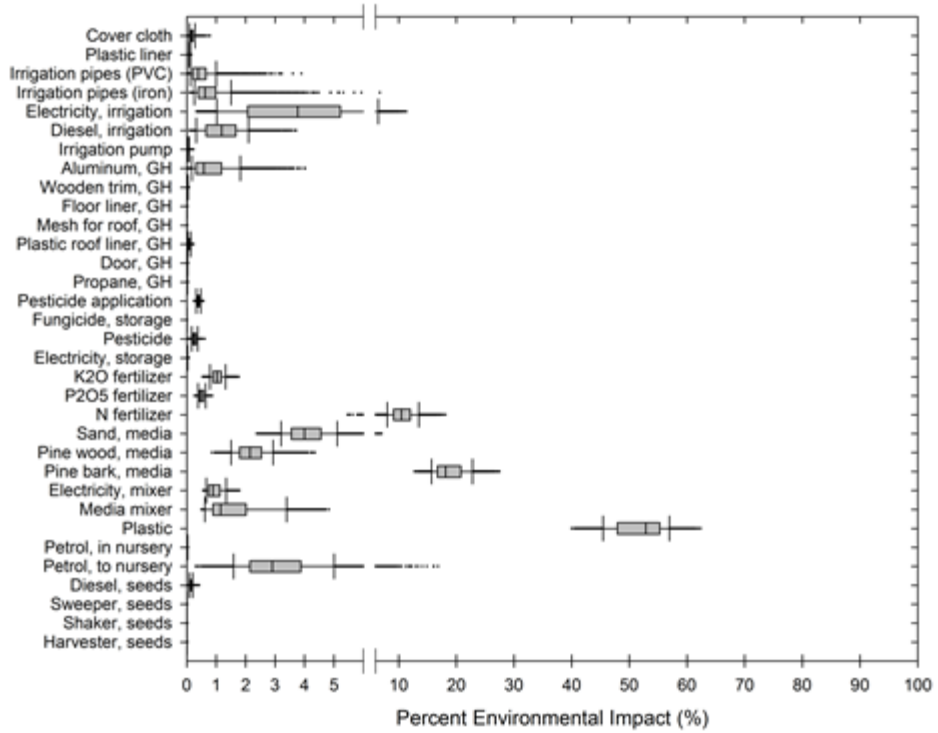


Figure 49: Percent environmental impact for which each input is responsible in the smog impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

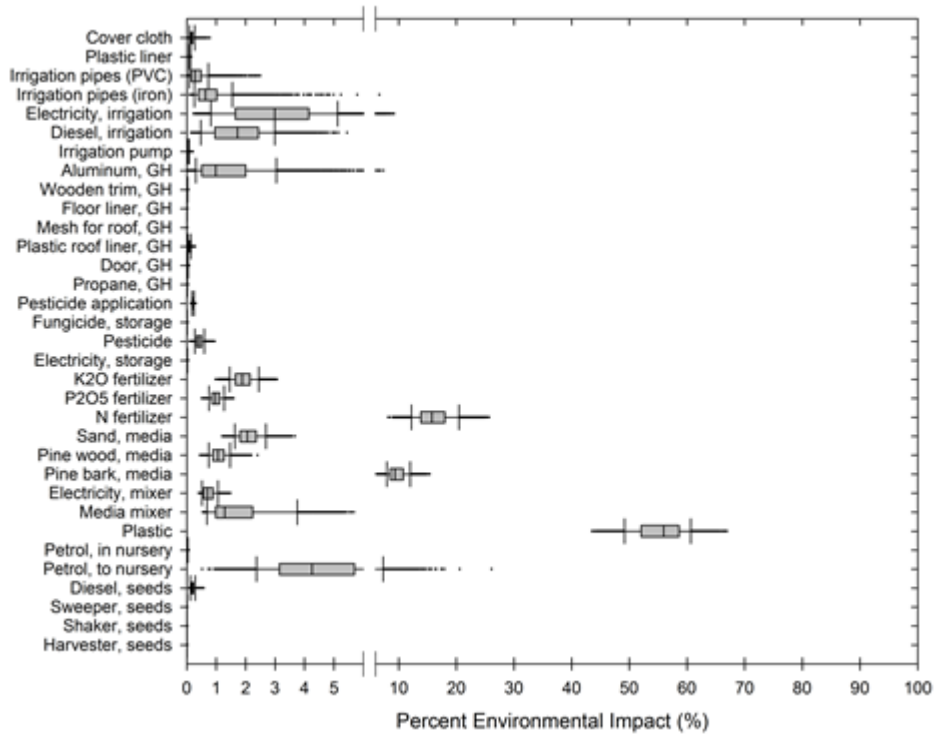


Figure 50: Percent environmental impact for which each input is responsible in the acidification impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

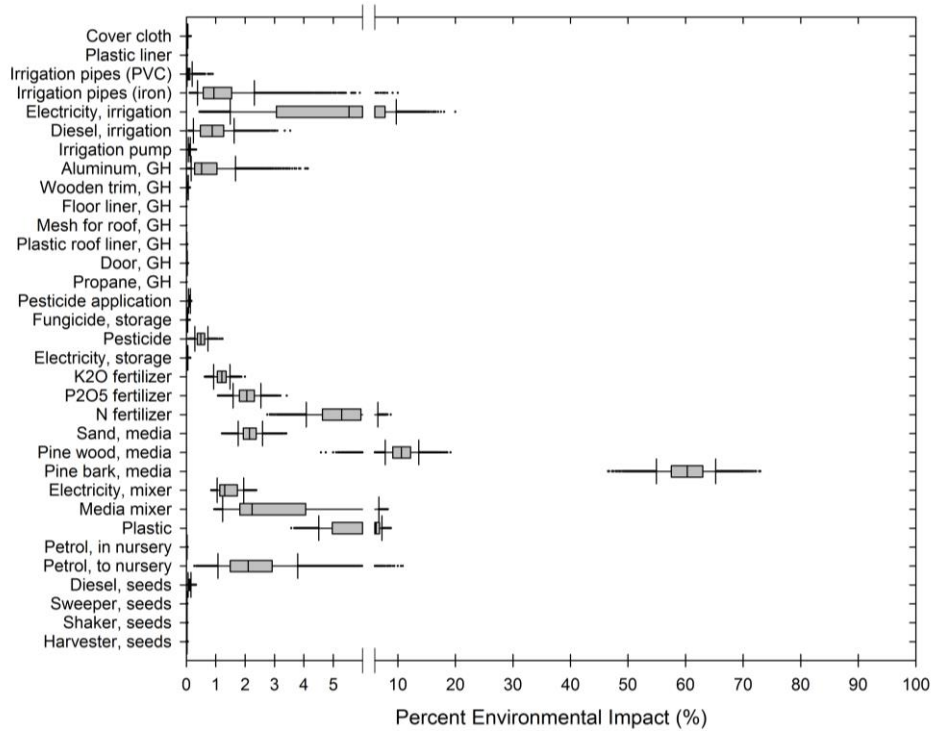


Figure 51: Percent environmental impact for which each input is responsible in the eutrophication impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

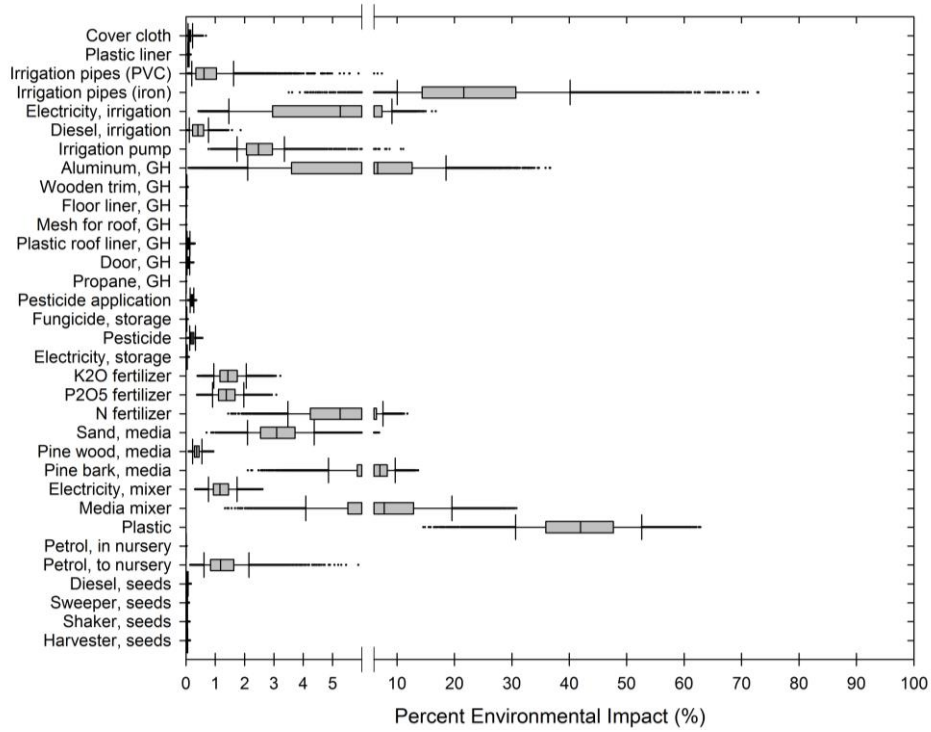


Figure 52: Percent environmental impact for which each input is responsible in the carcinogenics impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

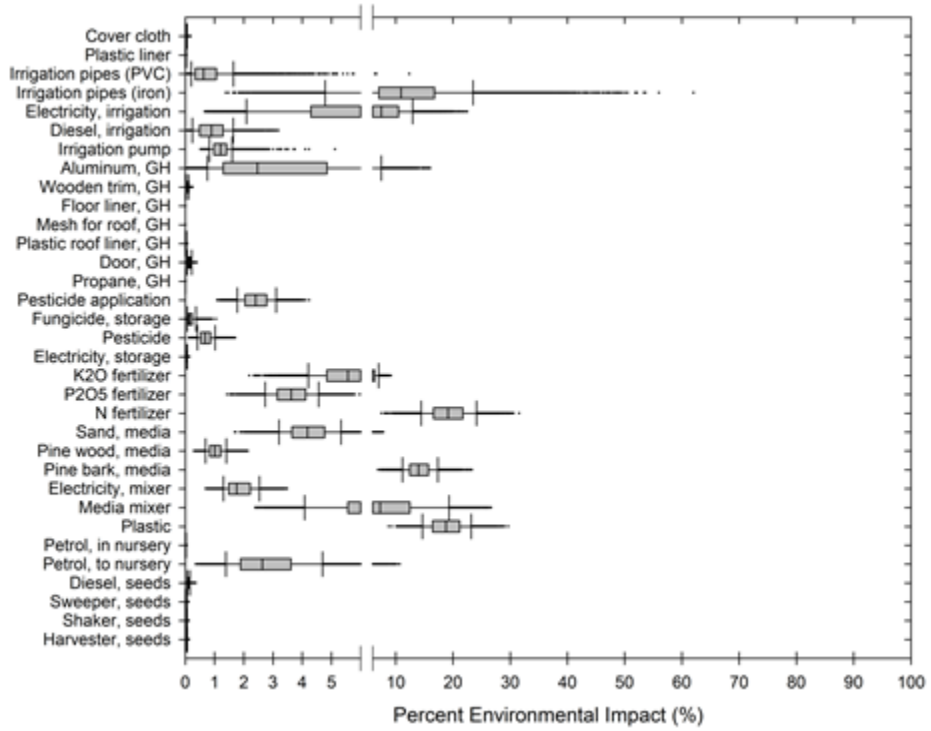


Figure 53: Percent environmental impact for which each input is responsible in the non carcinogenics impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

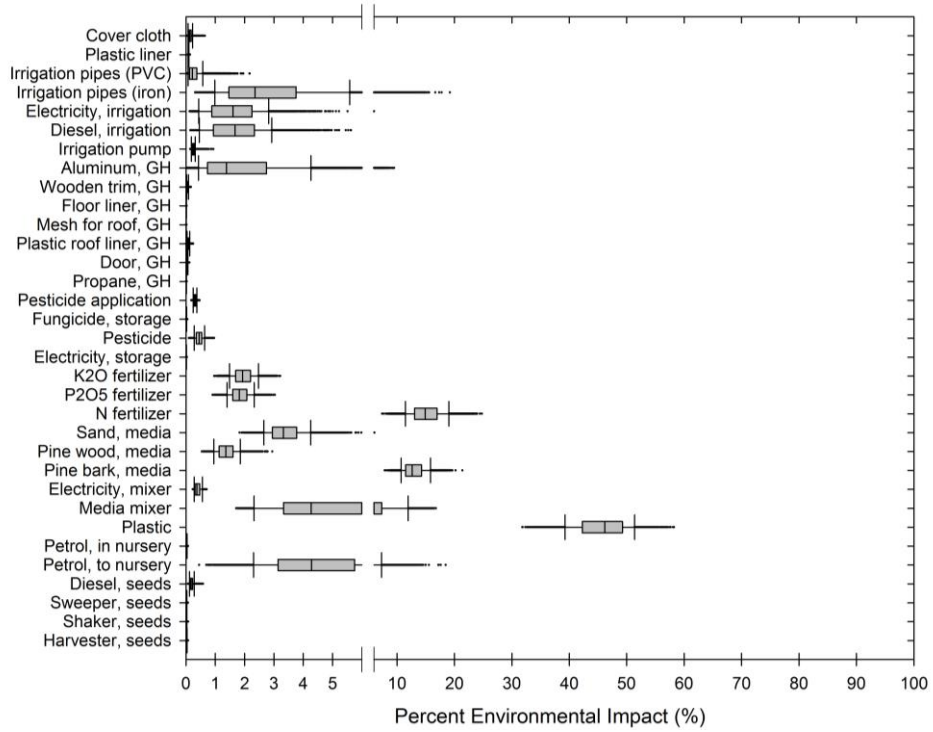


Figure 54: Percent environmental impact for which each input is responsible in the respiratory effects impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

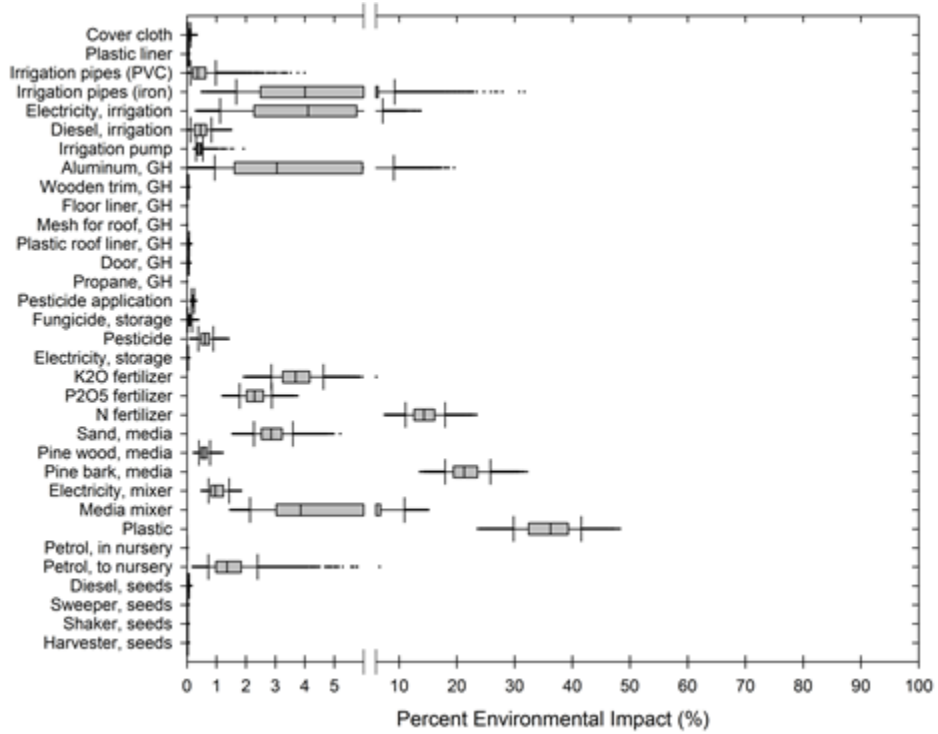


Figure 55: Percent environmental impact for which each input is responsible in the global ecotoxicity category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

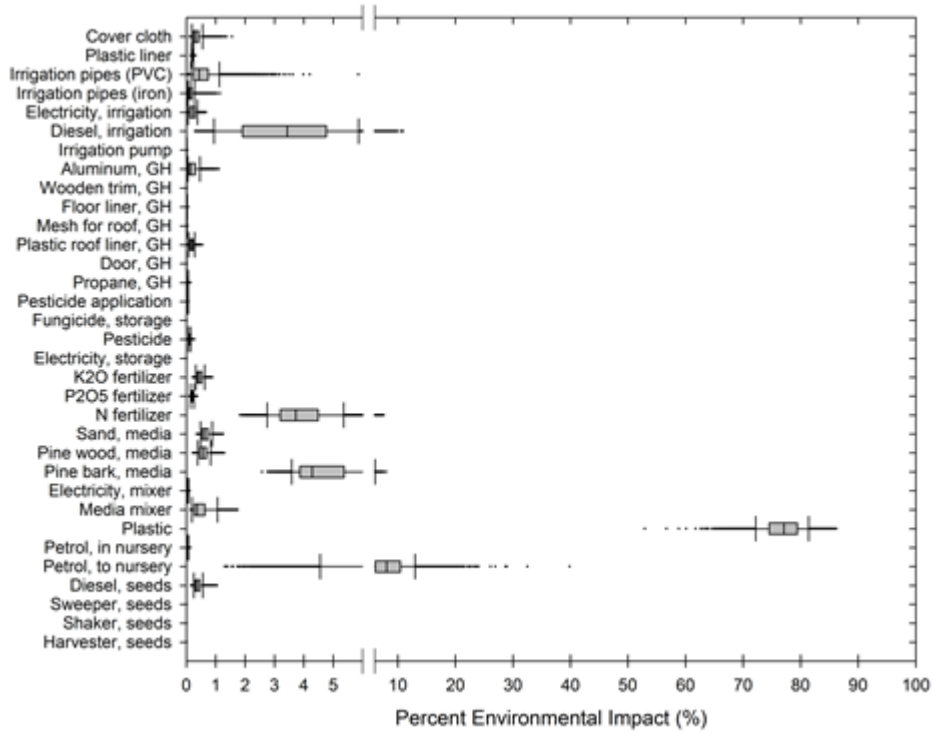


Figure 56: Percent environmental impact for which each input is responsible in the fossil fuel depletion impact category of the container grown rootstock nursery stage. The box and whisker plots represent the 10th, 25th, 50th, 75th, and 90th percentile values which resulted from uncertainty analysis performed on input parameters of the container grown rootstock nursery

5. Conclusions

In an effort to alleviate global environmental impacts and achieve sustainable agriculture systems that are able to provide for the growing population, some believe that transformation of conventional agriculture to perennial polyculture is a necessary step. It is projected that perennial polyculture may be able to resolve some of the issues produced by conventional agriculture, such as loss of biodiversity, soil erosion, as well as degradation of land and freshwater. It is also believed that perennial polyculture systems have a potential for nutrient recycling, soil conservation, and water quality improvement.

Due to lack of knowledge regarding the environmental, economic, and social tradeoffs of this transformation, this study aimed to help bridge that gap and add to the pool of knowledge of perennial polyculture. Specifically, in this study, I performed a life cycle assessment of a perennial polyculture system in an effort to determine stages and inputs responsible for significant contributions to the environmental impact of the system over its life time. The results of this study can later be used to compare environmental impacts of an orchard system comprised of chestnut trees and pasture to the environmental impacts of conventional agriculture, or other perennial polyculture systems.

Several conclusions can be made from results of this study. First, environmental impact of the nursery stage was determined for bare root and container grown rootstocks. It was determined that although for this system the nursery stage was found to be insignificant relative to the environmental impacts over the entire life cycle, the nursery stage should still be explored on a case-by-case basis, especially in instances of comparative studies. In order to help determine whether the nursery stage may be significant relative to the environmental impacts of the entire life cycle of an orchard, an analysis was performed and a guide created showing inputs which contribute to the environmental impact of the nursery stage the most. While this guide was developed to help determine the significance of the nursery, it must be kept in mind that the relative significance of the nursery stage is dependent on the relative significance of other stages. Therefore, if the production stage of the orchard is not machinery or energy use intensive, it is recommended that the inputs of the nursery stage are analyzed carefully as they may contribute significantly to the overall environmental impact of the system. In addition, this guide was developed by only analyzing

an orchard consisting of chestnut trees and pasture and was not verified in use with other crops.

In performing allocation analysis of the system, it was determined that pasture is a significant contributor to the environmental impact of the system over its life time. Further analysis must be done in determining the tradeoffs of not having pasture as part of the system. This analysis must include a cost analysis of not profiting from hay during the years chestnut trees are unproductive as well as on site environmental assessment which would include soil nutrient content and soil erosion analyses of not having pasture as ground cover. Further analysis must also be completed on the social aspect of having pasture as part of the system as it may be more labor intensive than conventional agriculture systems. All these analyses should provide a well-rounded impression of how sustainable it is having pasture as part of this system.

Some more analyses which are part of future work include comparing the environmental impacts of this system to the environmental impacts of the conventional agriculture. Cost analysis must also be completed in determining the cost of transforming conventional agriculture farm to a perennial polyculture system such as studied here. It would also be important to determine whether this system and other perennial polyculture systems would be viable options in providing for the growing population if this transition were to take place. In further studies, human labor should also be considered as it is expected that perennial polyculture systems may be more labor intensive than conventional agriculture systems. Water consumption implications and direct soil emissions must also be evaluated for this orchard system. In future assessments of this system, the production stage data must also be modified to reflect any changes made, or planned, to the system since July 2016. Furthermore, it is recommended that in future studies the boundary conditions are extended beyond the farm gate to include the quality of the product, which may also have a significant impact on the sustainability of this system.

As many agree that a need for agricultural reform is clear, it is more important now than ever for environmental engineers to get involved in agricultural projects in an effort to lend their expertise in life cycle environmental impact assessment and water quality analysis. Through working together, agricultural scientists and environmental engineers have the potential to make a true difference for the aquatic environment through soil and

water quality analyses as well as combining their knowledge in resolving some of the negative impacts of agriculture. It is our hope that this study will help further the research in the area of perennial polyculture through the data and results provided as well as encourage interdisciplinary projects between scientists in agriculture, engineering, economics, and biology.

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