Beyond School Gardens: Permaculture Food Forests Enhance Ecosystem Services While Achieving Education for Sustainable Development Goals

Beyond School Gardens: Permaculture Food Forests Enhance Ecosystem Services While Achieving Education for Sustainable Development Goals

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Abstract

Permaculture food forests are a form of regenerative agriculture that integrate methods of agroforestry by mimicking a multilayer forest ecosystem with edible and supportive plant species. This project assessed permaculture food forests as a new model for use in schools by evaluating how they perform as compared to traditional raised bed school gardens. Performance was based on a cost benefit analysis that accounted for the following ecosystem services: carbon sequestration, avoided runoff, air pollution reduction and food production. I developed a curriculum design tool to evaluate the relevance of food forest curriculum in correlation with Education for Sustainable Development (ESD) learning objectives and key competencies that is also applicable to other curriculum topics. I introduce the concept of 'cultural environmental responsibility' as a potential outcome from education that teaches children how to provide services to ecosystems (S2E), supporting a cultural shift towards humans as environmental stewards.

My primary research question was: Do food forests in schools provide greater ecosystem services as compared to raised bed school gardens while upholding food production and enhancing opportunities for education for sustainable development? Hypotheses included: Food forests in schools provide greater ecosystem services as compared to raised bed school gardens of an equivalent area; food forests financially outperform raised bed school gardens by reducing maintenance costs and inputs, and producing more food over 30 years; with increasing adoption rates, food forests in schools in California will contribute a significant amount of carbon sequestration, avoided runoff, air pollution reduction, and food production as compared to lawns.

In order to assess the potential of food forests, I created a model permaculture design of a quarter acre food forest applicable for schools and communities in California's Mediterranean climate. I compared cost benefit scenarios over 30 years for three land uses: food forest, raised bed school garden, and lawns. I conducted the valuation of ecosystem services by developing models of each land use scenario in iTree Eco. To assess the potential of widespread adoption, I calculated the sum of ecosystem service benefits over 30 years considering zero to 100% adoption rate in California public schools. I also estimated annual ecosystem services per acre based on my models of food forest and raised bed garden land use scenarios.

Based on my analysis, the model food forest outperformed the raised bed school gardens by enhancing ecosystem services, reducing costs, and upholding food production with NPVs of $159,845 versus $93,714, respectively. If 33% of California schools converted a quarter acre lawn to a food forest, it would result in 527,911,699 lb of healthy food for youth, 49,991 metric tons of carbon sequestration, 7,817,952 ft^3 of avoided runoff, and $4,638,557 worth of pollution removal over 30 years. In addition, by correlating food forest curriculum to learning objectives of UNESCO Global Action Program (GAP) on Education for Sustainable Development (ESD), I was able to demonstrate feasible application of ESD that is comprehensive and relevant for US schools. Others can also use the tool developed as a template to correlate curriculum to ESD. By implementing food forests, schools would experience all these benefits while enhancing opportunities to cultivate the human nature connection and develop ESD while offering a rich ecological learning environment in the transition to greener schoolyards.

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Creating a thesis in sustainability has been a deeply transformative process that has unfolded new levels of understanding and connection with my world. I want to first thank Harvard University and the Extension Studies team for creating the program in sustainability, which has never faltered in providing a rich educational experience. I am deeply grateful for my cohort, and other students within the program that are working to extend the reach of knowledge to edge humanity towards a more sustainable and just future. I cannot thank my thesis director and advisor, Mark Leighton, enough for his canny ability to provide thought provoking insights that enhanced the quality of my thesis time and again. David Shaw, of Santa Cruz Permaculture, in our brief yet fruitful time together, was able to transform my initially dull layout of a food forest by offering suggestions that inspired me to dive deep into permaculture and create my own integrated permaculture design. I want to also acknowledge the staff at iTree for providing incredibly thorough technical support that helped me leverage the software for my analysis. Special thanks to: Fred Yaeger of the California Department of Agriculture, and Amanda Recinos of GreenInfo Network, for answering my questions, and providing information about school campus land use. I cannot end without thanking my family, all of whom provided the support, time, and space needed for me to allow my thesis to unfold in its own time. Marcos, Cassiano, and Camila, you keep me inspired; thank you for believing in me.

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Definition of Terms

Agroforestry: “[A] dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels” (FAO, 2017).

Cultural environmental responsibility: The ideas, customs, and social behavior of a society that supports the protection of the environment through conservation ethic and by providing services to ecosystems (S2E).

Diameter at breast height (DBH): The diameter of the trunk of a tree at 4.5ft above ground level.

Cultural Social Responsibility: The ideas, customs, and social behavior of a society that supports a balance of environmental, economic, and social imperatives through a “regenerative conservation ethic” and prioritizes services to ecosystems (S2E).

Ecosystem services: “[T]he benefits people obtain from ecosystems [which include] provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth.” (Alcamo et al. 2003)

Food forest: Forest farming method of agroforestry, often used in permaculture, that incorporates plants that are useful to humans and includes up to nine layers of a forest ecosystem.

Green schoolyard: “Multi-functional school grounds designed for and by the school community that offer places for students, teachers, parents and community members to play, learn, explore and grow.” (Children & Nature Network, 2018)

Permaculture: An ecological method of cultivating permanent culture or agriculture designed to be self-sustaining ecosystems inspired by natural ecosystems and by utilizing renewable resources.

Regenerative Conservation Ethic: An ethic with a proactive focus on regenerating the health of the natural world that leverages a circular economy of renewable materials and energy to support a sustainable society.

Sustainable Development: Development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (UN, 1987).

Services to Ecosystems (S2E): “Actions humans have taken in the past and currently that modify ecosystems to enhance the quality or quantity of the services they provide, whilst maintaining the general health of the cognised ecosystem over time” (Comberti, Thornton, Wyllie de Echeverria, & Patterson, 2015).

Urban Food Forestry (UFF): “[A] multifunctional approach that combines elements of urban agriculture, urban forestry, and agroforestry” through perennial woody food-producing species (‘‘food trees’’) in cities (Clark & Nicholas, 2013)

Chapter I

Introduction

Considering that over half of the world population now lives in urban areas, and the trend of increasing urban populations is projected to continue, cities are seeking sustainable solutions to the ecological challenges of development. Urban forests are being recognized for the wealth of ecosystem services they provide, including carbon sequestration, air filtration, water regulation, reduced heat island effects, and enhanced human well-being (Livesley, McPherson, & Calfapietra, 2016). In addition, to address the food security of rising urban populations, solutions such as community gardens have increased in recent years (Draper & Freedman, 2010). Coupling community gardens with urban forestry through urban food forestry (UFF) adds food production to the multitude of ecosystem services provided by urban forests (Clark & Nicholas, 2013).

Community gardens in schools offer the added benefits of providing ecological learning environments, educating future populations about sustainable food choices, and helping to combat the rising levels of malnutrition and obesity in children (Blair, 2009). As part of the movement towards green schoolyards, school gardens offer a more ecologically diverse alternative to more traditional land use in schools, such as lawns, asphalt, and playgrounds. Due to their proven success, there now exist over 7,000 school gardens in the United States (USDA, 2015). Nevertheless, there are shortfalls with regards to school gardens. School gardens often plant raised beds with annual crops requiring extensive maintenance and inputs while adding little with regards to ecosystem services over the long run (Gregory, Leslie, & Drinkwater, 2016). In addition, the school garden sustainability curriculum has been limited in comparison to the breadth of learning objectives as defined by the UNESCO Global Action Program (GAP) on Education for Sustainable Development (ESD) (UNESCO, 2017).

Leveraging the movement for green schoolyards and school gardens in the US, food forests in schools could provide essential ecosystem services to urban environments while enhancing opportunities for ESD. While some studies have evaluated the benefits of food forests, further quantification of key ecosystem services would address assumptions regarding their ecological value as a community garden in an urban environment. While there do exist some examples of food forests in schools in the US, they are relatively new and rare in comparison to raised bed gardens. In addition, the curriculum has not yet been linked to GAP ESD.

It could very well be that food forests offer a unique application for teaching sustainability. However, whether or not the benefits of food forests outweigh the costs as compared to raised bed gardens that are more commonly found in schools needs to be evaluated. Due to the importance of food production to school gardens, it is imperative that food forests in schools are also able to produce comparable quantities of fruits and vegetables. In addition, if the cumulative environmental benefits of transforming school lawns into food forests are found to be significant, this could be another driver for establishing food forests in schools.

Research Significance and Objectives

My research assessed food forests as a new model for use in schools by evaluating how they perform as compared to traditional raised bed school gardens and lawns in terms of the following ecosystem services: carbon sequestration, avoided runoff, air pollution reduction, food production, and providing context for teaching sustainability. I quantified key ecosystem services and conducted a cost benefit analysis in order to provide educators and other decision makers with information and tools that could support initiatives to grow food forests in their community. Furthermore, by correlating food forest curriculum with the UNESCO Global Action Program (GAP) on Education for Sustainable Development (ESD), I expected to demonstrate a feasible application of ESD that is comprehensive and relevant for US schools.

My research objectives were as follows:

- To evaluate the viability of permaculture food forests in schools by calculating ecosystem services and conducting a cost benefit analysis that compared a quarter acre food forest to a raised bed garden and lawn of the same size
- To demonstrate the potential significance of transforming lawns into permaculture food forests in schools on a larger scale by calculating the cumulative ecosystem services assuming increasing adoption rates in California schools
- To document the food forest design process, and provide a quarter acre food forest example design that can be applied to other schools, including species selection and mapping
- To advance the integration of GAP ESD within the United States by creating a curriculum mapping template that correlates ESD learning objectives to curriculum applicable within a food forest ecological learning environment

Background

The UN describes Education for Sustainable Development (ESD) as education for social transformation that will result in sustainable societies. While we can seek to achieve sustainability by targeting each of the seventeen Sustainable Development Goals (SDGs) through technology and policy, education has the ability to generate the necessary "changes in mind-sets, values and lifestyles, and the strengthening of people's capacities to bring about change" (UN, 2012). The UNESCO Global Action Program (GAP) on Education for Sustainable Development (ESD) is attempting to do just that by working towards the Sustainable Development Goals within the classroom (UNESCO, 2017). Whereas schools and teachers in the United States are aware of aspects of education for sustainability, mainly Environmental Education (EE), few are aware of GAP and its comprehensive approach to ESD (Smith, 2015). Aligning curriculum with the UNESCO Global Action Program (GAP) on Education for Sustainable Development (ESD) would unite American schools with this global collaborative effort.

It is important to note that, "the kind of discipline-centric education that enabled us to industrialize the earth will not necessarily heal the damage caused by industrialization." (Orr, 2004, p.2). Beyond curriculum content, education must foster a conservation ethic that emerges from a deep connection to the natural world. Hence, we must bring children to nature, or bring nature to the children.

Education for Sustainable Development

Recognizing the power of education to catalyze change, the UN launched the Decade of Education for Sustainable Development which ran during 2005 through 2014

(UNESCO, 2014). These efforts are now continuing through UNESCO's Global Action Program (GAP) on Education for Sustainable Development (ESD). As guided by the seventeen UN 2030 Agenda for Sustainable Development Goals (SDGs), GAP ESD establishes learning objectives to address all of the SDGs while fostering sustainability key competencies (Figure 1). Quality education is one of the SDGs, but GAP ESD goes even further by suggesting that education should be a strategy to help achieve the SDGs. By both integrating sustainable development into education, and integrating education into sustainable development, the overall goal of GAP ESD is to create empathetic citizens willing and able to address the complex challenges of today (UNESCO, 2015).

Figure 1. United Nations Sustainable Development Goals: 17 goals to transform our world (United Nations, n.d.).

Education for Sustainable Development in the United States

Many countries successfully participated in the UN Decade of ESD; however, the United States has not yet required the integration of ESD into public education.

Nevertheless, we have seen great progress in the U.S. with regards to ESD. Many new programs have emerged as outlined in the report, "The Status of ESD in the United States," which also concludes that much more can be done (Smith, 2015). In some U.S. K-12 schools, initiatives related to ESD have been an integral part of their curriculum, and are often referred to as Environmental Education (EE). While EE addresses topics that relate to sustainable development, the full breadth of sustainable development is not necessarily integrated into the curriculum as topics mostly focus on the environment, rather than social and economic well-being.

Feinstein (2009) describes the barriers to implementation in the US, most notably the decentralization of education that allows states to maintain most of the decision making related to public education in their state. However, this may now be considered favorable given the current federal political agenda that seems unconcerned with sustainability; states are taking their own initiative to work towards a sustainable future. For example, some states have signed onto the "We are Still In" campaign committing to continue to support actions on climate to meet the Paris Agreement, such as California and New York (We Are Still In, 2017). With education in their hands, GAP ESD is another opportunity for states to demonstrate their commitment to global initiatives that support the development of a sustainable future for all. Through GAP, there is renewed effort in the United States to formally participate in ESD as outlined in the "US Roadmap for Implementing the Global Action Program (GAP) on Education for Sustainable Development," which puts the GAP roadmap into context for the U.S. (Smith, 2015).

Education for Sustainable Development in California

Some states lead the way on EE, such as Vermont, Washington, Massachusetts, and California, with Vermont and Washington directly integrating sustainability into state standards for K-12 education (Smith, 2015). California has also been a catalyst for initiatives related to EE, and has a strong history as an environmental leader. In order to improve science education overall, California is in the process of adopting Next Generation Science Standards (NGSS) that incorporates environmental topics and problem solving skills which “are exactly the types of skills required to meet the environmental challenges our students will face in the future” (CDE, 2015). The new standards encourage teachers to implement innovative interdisciplinary curriculum, rather than isolating science by discipline, and to also consider human impacts which are key to covering integrated topics that arise in ESD.

More recently, the passing of California Senate Bill 720 in September 2018 updated and expanded provisions related to environmental education “to ensure that the environmental principles and concepts are integrated into content standards and curriculum frameworks whenever those standards and frameworks are revised” (Allen, 2018, p.1). The California Department of Education (CDE) has proposed an approach to EE that seeks to achieve environmental literacy for all students by integrating environmental education into core subjects. As part of CDE’s Blueprint for Environmental Literacy, California is requiring that all new schools integrate an ecological learning environment on the school grounds (CDE, 2015). Already, we are seeing the greening of campuses and the removal of asphalt through programs such as the San Francisco Unified School District (SFUSD) Green Schoolyards bond program that provides funds for “greening” which often includes removing some asphalt and incorporating areas with natural features such as trees, ponds, and planting areas that can be used for gathering (SFUSD, 2018). These initiatives come together to create an opportune moment for California Schools to integrate food forests, as well as align curriculum with GAP ESD.

Green Schoolyards

Schoolyards are commonly devoid of ecological diversity and the grounds are often dominated by pavement, lawns, and play structures. Due to the growing body of evidence regarding the benefits of nature for children, the green schoolyards movement is building momentum in the US and around the world. Green schoolyards transform school grounds into more sustainable and ecologically rich environments for learning and play, enhancing both the wellbeing of the children and the environment by incorporating elements of nature and sustainable urban infrastructure (Danks, 2014). Some examples of the greening of schoolyards include removing asphalt and replacing it with mulch and vegetation, natural play areas, or implementing a school garden. In addition, converting lawns offer an easy opportunity for greening schoolyards because they lack ecological diversity and require significant water, fertilizer, and maintenance.

Land Use in California Schools

In order to consider the potential for green schoolyards in California, it is important to review the current state of land use in schools. California is a large state with varied geographical regions that include urban, suburban, and rural populations.

California has the largest population of any state in the United States, totaling 39,536,653 people as of July 2017, with 16.6% of the population of school age (United States Census Bureau, 2017). The California School Campus Database used ArcGIS to map public school campuses throughout the State, and made it publicly available for research and application (GreenInfo Network, 2016). The distribution of school campuses correlates with population densities, with more schools in more populous areas (Figure 2).

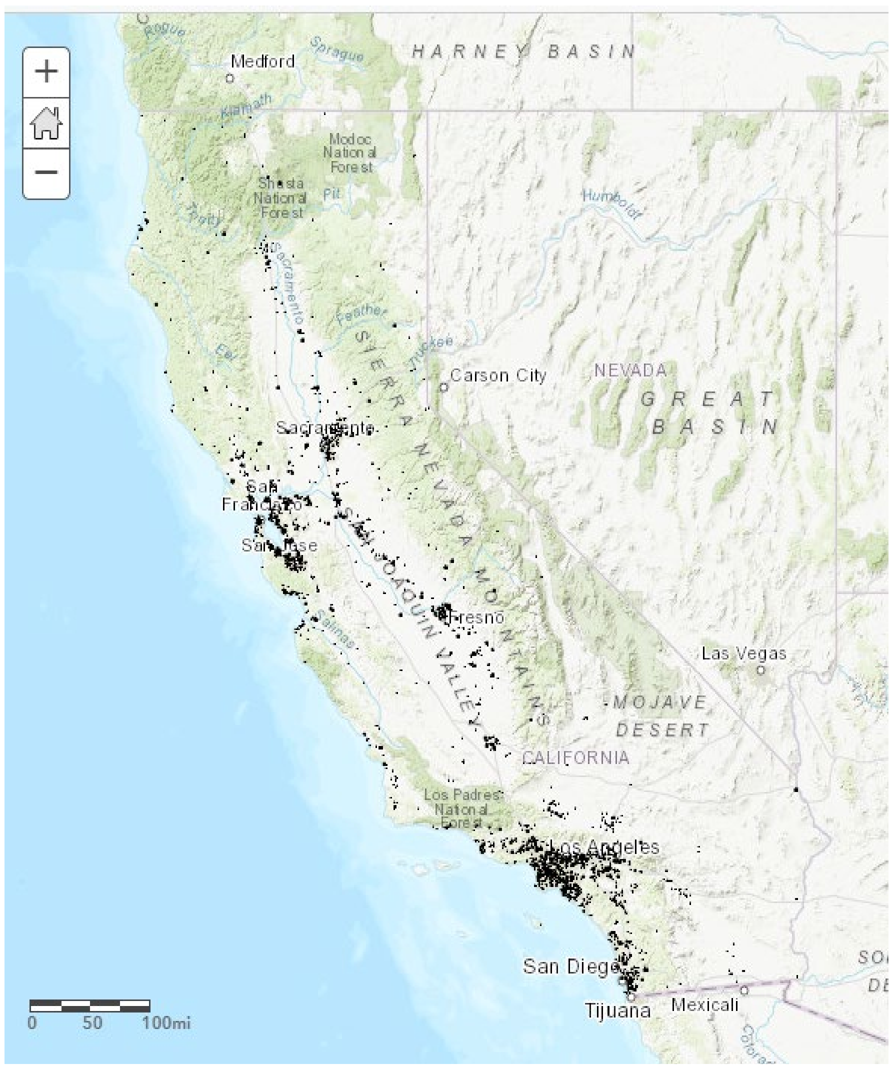


Figure 2. California School Campus Database ArcGIS map of public schools (GreenInfo Network, 2016).

As of 2018, there were a total of 10,473 public schools with an enrollment of 6,220,413 students (Table 1). High schools have the highest average enrollment per school, and typically the largest campuses. Serving almost half of the student population, the vast majority of these schools are elementary schools (56%) (Figure 3). Combined, middle

Table 1. California public school student enrollment by type (CDE, 2018).

School Type	Enrollment	Quantity	Average Enrollment per School
Elementary	3,048,199	5,873	519
K-12	231,523	339	683
Middle	992,566	1,296	766
Junior high	31,066	49	634
High	1,745,197	1,311	1,331
Continuation	51,811	435	119
Alternative	59,433	260	229
Community day	3,425	164	21
Special education	21,186	136	156
Other	36,007	610	59
Total*	**6,220,413**	**10,473**	

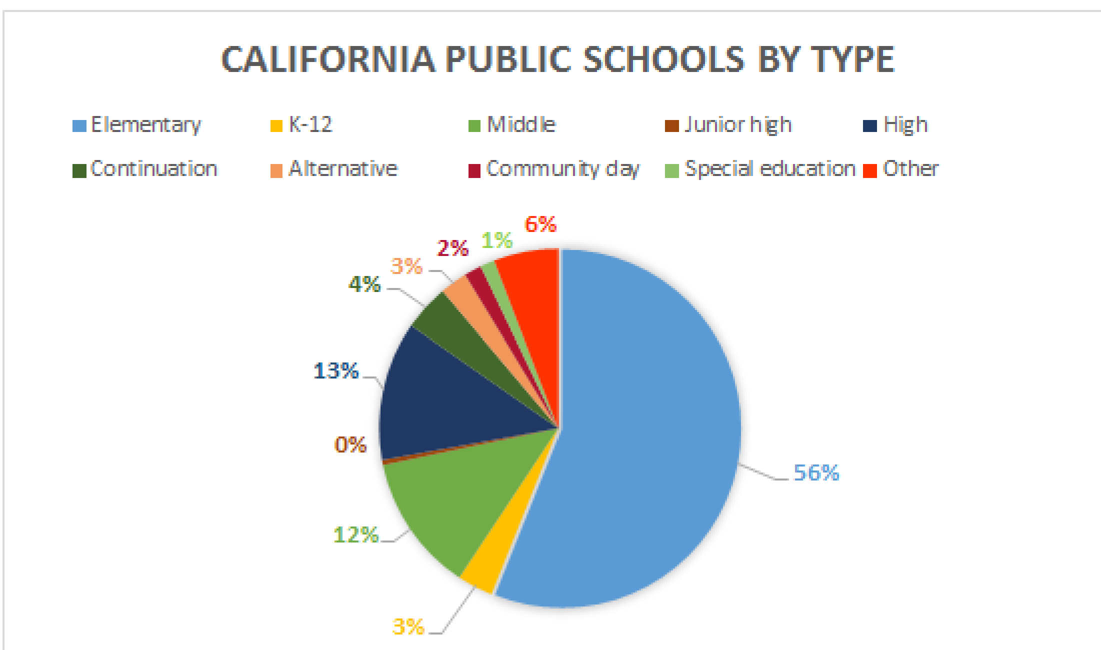


Figure 3. Percentage of California public schools categorized by type (CDE, 2018).

and high schools account for just 25% of all of the public schools, and serve a significant amount of students due to high average enrollment per school.

School districts follow the CDE site development guidelines for campus size and allocation of land use based on enrollment and grade span (CDE, 2000). In rural areas, land is more available for development than that of urban areas, and new school developments are adapting campus design accordingly to meet local needs. California school campuses vary greatly in size. The great majority of California public schools are over 5 acres, and over 2000 schools are between 10-14.9 acres (Figure 4).

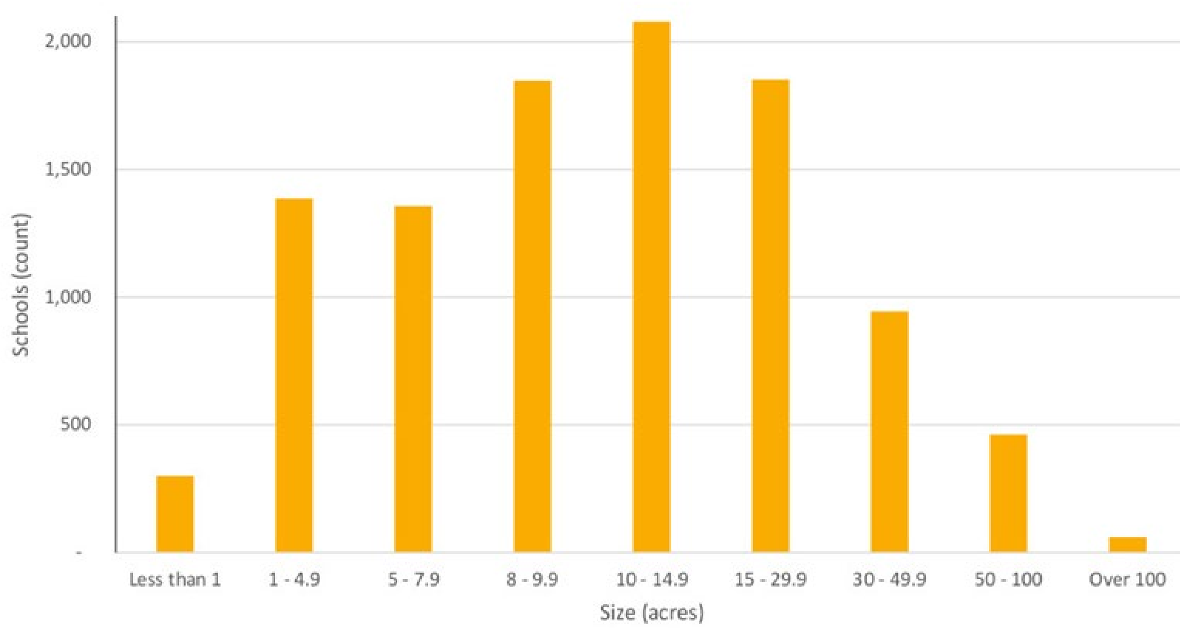


Figure 4. California public schools campus size distribution (GreenInfo Network, 2016).

Based on the guidelines, the suggested distribution of land use on campus is separated by buildings, parking and roads, and outdoor facilities which includes hardcourt, field, and apparatus areas. The suggested ratio of land use for outdoor facilities varies for each school type and size of school. For example, one of the tables provides information for grades sixth through eight, with enrollment of 601 through 1200 students (Table 2). However, actual land use likely varies as these are only guidelines.

Table 2. Useable acres required for land use in schools based on CDE guidelines for grades six through eight (CDE, 2000).

Area Use	Enrollment 601 to 750 Usable Acres Required	Enrollment 751 to 900 Usable Acres Required	Enrollment 901 to 1050 Usable Acres Required	Enrollment 1051 to 1200 Usable Acres Required
Physical Education	7.3	8.5	8.5	10.7
Buildings and Grounds	4.1	4.9	5.8	6.6
Parking and Roads	0.5	0.6	0.7	0.8
Total Acres without CSR	11.9	14.0	15.0	18.1
Added Buildings and Grounds for CSR	0.9	1.0	1.2	1.4
Added Parking and Roads for CSR	0.3	0.3	0.4	0.4
Total Acres with CSR	12.9	15.3	16.6	19.9

Note: These specifications are intended for grades six, seven, and eight or a combination of grades seven and eight. If facilities for football and track are not required, use the specifications on this table; if they are required, see the specifications on Table 5.

As per CDE, school campus land use coverage data is not available for the state as a whole, but regional studies may exist beyond what is available to the public. A study that evaluated tree cover of elementary school campuses in the Los Angeles Unified School District (LAUSD) revealed that on average only 12.3% of play areas are unpaved. Most notably, approximately 20% of the elementary schools evaluated had 0% unpaved outdoor facilities (Table 3) (Moreno, Tangenberg, Hilton, & Hilton, 2015).

Table 3. LAUSD elementary school site analysis of tree canopy and unpaved surfaces (Moreno, Tangenberg, Hilton, & Hilton, 2015).

	School Site Size (Acres)	Tree Canopy Cover School Site (Percent)	Tree Canopy Cover Play Area (Percent)	Unpaved Surface School Site (Percent)	Unpaved Surface Play Area (Percent) **
Count	509	509	509	509	509
Minimum	1.2 ac	0.2%	0.0%	0.6%	0.0%
Maximum	19.7 ac	34.7%	13.7%	68.8%	69.2%
Mean	5.4 ac	11.0%	4.5%	13.0%	12.3%
Standard Deviation	2.1 ac	6.1%	2.8%	9.3%	13.1%

This analysis of tree cover in LAUSD is limited to paved, unpaved, and tree cover areas, and does not include more specific land use categories such as lawns, school gardens, parking, etc. It is also restricted to a small selection of LAUSD schools, and does not necessarily reflect land use distribution in other districts. Due to the geographical limitation to the LA school district, it could be beneficial to apply these methods to other school districts in order to improve our knowledge of land use in schools.

Children and Nature

The lack of tree canopy in LAUSD schools highlights the deficit of nature present in the daily lives of children. Land use in schools could be transformed to bring nature to children through the greening of schoolyards. This is critical because if we consider the extent of our dependence on nature, our modern lives are profoundly disconnected from nature, removing us both physically and emotionally. Some argue that this nature disconnect is at the root of continued environmental degradation. The biophilia hypothesis states that humans have an innate love of life, and emphasizes that ecoliteracy helps to develop a conservation ethic in that the more we understand other organisms, the greater value we place on them and on ourselves (Wilson, 1984).

Connection with nature (CWN) arises through experience outdoors witnessing life in its many forms, consequently developing ecoliteracy. Our connection with nature is an awareness of the interrelatedness between one's self and the rest of nature, and it is linked to happiness, helping us to live more purposeful, meaningful and fulfilling lives (Zylstra, Knight, Esler, & Le Grange, 2014). Consequently, our connection with nature is directly correlated to enduring environmentally responsible behavior (ERB). Hence, the children and nature connection is of reciprocal benefit.

With regards to education, nature provides a dynamic multidimensional context for learning that draws forth the necessary critical thinking and systems view of life needed to regenerate the earth, all while inspiring a sense of wonder. In addition, contact with nature supports physical health, cognitive functioning and self-control, psychological well-being, affiliation and imaginative play which can result in beneficial outcomes in schools (Chawla, 2015). Simply providing views to green space from classrooms, can improve attention and accelerate recovery from stressful events (Li & Sullivan, 2016). Integrating nature on school grounds provides a multitude of benefits to the school community, positively reinforcing the mutually beneficial children and nature connection. School gardens have served to develop CWN by restoring children's connection to food and where it comes from.

School Gardens

School gardens have been a mechanism by which schools can develop greener schoolyards and build the children and nature connection. School gardens as ecological learning environments are now established throughout California, as well as the country, through the support of organizations and programs such as the Center for Ecoliteracy, Life Lab, and the Edible Schoolyard. Considering school gardens as community gardens, some of the benefits include food equity, social integration, and the development of natural human capital, meaning developing the skills of the participants (Macias, 2008). School garden programs work to address the double burden of malnutrition and obesity among children, resulting in significant improvements in dietary outcomes for students by increasing fruit and vegetable intake (Berezowitz, Bontrager Yoder, & Schoeller, 2015). During the exploration of food systems, students encounter topics on health, water, energy, poverty, hunger, climate change, biodiversity, systems, soil, ecology, natural resources, human impacts, and more. Hence, school gardens provide rich experiential learning opportunities for ESD.

Although there may be interest, some schools do not have existing school gardens due to barriers related to time, lack of funds, uncooperative administration, burned-out teachers, lack of dedicated volunteers, and not having access to a garden coordinator (Hazzard, Moreno, Beall, & Zidenberg-Cherr, 2012). Many schools that already have school garden programs encounter challenges such as time, gaining support from school staff, and maintaining school gardens at schools that do not have summer programming (Nocito, 2012). Some of these barriers and challenges to launching and sustaining a successful school garden program overlap, and can be resolved somewhat by food forests, mainly minimizing ongoing maintenance, reducing ongoing costs, and avoiding summer maintenance by designing for harvest throughout the school year and installing automatic irrigation. Another consideration is that as the number of school gardens increase, more and more students will have experienced school garden curriculum by the time they reach middle school. The complexity of a food forest ecosystem is a natural extension from elementary school garden curriculum into the upper grades. Resolving these issues by implementing food forests in place of raised bed gardens could also help address the primary challenge related to gaining ongoing support from administrators, teachers, and volunteers.

Leveraging the significant achievements and widespread adoption of school gardens, a transition towards food forests could be far reaching, providing significant ecological, educational, and economic benefits beyond the traditional school garden of raised beds planted with annual crops.

Food Forests

Food forests, a method of agroforestry, have been cultivated throughout the centuries, and are still encountered in rural tropical environments as a traditional means of subsistence farming. More recently, food forests have been developed as an important aspect of permaculture, and are reminiscent of the intention the originator of permaculture, Bill Mollison, to intentionally design forests that are as healthy and thriving as those found in nature with plants that are also functional for humans (Mollison, 1979). The plants selected are used as food, medicine, or for other applications, or provide a key service to the ecosystem. Trees are often surrounded by plants beneath the canopy that support its health and development, forming what is referred to as a guild (Figure 5).

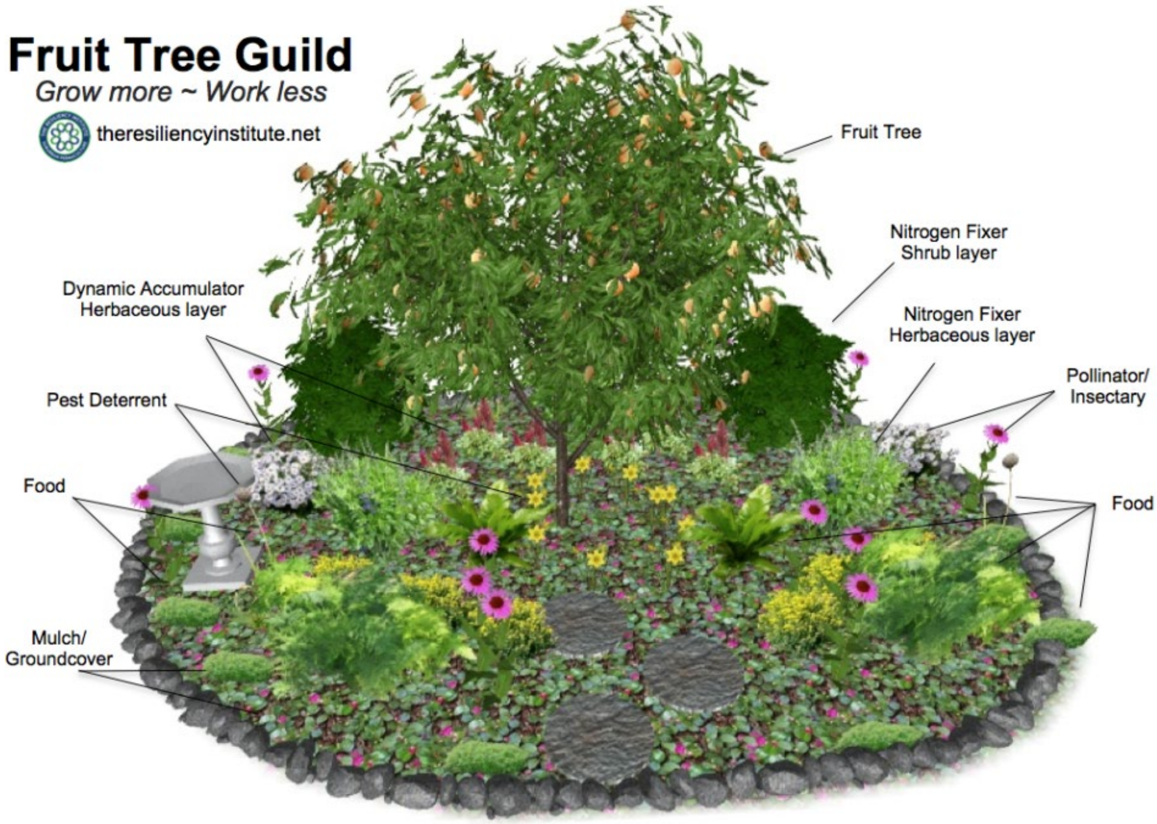


Figure 5. Supporting functions of plant species in a fruit tree guild.

Intentional placement of each plant generates microclimates, nutrient cycling, pest control, and other benefits that enhance biodiversity, build fertile soils, increase resilience, and supports organic cultivation. Although there are differences between sources, permaculture practitioners have identified up to nine layers in a food forest (Figure 6). These nine layers take full advantage of the variety of species that can exist in a cultivated food forest ecosystem including trees, shrubs, herbs, ground cover, root crops, climbers, aquatic species, and decomposers.

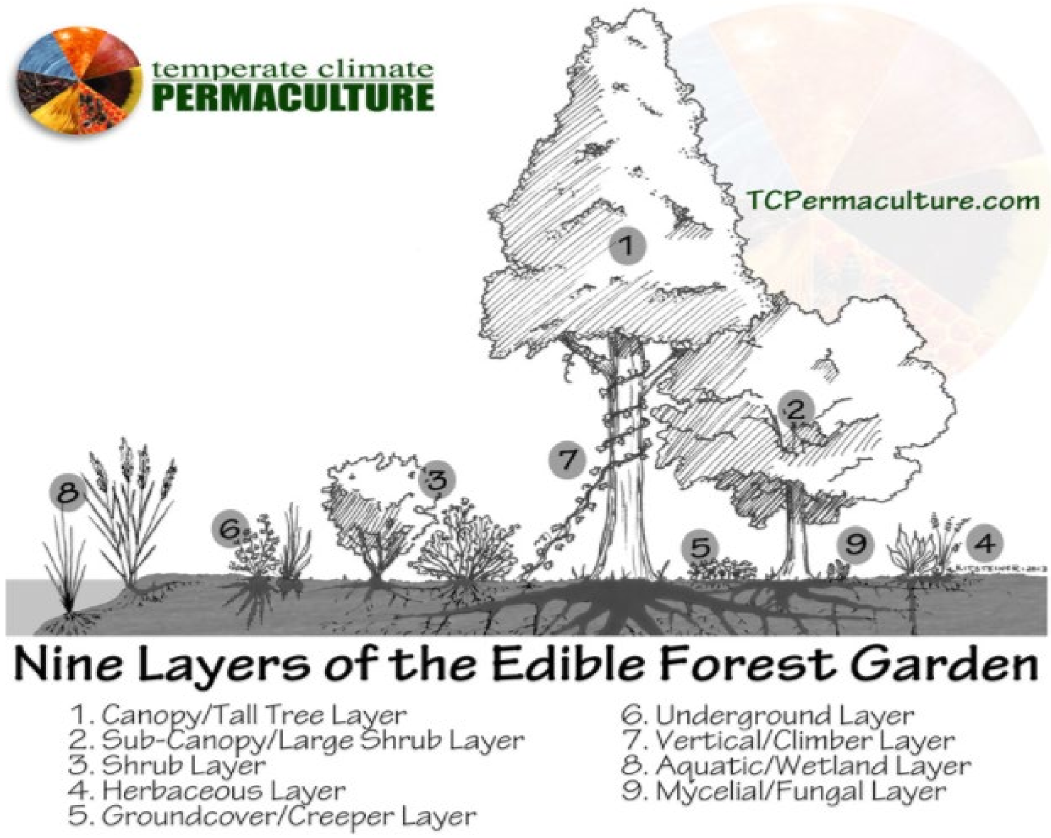


Figure 6. Nine layers of the edible forest garden (food forest) (Kitsteiner, 2013).

Optimally, food forests are designed to require little maintenance and limited external inputs, such as fertilizer or pest management, thus enhancing economic benefits. Food forests are considered a regenerative agricultural practice that enhances ecosystems, and could provide significant benefits to urban environments. The forest garden pattern language was developed in order to support food forest design by providing proven ecological patterns that can be considered for each element in the food forest (Jacke & Toensmeier, 2005b). The concept map provides a visualization of the forest garden pattern language that can be readily applied in food forest design (Figure 7).

Figure 7. A forest garden pattern language concept map (Stedman, 2010).

Agroforestry

Agroforestry, a form of agroecology, is gaining grounds in the transition to more sustainable agricultural practices within the United States and throughout the world. Agroforestry is described as “the intentional mixing of trees and shrubs into crop and animal production systems to create environmental, economic, and social benefits” (USDA, 2011a). There are five main categories of agroforestry: silvopasture, alley cropping, forest farming, windbreaks, and riparian forest buffers. Food forests, based on permaculture, most commonly apply the forest farming method of agroforestry.

On the global scale, while many agroforestry programs have been successful, the FAO has identified challenges to widespread adoption. In order to overcome these challenges, there is a concerted effort to expand research in agroforestry that supports policy transformation, and to develop and disseminate practical tools and solutions that enhance food security and resilience in the face of climate change (FAO, 2017). In the US, the USDA released the Agroforestry Strategic Framework as a roadmap to advance agroforestry practices in that promote prosperity and protect our natural resources (USDA, 2011b). Teaching agroforestry in US schools would provide a global perspective of sustainable development, raising awareness of the challenges faced by the most vulnerable communities by exploring agroforestry as a promising solution to food security and environmental protection.

Permaculture

Permaculture, or permanent culture/agriculture is a form of agroforestry, but it is less prominent in academia. Part of the challenge is that permaculture involves a more integrated approach that does not necessarily fit within discipline-specific traditional formal education. This is changing as interdisciplinary studies in sustainability gain grounds in institutions around the world, and permaculture emerges as a topic of analysis. In a review of permaculture literature, Ferguson and Lovell (2014) note that while the potential contribution of permaculture to agroecological transition is great, permaculture remains relatively isolated from scientific research, oversimplifies claims, and lacks a clear definition. However, they also point out that the approaches, principles, and topics largely complement and even extend what exists in agroecological literature, and scholarship has been marginal but is growing, thus suggesting promising avenues of inquiry.

Permaculture seeks to establish sustainable ecological communities through the application of its core principles (Hemenway, 2009). Although not tied to the SDGs, permaculture design courses are currently available around the world, and permaculture has been a form of education for sustainability since the 1970's. In parallel to the three pillars of sustainability (environmental, economic and social), permaculture introduces its three ethics: earth care, fair share, and people care (Figure 8). In addition, the twelve principles integrate a way of knowing and being that incorporates ethical and responsible management of the environment that engages us in the full life cycle of the natural resources we use. Permaculture thus has the ability to transform discipline-specific education to a more integrated approach as called for in GAP ESD.

Research on food forests can contribute to permaculture scholarship by quantifying ecosystem services, and evaluate a practical way to implement permaculture for ESD by considering the adoption of food forests in schools.

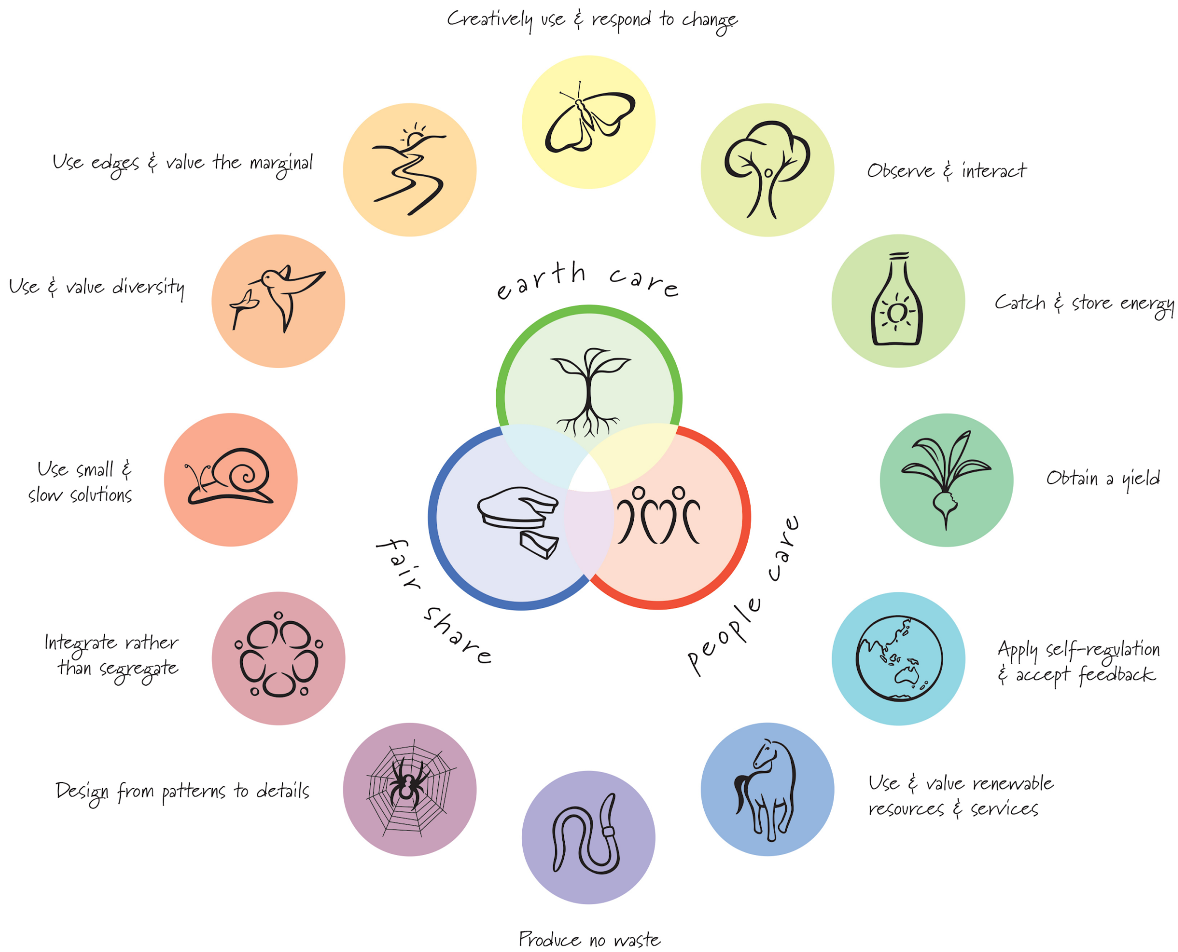


Figure 8. The three ethics and twelve design principles of permaculture (Holmgren, n.d.)

Ecosystem Services of Urban Food Forestry

Ecosystem services are viewed as the benefits ecosystems provide to humans grouped into four categories: provisioning, supporting, cultural, and regulating services (Alcamo et al. 2003) (Figure 9). The US Department of Forestry (USDF) has long recognized the value of trees in urban environments and has implemented programs to monitor, support, and promote urban forestry. Some of the recognized ecosystem services of urban forests include energy conservation, carbon storage, reduced stormwater runoff, improved air quality, and enhanced human health and well-being (McPherson, Simpson, Xiao, & Wu, 2011).

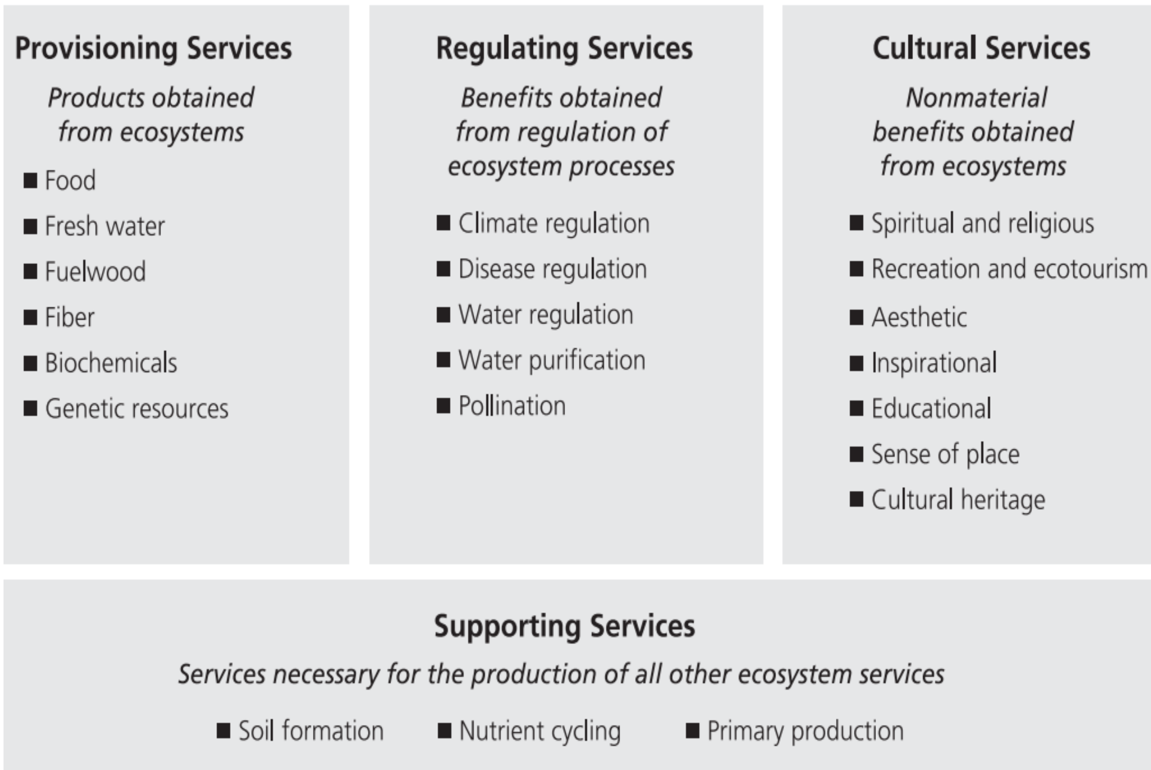


Figure 9. Ecosystem services (World Resources Institute, 2003).

At the tree scale, trees provide shading and cooling through transpiration, absorb carbon dioxide via photosynthesis, intercept rainfall and evaporate moisture, and reduce air pollution by deposition of particulate matter on leaves (Figure 10). USDF analysis tools, such as the UFORE method that is used in iTree, supports the quantitative assessment of these ecosystem services (USDF, n.d.). Tree planting can be designed to maximize these ecosystem services based on placement and plant selection. Food forests in urban environments, also provide food provisioning as an ecosystem service.

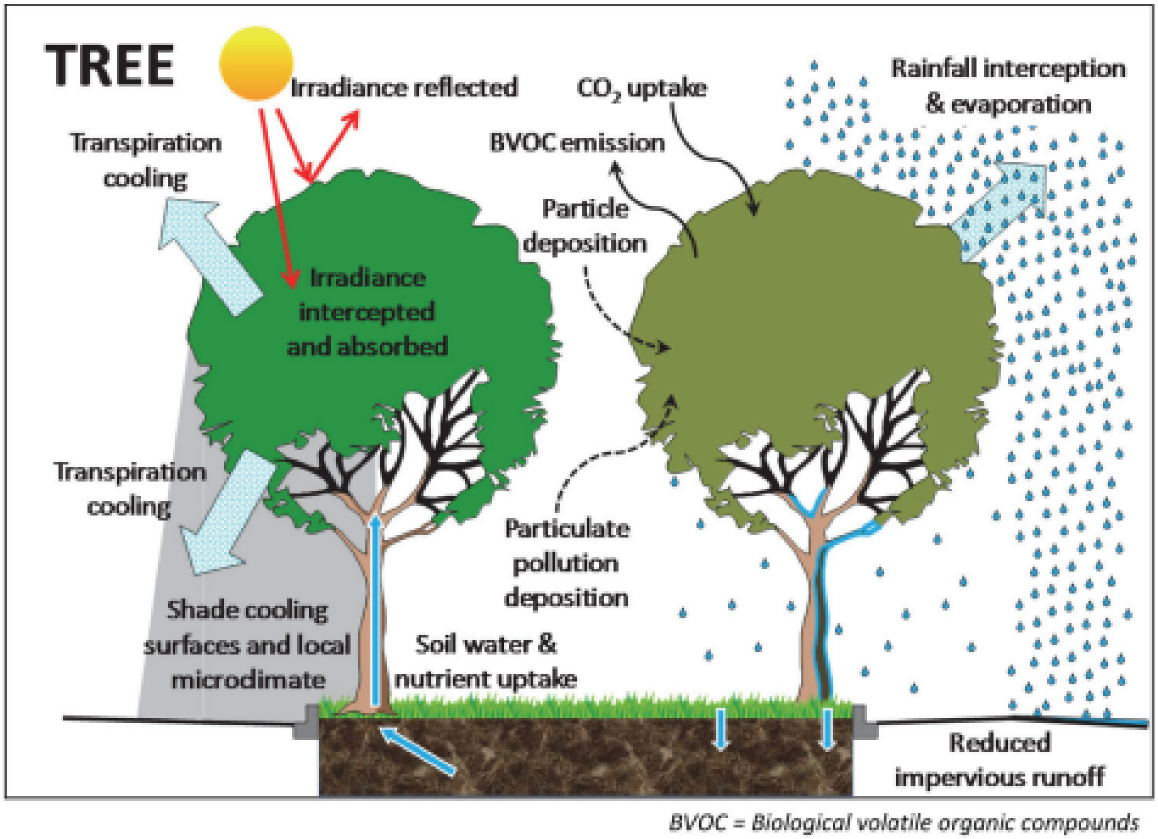


Figure 10. Urban forest ecosystem service and function at the tree scale (Livesley, McPherson, & Calfapietra, 2016).

Clark and Nicolas (2013) introduced urban food forestry (UFF) as a multifunctional approach to increase food security and provide ecosystem services. Their research consisted of analyzing existing urban food tree initiatives and urban forest initiatives, as well as conducting their own case study of a large-scale food forest initiative. They found that there are numerous grassroots initiatives to support urban fruit trees targeting what they identify as the three pillars of UFF: planting, mapping, and harvesting. However, there exist very few mentions of food or fruit trees in urban forestry master plans, which seems that food production is a low priority for urban forestry at the government level. Through their case study, they demonstrate the potential of an UFF program to fill the gap of calories for the food insecure population in Vermont by planting open space with species of apple trees. While they do not suggest apples will provide the nutritional requirements in themselves, the case study demonstrates the potential of such a program.

Their research is valuable in that it introduces the term UFF, defines the three pillars of UFF, describes the current state of UFF, and provides an inspirational case study. However, their case study is very general, using only apple trees, and it is primarily focused on food provisioning. Ecosystem services besides food provisioning, are only discussed, and not quantified.

Food Forests in Schools

Developing food forests on school campuses not only enhances ecosystem services, but also brings a model forest ecosystem to the students that can be readily accessed as an outdoor laboratory. In considering GAP, food forests would provide real world context for ESD to explore the integrated curriculum of the SDGs. The outdoor learning environment would simulate a forest ecosystem, providing new context for topics beyond what is available in a school garden by introducing new layers of complexity and species interactions. For example, enhanced topics could include forest ecology, carbon sequestration, soil regeneration, ecological restoration, nutrient cycling, tree care, plant propagation, species interactions, water management, and more. As promoted by FAO and USDA, food forests can provide a global perspective by considering agroforestry as a means towards developing food security for the world's most vulnerable communities. In addition, once established, food forests can resolve some of the challenges encountered with school gardens by requiring less external inputs and maintenance than a raised bed garden planted with annuals. Most importantly, students would have access to a highly biodiverse natural environment that can provide the benefits children experience in nature.

Ecosystem Services of Food Forests in Schools

Beyond adding educational value, food forests in schools could provide needed ecosystem services in urbanized areas by regenerating developed lands. Carbon sequestration, avoided runoff, air pollution reduction, and food production are significant ecosystem services that could be quantitatively analyzed in urban settings. Food forests can provide additional ecosystem services including, but not limited to: nutrient cycling, soil formation, climate regulation, energy savings in buildings, wildlife habitat, aesthetic and spiritual services. The qualitative assessment of educational benefits by linking food forest curriculum to ESD should also be assessed.

While some argue that ecosystem services are a limiting perspective that simplifies the value of the natural world for human benefit, we can also consider what humans can do in turn to support ecosystems. A transformative perspective considers ecosystem services as a reciprocal relationship with humans providing services to ecosystems (S2E), and ecosystems providing services to humans (ES) (Figure 11). Integrating this perspective of humans as stewards of ecosystems into school curriculum has the potential to fundamentally change how we interact with our natural environment, resulting in a necessary widespread cultural shift towards what I term 'Cultural Environmental Responsibility.' Here I build upon the concept of S2E, by introducing the concept of ‘cultural environmental responsibility’ as the ideas, customs, and social behavior of a society that supports the protection of the environment through conservation ethic and by providing services to ecosystems (S2E).

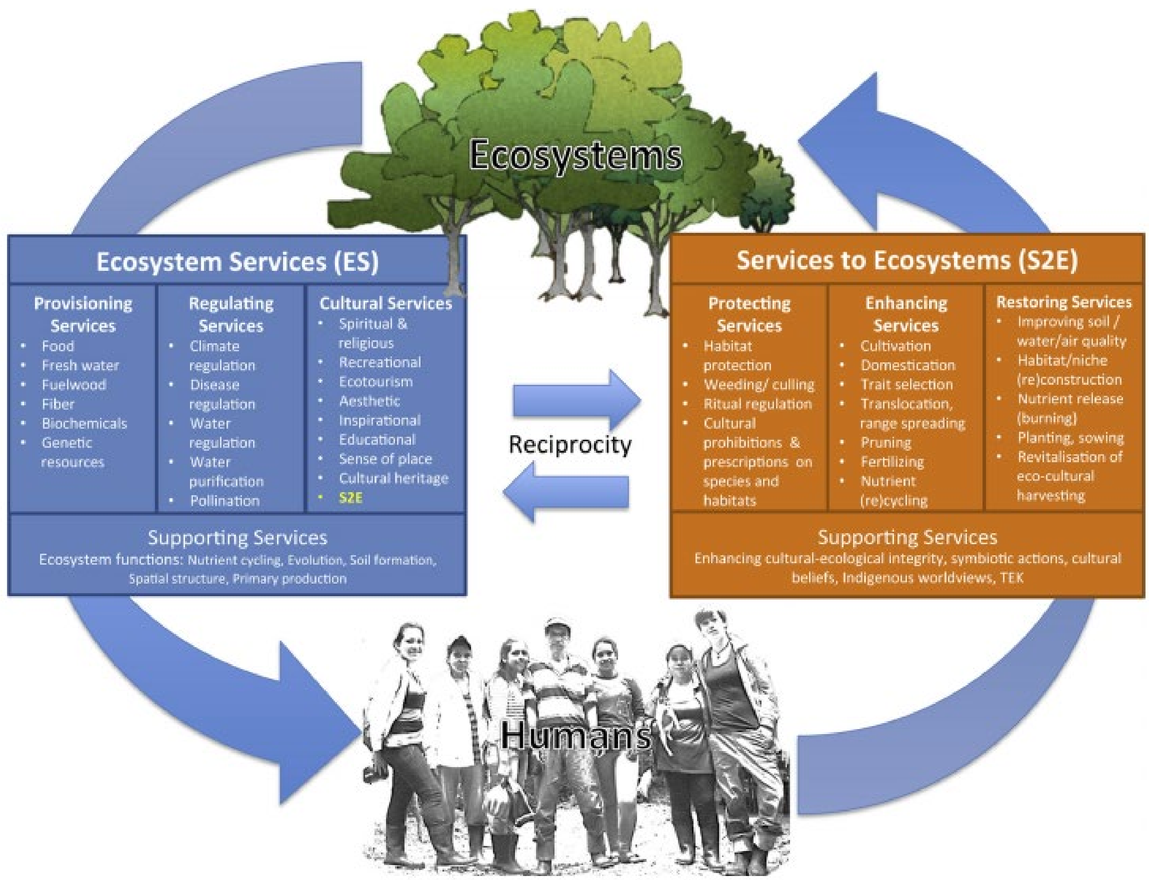


Figure 11. A revised framework of ecosystem services as a reciprocal relationship (Comberti, Thornton, Wyllie de Echeverria, & Patterson, 2015).

Comparing the Feasibility of School Gardens vs Food Forests

As mentioned, funding is often identified as a barrier to school garden initiatives. To examine the economic feasibility of food forests, I will compare the costs and benefits of establishing and maintaining a food forest to the more popular raised bed school garden. I will also quantify the summative ecological benefits of widespread adoption of food forests in place of lawns. By conducting a cost-benefit analysis (CBA) of food forests as compared to traditional raised bed school gardens and lawns, I expected to determine whether or not food forests would in fact be beneficial to schools by enhancing ecosystem services and reducing costs. No such CBA has been conducted.

Research Question, Hypotheses and Specific Aims

My primary research question was: Do food forests in schools provide greater ecosystem services as compared to raised bed school gardens while upholding food production and enhancing opportunities for education for sustainable development? To address this question, I tested the following hypotheses:

- Food forests in schools provide greater ecosystem services as compared to raised bed school gardens and lawns of an equivalent area, over time.
- Food forests financially outperform raised bed school gardens by reducing maintenance costs and inputs and producing more food over a 30 year period.
- With increasing adoption rates, food forests in schools in California will contribute a significant amount of carbon sequestration, avoided runoff, air pollution reduction, and food production as compared to lawns.

Specific Aims

With the aim of fulfilling my research objectives and testing my hypotheses, I completed the following tasks:

1. Calculated the ecosystem services of a quarter acre model food forest, raised bed garden, and lawn to include carbon sequestration, avoided runoff, air pollution reduction, and food production.
2. Designed a quarter acre model food forest to be used for analysis using permaculture design techniques and considerations that are applicable to schools.
3. Created a spreadsheet to conduct a cost-benefit analysis of the quarter acre model food forest as compared to a raised bed garden and lawn. The spreadsheet will incorporate installation and maintenance costs of each land use, as well as a financial appraisal of ecosystem service benefits over time.
4. Conducted a case study that calculates the cumulative ecosystem services resulting from increasing adoption of food forests in California schools, using the quarter acre model food forest.
5. Correlated GAP ESD learning objectives to curriculum applicable to a food forest ecological learning environment by generating a curriculum mapping tool.

Chapter II

Methods

The overall research assessed the benefits of food forests in schools as compared to other land use scenarios by estimating the ecosystem services of each land use, and conducting a comparative cost benefit analysis. I created a hypothetical permaculture food forest design based on a specific site location for demonstrative and modeling purposes. From the design, I conducted a 30 year forecast of ecosystem services of the quarter acre food forest using iTree modeling software. I also modeled ecosystem services of a quarter acre lawn and raised bed garden as the baseline for comparison. The iTree models were used to calculate carbon sequestration, avoided runoff, and air pollution reduction, and the monetary value of each ecosystem service. In addition, food production was estimated using data from the California Department of Food and Agriculture (CDFA). Food production values were based on data from the USDA. By conducting a cost benefit analysis of each land use scenario, I was able to compare the value of ecosystem services over time. Finally, I created a curriculum mapping template that I used to correlate food forest curriculum with GAP ESD in order to demonstrate the educational benefits of the food forest and provide an example for applying ESD.

Permaculture Food Forest Design

I am not certified in permaculture design. Therefore, I consulted with David Shaw of Santa Cruz Permaculture, an expert and educator in this field. David Shaw provided guidance, suggestions, and reviewed my final permaculture design to ensure that it properly integrated permaculture design methods. I designed the quarter acre model food forest using three primary permaculture design guides: *Edible Forest Gardens* (Jacke & Toensmeier, 2005), *Gaia's Garden* (Hemenway, 2009), and *The Permaculture Earthworks Handbook* (Barnes, 2017). The Plant Species Matrix in *Edible Forest Gardens* was especially useful for species selection, and included data on a multitude of plant species with regards to tolerances, architecture, uses, functions, and drawbacks. For analytical purposes, the design is meant to maximize use of the space, and does not integrate many aesthetic features or other elements often included in permaculture design. However, a few additional features are included within the garden as well as outside of the quarter acre boundary to highlight as suggestions to incorporate in an educational permaculture food forest: sun mandala keyhole garden bed, herb spiral, outdoor classroom space, compost bins, and greenhouse.

Site Selection

To design a model food forest, it was best to choose an actual site where I could apply real world design techniques and considerations. The design was made for demonstration purposes only, and was not planned for implementation. I chose to focus on schools in the San Jose Unified School District (SJUSD) because the city is relatively large, it is close in proximity, and there are local programs that promote and support community gardens and tree planting, such as Valley Verde, and Our City Forest. The existence of these local programs validates the demand for such programs, and can also serve as a valuable resource.

Many school garden programs have focused on elementary schools; I see food forests as a natural progression that can be implemented in middle or high schools. I narrowed my selection to middle schools because the campuses tend to be smaller than high schools, so a food forest could be more difficult to place. While there was substantial land available at other middle schools within SJUSD, I chose Castillero Middle School specifically because I could easily place on its grounds a relatively rectangular quarter acre food forest, a generic shape for a food forest with design elements that could be applied to many schools. I did not take into consideration demographics or any other factors in the selection process because it is expected that the best actual site selection would be at a school community that was motivated to implement an integrated food forest program. Note, actual food forest design need not be limited to rectangular plots and should be tailored to the particular location.

Food Forest Design Map Creation

I began the food forest model design process by exploring satellite imagery of the Castillero Middle School campus using Google Earth. From the satellite images, I could observe lawns used as sports fields on the west side of campus, and I also identified areas of lawn that were not being utilized (Figure 12). I mapped out tentative locations for a one quarter acre food forest using google earth measurements. Next, I conducted a site visit to gather additional information about the site, verify measurements, and select a location. As a result of the site visit, I selected the location that was best suited for the food forest for the following reasons: excellent sun exposure, under-utilized, easy access for vehicles and pedestrians, proximity to classrooms, offset from main roads for security, existing Northwest windbreak, existing irrigation, and close to potential rainwater harvesting from rooftops.

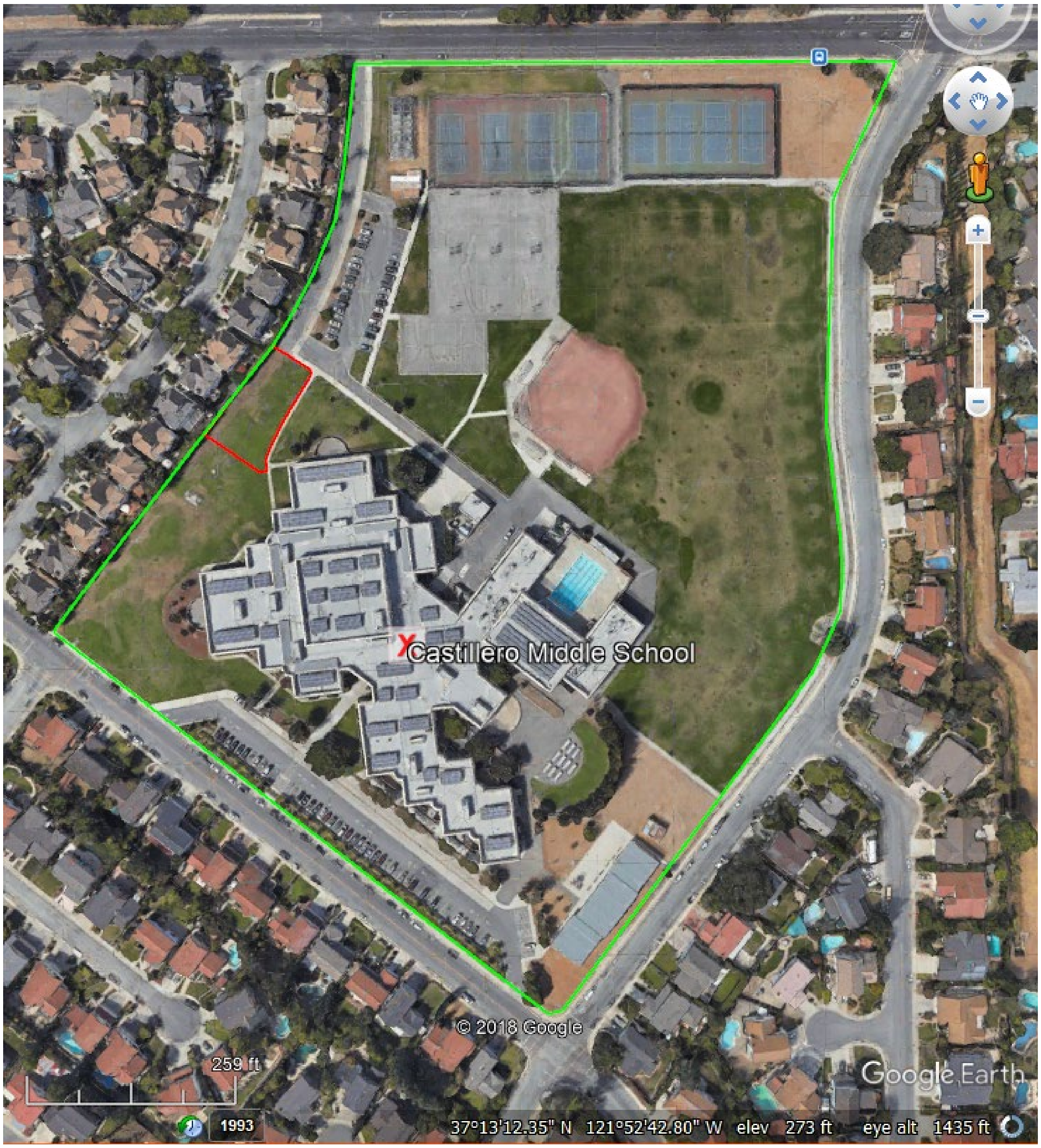


Figure 12. Castillero Middle School satellite image of proposed food forest location on campus.

I created the following maps as part of the Castillero Middle School permaculture food forest design:

- Base Map: I first drew the boundary of the food forest in Google Earth. I imported the satellite image with the boundary into Sketchup and traced the boundary and pathways to draw the base map, then applied dimensions.
- Contour Map: Utilizing the "Ruler" function within Google Earth, I drew multiple linear paths crossing the property that were both parallel and perpendicular to the Northwest fence (Figure 13). While viewing the elevation profile, I noted maximum

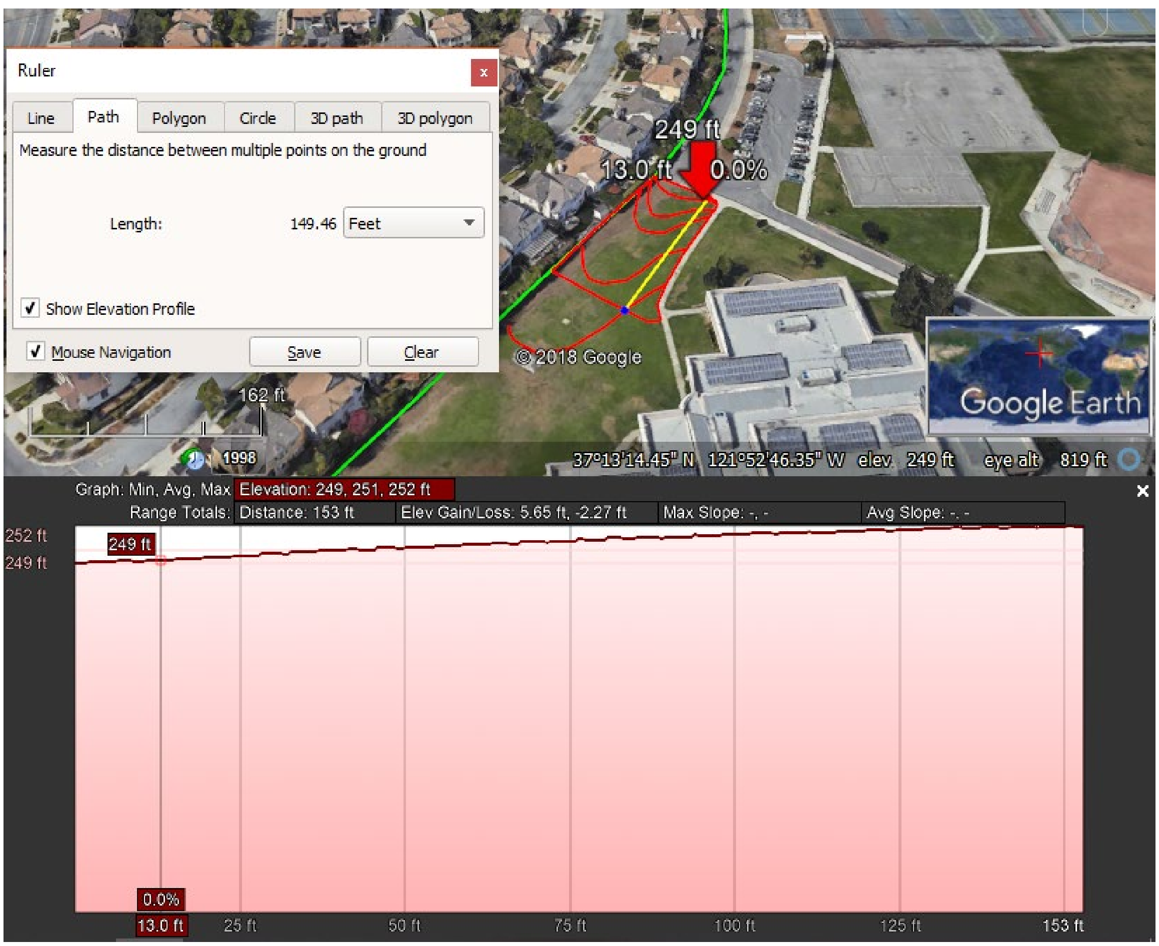


Figure 13. Google Earth ruler-path with elevation profile for drawing contour lines.

and minimum altitudes, and could visualize the contour of the land, congruent with my site visit. I then drew the contour lines using the same Ruler-Path function in Google Earth, by connecting short linear lines that changed direction to stay at the same elevation, forming curved paths.

- Sector Map: The sector map I created includes the sun resource map, as well as water flow direction before food forest vegetation and earthworks. I mapped the sun and shade patterns by adjusting time of day in Google Earth for sunlight throughout the four seasons and noted existing areas of full shade, partial shade, and full sun. With regards to wind patterns, I found a wind chart developed by an independent researcher, and cross referenced his data with weather data available for San Jose, CA and they were aligned (Figure 14). The water flows perpendicular to the contour lines

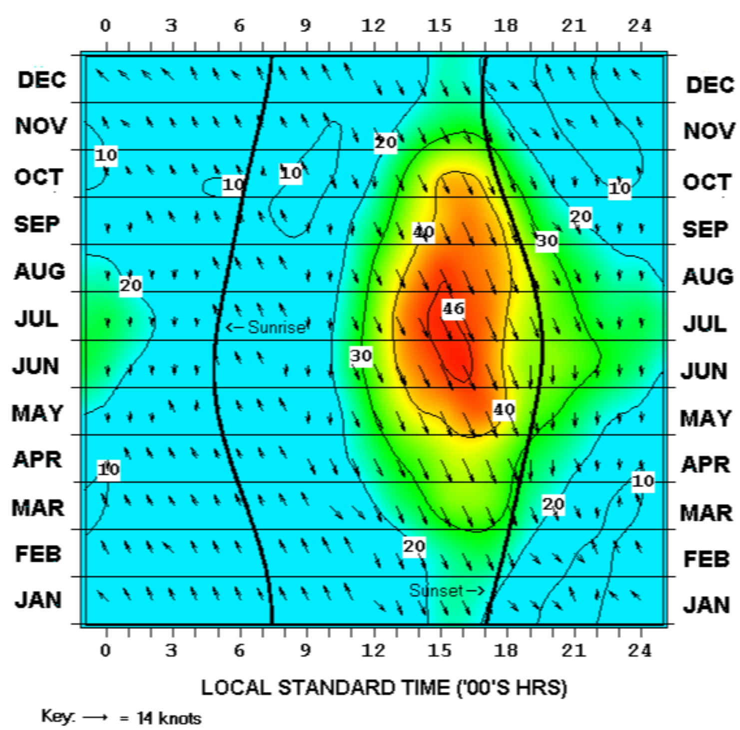


Figure 14. Prevailing winds chart for San Jose, CA (Fisk, 2009).

with gravity. To determine the sun path, there were many free tools available online. I utilized the online calculator, Sun Earth Tools, to calculate the sun's position at winter and summer solstice. While winter winds often blow from the Southeast direction, the stronger winds still travel from the Northwest.

- Zone Map: The zone map separated areas based on permaculture zoning. Zoning was planned according to frequency of use and maintenance, placing highly intensive use areas closer to the home, or in this case, the classroom. I adapted the traditional zoning of permaculture design for school application, and included sample patch themes and design elements that could be used in these zones.
- Berms, Swales, and Paths Map: The distribution of berms and swales was calculated based on a logarithmic formula that spaces the swales closer together towards the upper part of the slope, and further apart towards the base. The distribution was based on the following expression:

$$\log_{(n+2)} S \times D$$

  where n was the total number of swales, S was the swale whose position you are calculating, and D was the distance from the base (Barnes, 2017).
- Planting Plan: Optimally, the garden's long axis would be oriented east-west for greatest southern exposure. However, in the case of the Castillero site, the long axis was SW-NE, and plant placement was laid out accordingly. Taller trees were placed at the north edge of the garden and progressively shorter trees planted towards the south to reduce shade cast on other plantings. Plants were spaced according to estimated canopy size at maturity; intercropping can take advantage of unused space

while adapting to changing conditions throughout forest succession. The density of the food forest was moderate, and the spacing included gaps between taller species to allow for easy access as well as sunlight to penetrate into the forest in order to enhance growth and productivity. Shrubs filled some of the gaps. Although not drawn in the design, each tree would be planted as a tree guild that includes plants with supporting functions in the understory. In addition, cover crops were not included in the analysis, but their use is suggested.

Plant Selection

I selected the primary plant species based on some or all of the following criteria: ability to grow in California, harvest primarily during the school year, edible, size, diversity, partial sun or shade tolerant, nitrogen fixer or dynamic accumulator, and included in the iTree database for modeling purposes. California crop season has many species that can be harvested during the school year, and some variations can be selected for late or early harvest to better align with school calendars (Figure 15). In a food forest, edible plants that can tolerate partial sun or shade are especially valuable once the trees reach maturity. The understory and cover crop species were not defined because it was not necessary for analysis purposes.

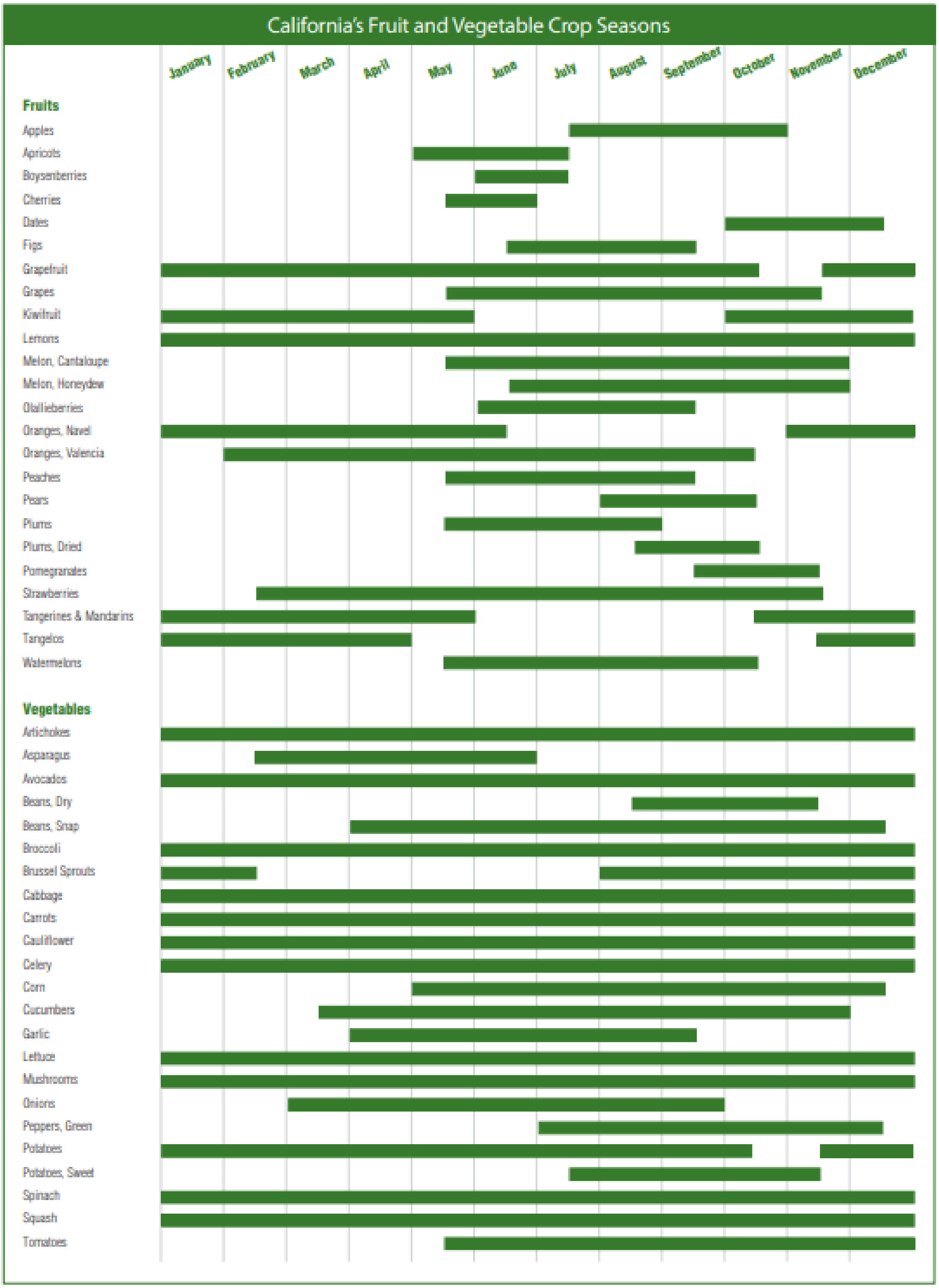


Figure 15. California fruit and vegetable season (CDFA, 2018).

iTree Eco Modeling

The iTree Eco software is an industry accepted peer reviewed software that analyzes ecosystem services of urban forestry based on the UFORE methods (USDF, n.d.). The software is available on the internet and is free to the public. Typically, iTree Eco is applied to existing tree plots, and the iTree Planting tool is used to determine the future benefits of a tree planting project. However, iTree Eco is far more robust, and was better suited to this analysis. I was able to utilize the software to forecast ecosystem services of the model food forest, raised bed garden, and lawn land use scenarios. All simulations used the same location (San Jose, CA), weather station (72495-23293) weather and pollution year (2015), urban stratum, and institutional land use, for ease of comparison. A sensitivity analysis was conducted to evaluate the impact of changing these variables. Default settings based on average values were selected whenever possible because the food forest does not yet exist and actual values cannot be measured.

UFORE Methods

The Urban Forest Effects (UFORE) computer model can quantify urban forest structure and functions to include:

> other structural characteristics; hourly volatile organic compound emissions (emissions that contribute to ozone formation) throughout a year; total carbon stored and net carbon sequestered annually; and hourly pollution removal by the urban forest and associated percent improvement in air quality throughout a year (Nowak & Crane, 2000, p. 714).

Ecosystem services of the urban forest structure are calculated based on species composition, diameter distribution, tree density and health, leaf area, leaf biomass, standard field data for air pollution sourced from the EPA, as well as meteorological data from weather stations throughout the US. The monetary values of ecosystem services are calculated based on existing literature.

In UFORE, carbon sequestration refers to the removal of carbon in the form of carbon dioxide from the atmosphere through photosynthesis, while carbon storage refers to the amount of carbon bound up in woody biomass, both above and below ground.In iTree, the above-ground biomass is calculated based on forest derived allometric equations available for each tree species (Nowak, 1994). Trees sequester carbon through the photosynthetic growth process by removing atmospheric carbon dioxide and storing the carbon as biomass. Each tree has both above and below ground biomass. If equations are not available by species, biomass is calculated using equations by genus when available, or by the average of all broadleaf or conifers accordingly. A root-to-shoot ratio of 0.26 is used to derive the whole tree biomass to include both above and below ground biomass (Cairns et al., 1997). Dry-weight biomass is computed based on average moisture content by species. Biomass of urban trees is reduced by a factor of 0.8 due to the tendency to have less above-ground biomass than forest grown trees with the same DBH based on maintenance practices (Nowak, 1994). Due to annual foliage loss for deciduous trees, stored carbon is calculated by multiplying total tree dry-weight biomass by 0.5 to account for carbon stored only as wood biomass (Forest Products Lab, 1952; Chow & Rolfe, 1989).

Using hourly meteorological data from the closest weather station and air pollution data from the EPA, UFORE quantifies the amount of pollution removed annually by the food forest for O3, SO2, NO2, CO, and PM10. In UFORE, the pollutant flux (F; in g m $^{-2}$ s^{-1}) is calculated as the product of the deposition velocity (V_d; in m s^{-1}) and the pollutant concentration as sourced by hourly data (C; in g m^{-3}):

$$F \times V = C_d$$

The deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasilaminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi et al. 1987):

$$V_d = (R_a + R_b + R_c)^{-1}$$

The resistances are directly related to leaf area, and are affected by weather conditions.

Avoided runoff is correlated with precipitation interception based on leaf area. The iTree models incorporate changes in leaf area due to seasonal variations for evergreen and deciduous trees. Rainfall data from the local weather station provided data for that year.

Food Forest iTree Model

The food forest model in iTree is based on the layout in Figure 27. Since the iTree model is not based on existing trees, but rather a new plantation, the inputs are not based on actual measurements in the field. As such, I utilized many of the default values in iTree that are either applied to categories (such as small trees, or shrubs) or species specific when available. For improved accuracy and ease of modeling, the majority of the species selected in the food forest design were included in the iTree database and also fit the criteria for a food forest in California schools. The model included 125 trees and shrubs, with over 25 different species, some generically labeled, such as citrus.

For year one, all plants started with a one inch diameter at breast height (DBH) which is commonly available at most nurseries. To forecast benefits as the food forest matured, I ran individual simulations for each year using the same input variables, and only adjusting DBH. The iTree software does include forecasting ability, but the results were more limited and avoided runoff cannot be included. I used the following formula to calculate the DBH for each species for every year: $DBH_y = DBH_{y-1} + DBH_g$, where DBH_y was the value for the year of the simulation, DBH_{y-1} was the value for the year prior, and DBH_g was the average annual growth. The average annual DBH growth varied by species and growing conditions.

Todetermine the DBH_g for each species, I ran a forecast model using the same input variables as the food forest model for each individual tree, starting at year one, with a DBH of one inch. The forecast simulation revealed that the average annual DBH growth changes year after year, and often decelerates over time for some species, as is the case for peach (*Prunus persica*) (Figure 16).

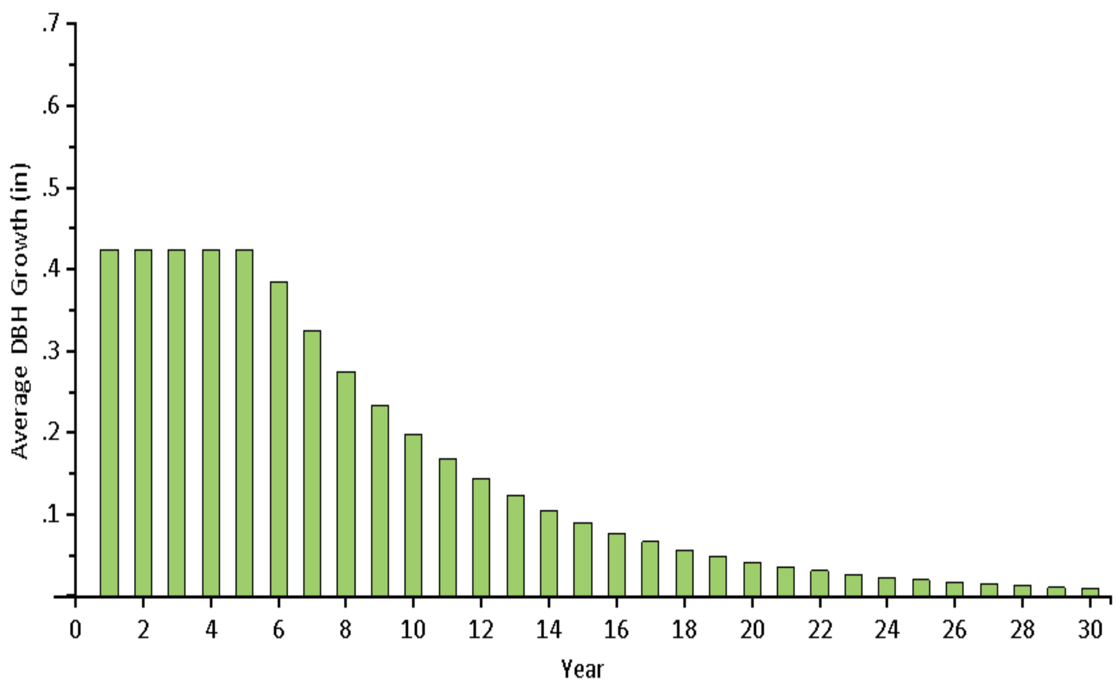


Figure 16. The average annual dbh growth for peach (*Prunis persica*) in San Jose, CA.

In some cases the DBH data were not available for a specific species. In that case, I used a species in the same family, or category such as small tree. After running the forecast for each year, I compiled the results of annual benefits in a spreadsheet.

In addition to the food forest model in iTree, the food forest also included intercropping of the understory and forest succession. Consistent with the coverage of the raised bed garden, the model considered 60% of the understory of trees were planted, and 40% were reserved for paths and utility space. According to David Shaw of Santa Cruz Permaculture, a goal of any food forest should be to take advantage of all space for planting, and understory planting could achieve even greater percent coverage, so the 60/40 ratio could be considered conservative. To calculate the understory area available for planting, I summed the circular canopy area of each tree species at maturity, A_t, excluding citrus and mulberry which are too dense to allow optimal growth under the canopy. I also included the circular area of the sun garden mandala with perennial vegetables and herb spiral, A_m. I then applied the 60/40 ratio to calculate the total area of understory crops, A_u, at 60% of the sum of circular areas using the following equation:

$$A_u = (\Sigma A_t + A_m) \times 0.60$$

I ran iTree using the identical model for the raised bed garden, but only used the amount of plants necessary for the understory crop area. I then added the results to the food forest model. Raised bed gardens often integrate vines, shrubs, herbs, and tubers into its vegetation layers, and permaculture has identified a variety of edible crops that are shade tolerant. Hence, this can be considered a reasonable approximation for the understory ecosystem services of a food forest, or as part of a forest succession plan.

Runoff is the only ecosystem service that may be overestimated by this scenario due to a slight reduction of rain that is intercepted by the mature canopy. To maintain transparency, I ran the food forest scenario both with and without understory for comparison.

Raised Bed Garden iTree Model

For the purposes of this analysis, the definition of the raised bed garden considered annual crops that are sowed and harvested each season. Therefore, each year, the crop biomass is consumed or decomposed, and the carbon is no longer stored within the living plant biomass, resulting in zero net carbon sequestration. To calculate air pollution reduction and avoided runoff, a model was generated in iTree to simulate a raised bed garden. This analysis assumed that the raised bed garden used 60% of the garden area for crops, and 40% for mulched paths and utility, which is a common ratio based on best practices in design for school gardens. Based on this ratio, the vegetation canopy in the model covered 0.15 acres (6534 sqft), or 60% of the quarter acre plot.

The UFORE model uses LAI as the primary input to calculate air pollution and avoided runoff. LAI is calculated as the ratio of leaf area to canopy cover. The database of plants in iTree is limited to perennial trees and shrubs, and there are no annuals. To utilize iTree to calculate ecosystem services for annual crop varieties, it was necessary to select perennial species that have a Leaf Area Index (LAI) similar to common crops. To select the species to use in modeling, I ran a simulation to determine the LAI of various shrub species in iTree, I found that given a fixed canopy size, the LAI and resulting ecosystem services are identical for the majority of evergreen shrub species (Table 4; Table 5). Hence, any of these shrub species could be used for modeling

Table 4. Identical LAI of shrubs in raised bed model species selection analysis in iTree.

Species Name	DBH (in)	Height (ft)	Canopy Cover (ft^2)	Tree Condition	Leaf Area (ft^2)	Leaf Biomass (lb)	Leaf Area Index
apple spp	0.5	3.0	7.1	Fair	31.2	0.6	4.4
Strawberry bush	0.5	3.0	7.1	Fair	28.5	0.4	4.0
American cranberrybush	0.5	3.0	7.1	Fair	28.5	0.4	4.0
bush honeysuckle spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
bushmint spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Jerusalem sage spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Mexican mint	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Silver Peppermint	0.5	3.0	7.1	Fair	28.5	0.8	4.0
sage spp	0.5	3.0	7.1	Fair	28.5	1.4	4.0
Sweetpea	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Wine grape	0.5	3.0	7.1	Fair	28.5	0.4	4.0
grape spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Lemon	0.5	3.0	7.1	Fair	28.5	0.9	4.0
gardenia spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
California huckleberry	0.5	3.0	7.1	Fair	28.5	0.4	4.0
California blackberry	0.5	3.0	7.1	Fair	28.5	0.2	4.0
riverhemp spp	0.5	3.0	7.1	Fair	28.5	0.4	4.0
Moundlily yucca	0.5	3.0	7.1	Fair	59.4	2.0	8.4
yucca spp	0.5	3.0	7.1	Fair	59.4	2.0	8.4
teabush	0.5	3.0	7.1	Fair	28.5	0.4	4.0

Table 5. Identical ecosystem services of shrubs in raised bed model species selection analysis in iTree.

					Annual benefits							
Species Name	DBH	Structural Value	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Carbon Avoided		Pollution Removal	
	(in)	($)	(lb)	($)	(lb/yr)	($/yr)	(ft^3/yr)	($/yr)	(lb/yr)	($/yr)	(oz/yr)	($/yr)
apple spp	0.5	48.81	0.2	0.01	0.4	0.02	0.4	0.02	N/A	N/A	1.3	0.15
Strawberry bush	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
American cranberrybush	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
bush honeysuckle spp	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
bushmint spp	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Jerusalem sage spp	0.5	48.81	0.4	0.02	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Mexican mint	0.5	48.81	0.4	0.02	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Silver Peppermint	0.5	40.78	0.5	0.03	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
sage spp	0.5	48.81	0.8	0.05	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Sweetpea	0.5	48.81	0.4	0.02	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Wine grape	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
grape spp	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Lemon	0.5	48.81	0.5	0.03	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
gardenia spp	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
California huckleberry	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
California blackberry	0.5	48.81	0.3	0.02	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
riverhemp spp	0.5	48.81	0.2	0.01	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14
Moundlily yucca	0.5	179.44	0.8	0.05	0.0	0.00	0.7	0.05	N/A	N/A	2.5	0.29
yucca spp	0.5	179.44	0.8	0.05	0.0	0.00	0.7	0.05	N/A	N/A	2.5	0.29
teabush	0.5	48.81	0.4	0.02	0.4	0.02	0.3	0.02	N/A	N/A	1.2	0.14

purposes so I selected to run the raised bed model using bushmint. Due to the variety of raised bed garden crops and composition, no two gardens are identical, resulting in a great variation of plant size and DBH. For modeling purposes, I applied an average plant size of 3ft by 3ft by 3ft and a DBH of 0.5 in, which resulted in an LAI of 4.0. The resulting model was within the range of LAI values for three out of four common crops of various shapes, validating the selected plant size to run in the model (Figure 17). The canopy cover of a plant of this size is 7.07 sqft. Utilizing these values, the iTree model for raised bed gardens included 924 bushmint plants of this size, resulting in 0.15 acres of canopy cover, or 60% of the quarter acre plot. As defined, there are no permanent crops in the raised bed garden, since the garden will be replanted, the ecosystem services remain the constant year after year. The annual carbon storage for the raised bed garden was assumed to be zero due to removal of annual crops and mowing, whereas the majority of carbon storage in the food forest is maintained within the biomass of the trees, shrubs and perennial understory vegetation.

In a raised bed garden, crops are seasonal and often require replanting from seed or seedlings; plants are not full size for most of the year, and there is often a dormant stage between seasons. Hence, the actual average annual crop size, LAI, and resulting ecosystem services of a raised bed garden is likely less than as modeled. As such, the results will conservatively estimate the benefits of a food forest as compared to a raised bed garden.

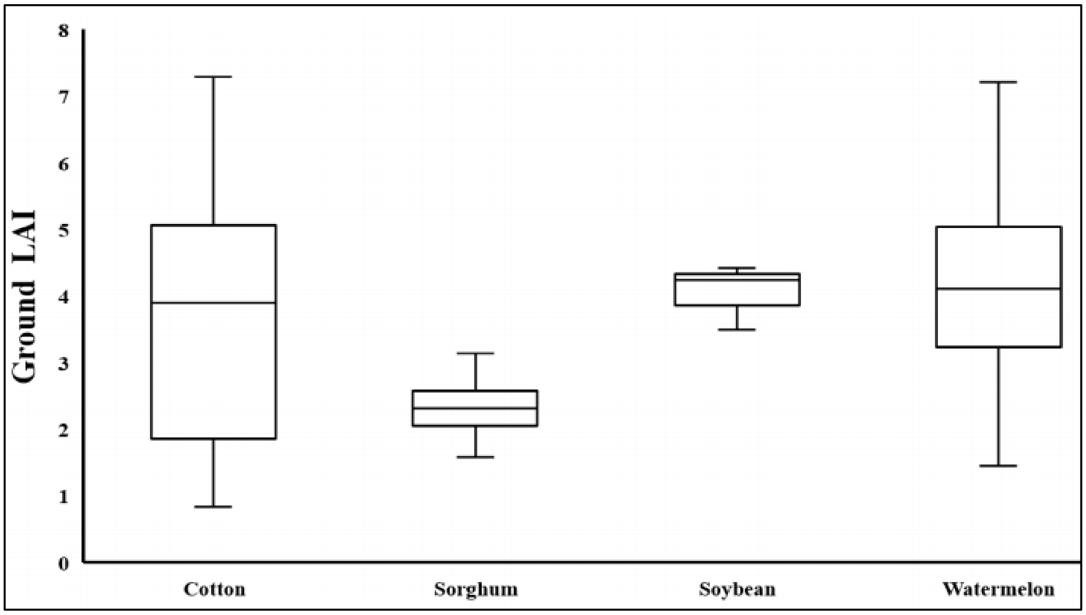


Figure 17. Box plots for ground LAI of four crops.

Herbaceous Ground Cover in iTree

Prior to selecting the above modeling approach for the raised bed garden, I ran a simulation using iTree's herbaceous ground cover and found that it estimated less air pollution reduction than grass groundcover likely due to the leaf area value used for the herbaceous cover, and grass having stomata on both sides. As a result, I determined that the herbaceous ground cover was not sufficient to estimate the ecosystem services of the raised bed garden, presuming that LAI would be greater in a raised bed garden than for grass.

Lawn iTree Air Pollution Removal

For grass groundcover, the only ecosystem service that can be calculated within iTree is air pollution reduction. All other ecosystem services for the lawn scenario were calculated outside of iTree. To analyze lawns in iTree, I created a model of a land area that included 100% grass ground cover. The model included a small apple tree which was necessary to run the model, but it had no impact the results from the grass groundcover because they are calculated separately.

Lawn Carbon Storage and Sequestration

The annual carbon storage for the lawn was assumed to be zero due to mowing, while the carbon sequestration values included soil organic carbon sequestration. Annual carbon sequestration of the lawn scenario was determined using values based on net sequestration rates that included soil organic carbon sequestration less lawn maintenance practice carbon emissions. Carbon emissions were based on mowing, irrigating, fertilizing, and using pesticides. The estimated net carbon sequestration for lawns ranged from 25.4 to 204.3 g $C/m^2/yr$ based on varying best management practices from low maintenance to high maintenance. For this study, I used low management minimum input (MI) values which only considers mowing; these net sequestration values better compare to carbon sequestration values used for the raised bed and food forest scenarios which do not account for carbon emissions of maintenance practices for fertilizers and more. In the case of California, lawns typically do not survive without irrigation, but the assumption was that these lawns were irrigated by rainfall throughout the year and productivity would be comparable to a conservatively irrigated lawn in California. The range of net carbon sequestration for MI practices was 25.4 to 204.3 g $C/m^2/yr$, with the average of the maximum and minimum used for analysis purposes at 69.8 g $C/m^2/yr$, or 0.078 ton per quarter acre per year.

Lawn Avoided Runoff

I approximated the avoided runoff for the lawn scenario, R_l, based on the iTree results for the avoided runoff of the food forest scenario with no understory, R_{ff}. I utilized a ratio between the rational runoff coefficient for wooded areas (0.20), C_w, versus lawns (0.15), and C_l, for lawns with heavy soil and average slope, as with the Castillero site. Note that this is site dependent and the values could range from 0.10 to 0.30 (Table 6). The rational runoff coefficient of 0.20 was also the median of all lawn rational runoff coefficients. The equation I used for calculating avoided runoff for the lawn scenario was as follows:

$$(C_l / C_w) \times R_{ff} = R_l$$

Table 6. Rational runoff coefficient, C, by surface (North Carolina Environmental Quality, 2017).

(ASCE 1975, Viessman, et al. 1996, and Malcom 1999)

Description of Surface	Rational Runoff Coefficient, C
Unimproved Areas	0.35
Asphalt	0.95
Concrete	0.95
Brick	0.85
Roofs, inclined	1.00
Roofs, flat	0.90
Lawns, sandy soil, flat (<2%)	0.10
Lawns, sandy soil, average (2-7%)	0.15
Lawns, sandy soil, steep (>7%)	0.20
Lawns, heavy soil, flat (<2%)	0.15
Lawns, heavy soil, average (2-5%)	0.20
Lawns, heavy soil, steep (>7%)	0.30
Wooded areas	0.15

Essentially, the expected avoided runoff from the lawn would be three quarters the avoided runoff of the wooded area of the food forest. I utilized the avoided runoff value for the food forest with 60% understory at five years as C_w, at which time trees will be of significant size. A later year results in values that far exceed expected values as compared to the raised bed garden and food forest avoided runoff results over time. Note that this was slightly above the annual avoided runoff for a raised bed garden, but the raised bed garden considered only 60% coverage, and the lawn was 100% coverage.

Valuation of Ecosystem Services

Within iTree, the carbon storage and gross carbon sequestration values were calculated using a rate of $129.73 per ton. The value of avoided runoff value was calculated using a rate of $0.067/ft³, and 7.8 inches of total annual precipitation based on the San Jose, CA weather station in iTree. The value of air pollution was valued differently based on the pollutants analyzed: $1,379.71 per ton (CO), $5,787.71 per ton (O3), $933.09 per ton (NO2), $321.32 per ton (SO2), $321,424.43 per ton (PM2.5). These same monetary values were also applied to the ecosystem services benefits for lawns calculated outside of iTree.

Cost Benefit Analysis

The cost benefit analysis (CBA) calculated the net present value (NPV) based on four scenarios as follows:

- Food Forest – 60% Understory
- Food Forest – No Understory

- Raised Bed Garden
- Lawn (Baseline Model)

The baseline was an existing lawn which was assumed to be the most likely land use to be converted into a raised bed garden or food forest. New schools are less common, and most lawns are already established and easily converted. Results for NPV accounted for the difference between annual benefits and costs, and applied the time value of money to convert the net benefits over the thirty year lifetime of each land use scenario into present value. The calculations accounted for the increasing productivity of the food forest as the trees mature over time.

The costs of each land use scenario were approximated based on information with regards to initial costs, ongoing maintenance, labor costs, materials, cost of water, and other inputs. Cost inputs were determined as follows:

- Cost of Materials: The cost of materials for implementing a food forest or raised bed school garden can be minimized by receiving donations from local businesses as well as community members. For this CBA, I assumed that all materials were purchased with prices based on The Monterey County Farm to School Partnership school garden budget sheet for their Life Lab program (n.d.). The cost of raised beds were $238 each based on the large bed design, and the are would need 182 large beds to provide 6,534 square feet of raised beds (Figure 18). For both the food forest and raised bed, fencing costs were calculated to be $1,000 for a perimeter of 367 feet, initial compost and amendments were estimated to be $720 year one, followed by $150 annually, and irrigation was $1,650 year one, followed by $100 annually to replace damaged equipment. The lawn was assumed to be existing and did not require the purchase of additional materials. Mulch was assumed to be free as many tree companies will deliver mulch at no cost.

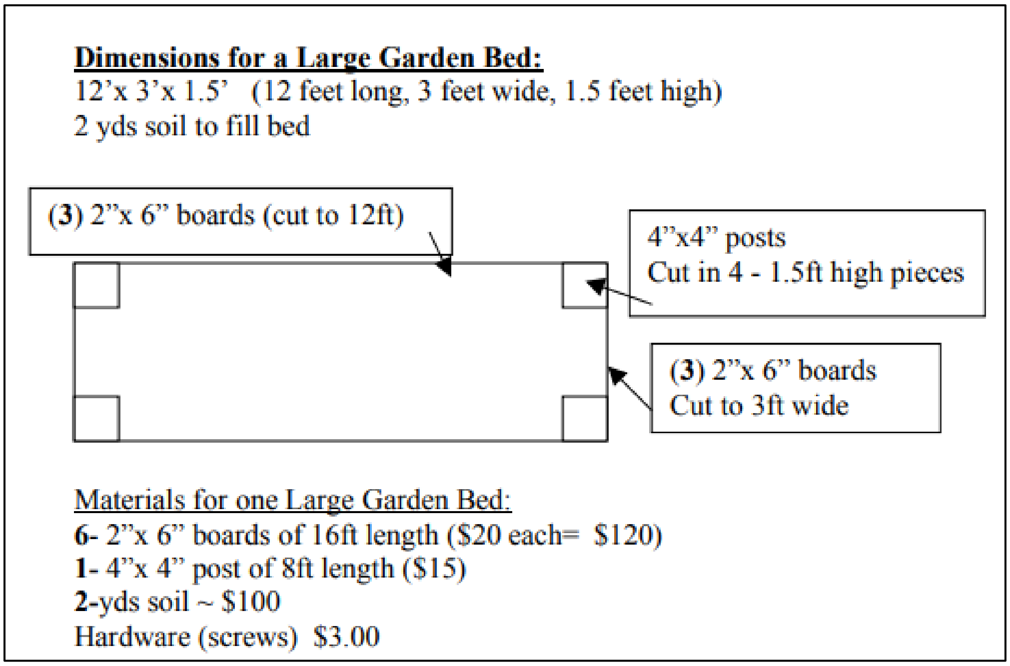


Figure 18. Large garden bed design and cost estimate (Monterey County Farm to School Partnership, n.d.).

- Ongoing Maintenance: In addition to materials, labor for ongoing maintenance of the food forest and raised bed garden were assumed to be free and primarily performed by students and faculty during class time. Additional maintenance can be conducted by establishing a student club, or by parent volunteers. Another viable option would be to establish a volunteer program for high school students where they can be trained in permaculture and earn community service credits.
- Cost of Water: Water use for all three land use scenarios was considered to be the same, and based on the value of 0.623 gallons per square foot required during the summer dry season in California for 25% of the year, and then 0.3115 for 50 % of the

year, and zero watering during the remaining wet season (Peyster, 2014). The value of water was based on utility data for the City of San Jose, at approximately $4 per HCF (City of San Jose, 2018). Lawn irrigation was included in the general maintenance rate.

- Lawn Baseline Scenario Costs: The existing lawn included zero installation cost but lawn maintenance costs were estimated to be $0.0385/sqft (Rosenberg et al., 2011). Lawn conversion costs were built into the raised bed and food forest scenario, with lawn removal assumed to be zero dollars with volunteer labor.
- Cost of Plants: The food forest costs included the cost of 24 trees at $30 each, 101 shrubs at $10 each, and 667 transplants at $1 each for the understory. Raised beds only included the cost of transplants for 924 plants, or $924 total. Ground cover seed costs were also included as part of the food forest, beginning with $100 year 1, $50 year 2, and $25 all subsequent years once established. These costs were based on common values found at garden supply stores and community plant sales. Transplants can also be grown by seed at a lower cost, but this was not included in the analysis.
- Annual Survivorship: The CBA of both food forest scenarios assumed a high annual survivorship due to small area and high oversight. Annual survivorship was assumed as 100% at year 1, then dropped to 90% year 2, and returned to 95% for all subsequent years once established. All dead plants were assumed to be replaced and the cost for replacement was included in the CBA. Survivorship was not captured within the ecosystem services analysis due to continuous replacement of plants over time.

The benefits considered in the CBA included the value of food production, as well as the economic appraisal of carbon sequestration, avoided runoff, and air pollution reduction as calculated using iTree. Although there are additional benefits not captured by the CBA, many of the benefits were effectively translated into monetary value. Converting various benefits into dollars facilitated comparison by establishing an identical unit of measure.

Food Production

The food forest and raised bed gardens were the only scenarios that included food production as an ecosystem service as lawns do not produce food. In order to estimate food production from the food forest, it was necessary to consider the multiple layers of the food forest: large trees, small trees, vines, shrubs, herbs, tubers, decomposers. These layers, integrated in tree guilds, intercropping of the understory, and forest succession plantings, can include edible perennial crops, or self-sowing annuals. Typically, food forests often integrate plants that are not necessarily edible in order to enhance soil fertility, attract pollinators, mitigate pests or provide other supporting functions. However, for this study, I assumed that all plants in the understory were edible considering the conservative 60/40 planting ratio. I ran two scenarios, one that included the 60% of the understory planted, and one with no understory. The productivity for the understory and raised bed garden was approximated at a rate of 0.75 lbs/sqft, based on average food productivity of community gardens in San Jose (Algert, Baameur, & Renvall, 2014). Using the canopy area, productivity of the trees and shrubs was approximated at 16,041 lbs/acre/yr based on the median productivity rate of selected fruit and nut crops for the State of California (Figure 19). The food productivity rates of each fruit category were calculated based on area harvested and production in tons for 2017 (CDFA, 2018). The CBA also assumed that the trees and shrubs will ramp up production beginning with 0% year 1, 0% year 2, 25% year 3, 50% year 4, and 100% year 5 and beyond. Understory and raised bed gardens were assumed to reach full production by year one, with stable production values year after year.

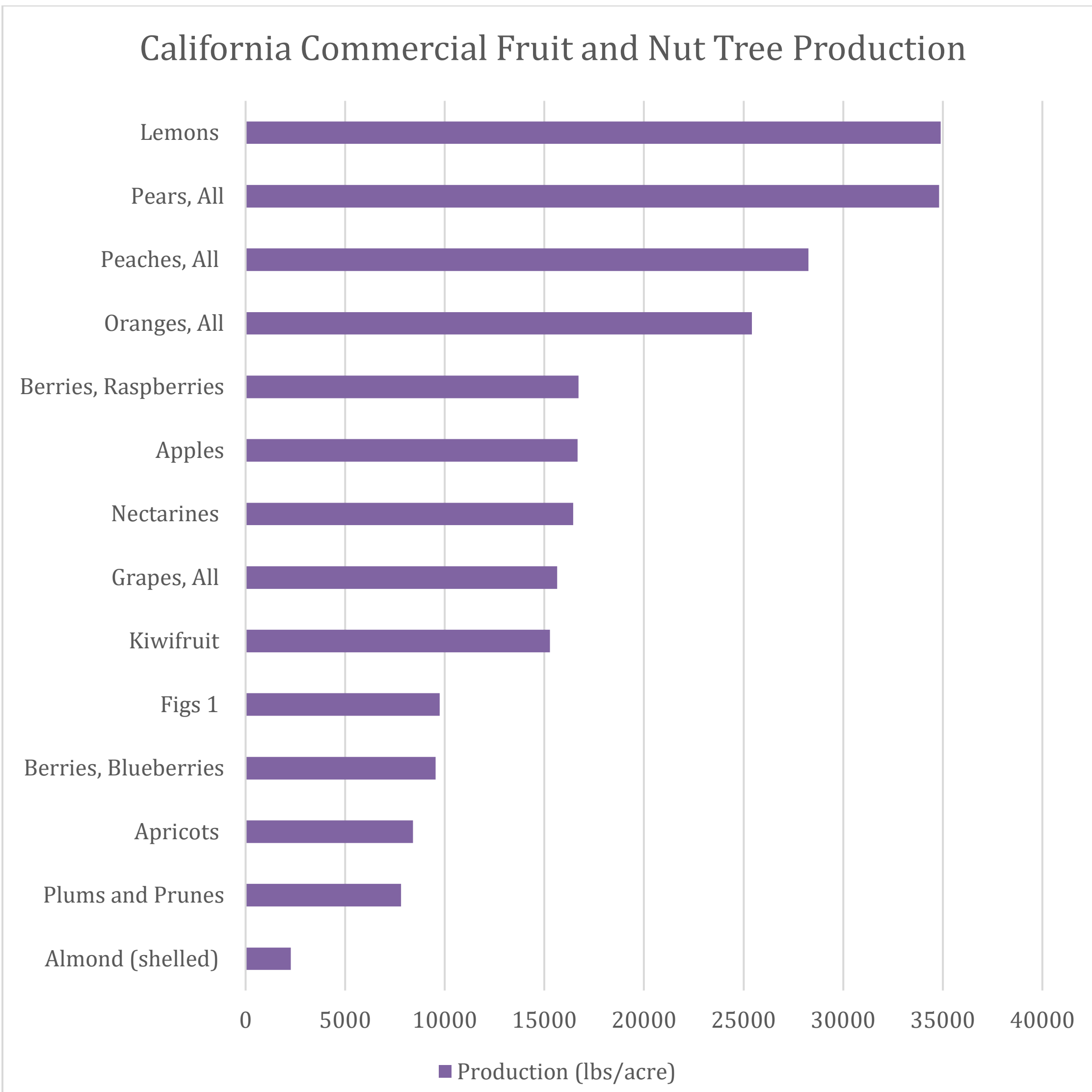


Figure 19. Commercial fruit and nut tree production rates for 2017 (CDFA, 2018).

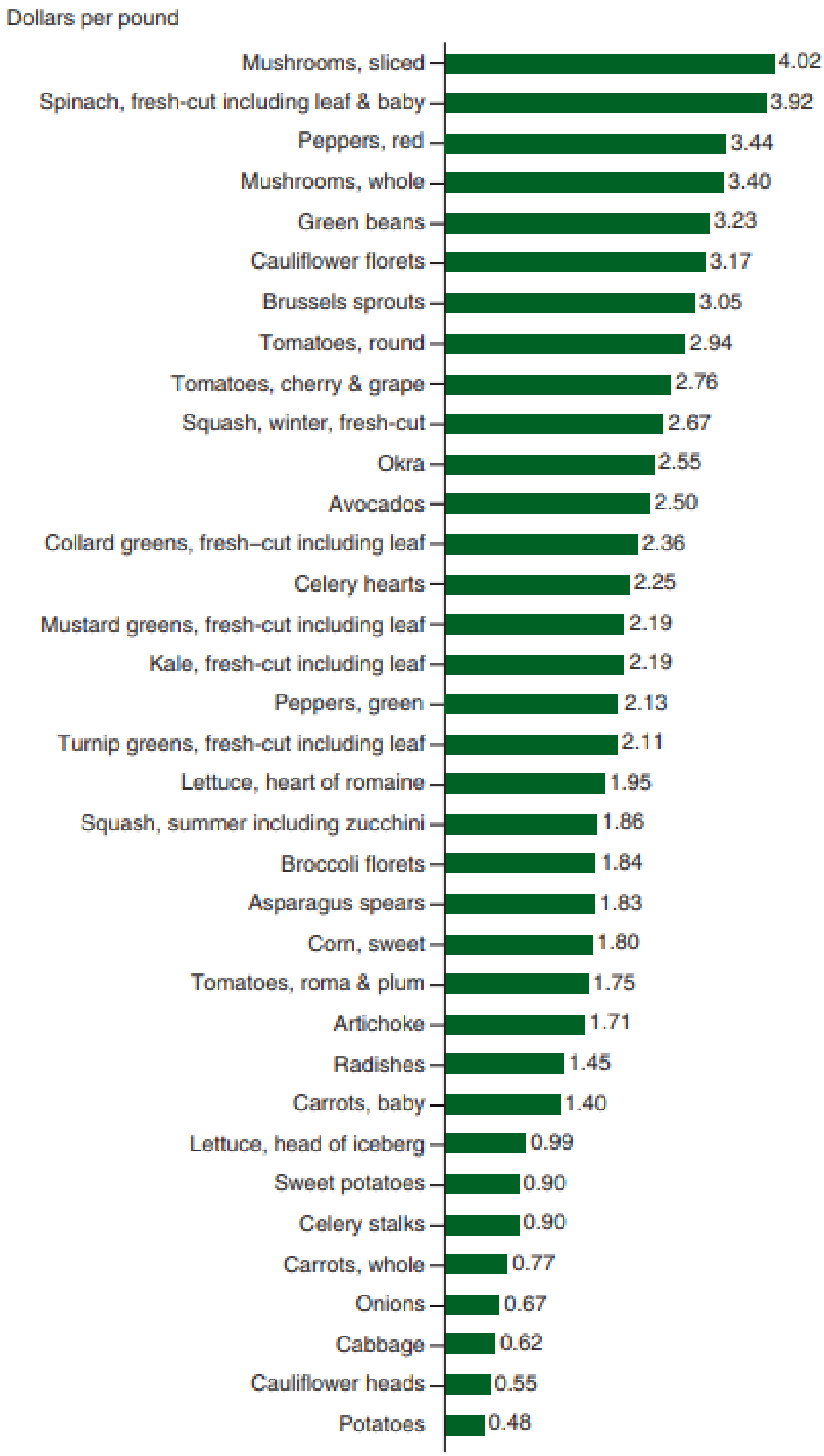
Recently, iTree incorporated a foodscapes benefits component for food forest applications, but only four species were included. Therefore, I did not include this in my analysis.

Value of Food Production

Food production value was estimated based on USDA median values for fresh fruits and vegetables. Prices are likely to vary year to year based on inflation and market conditions. While the raised bed garden and the understory of the food forest were assumed to be primarily vegetables, and food forest's trees and shrubs primarily fruit, the value is not as important as the quantity of food produced. Using the same value for all food production would result in more comparable food production benefits. Therefore, I used the average of the median of vegetable prices, at $2.11 per pound (Figure 20), and median value of fruit prices at $1.24 per pound (Figure 21), resulting in $1.675 per pound for all food production. If it was important to the site to generate value from food production, a more detailed analysis could be done to optimize species selection for food forests.

Cumulative Benefits with Increasing Adoption Rates for California Schools

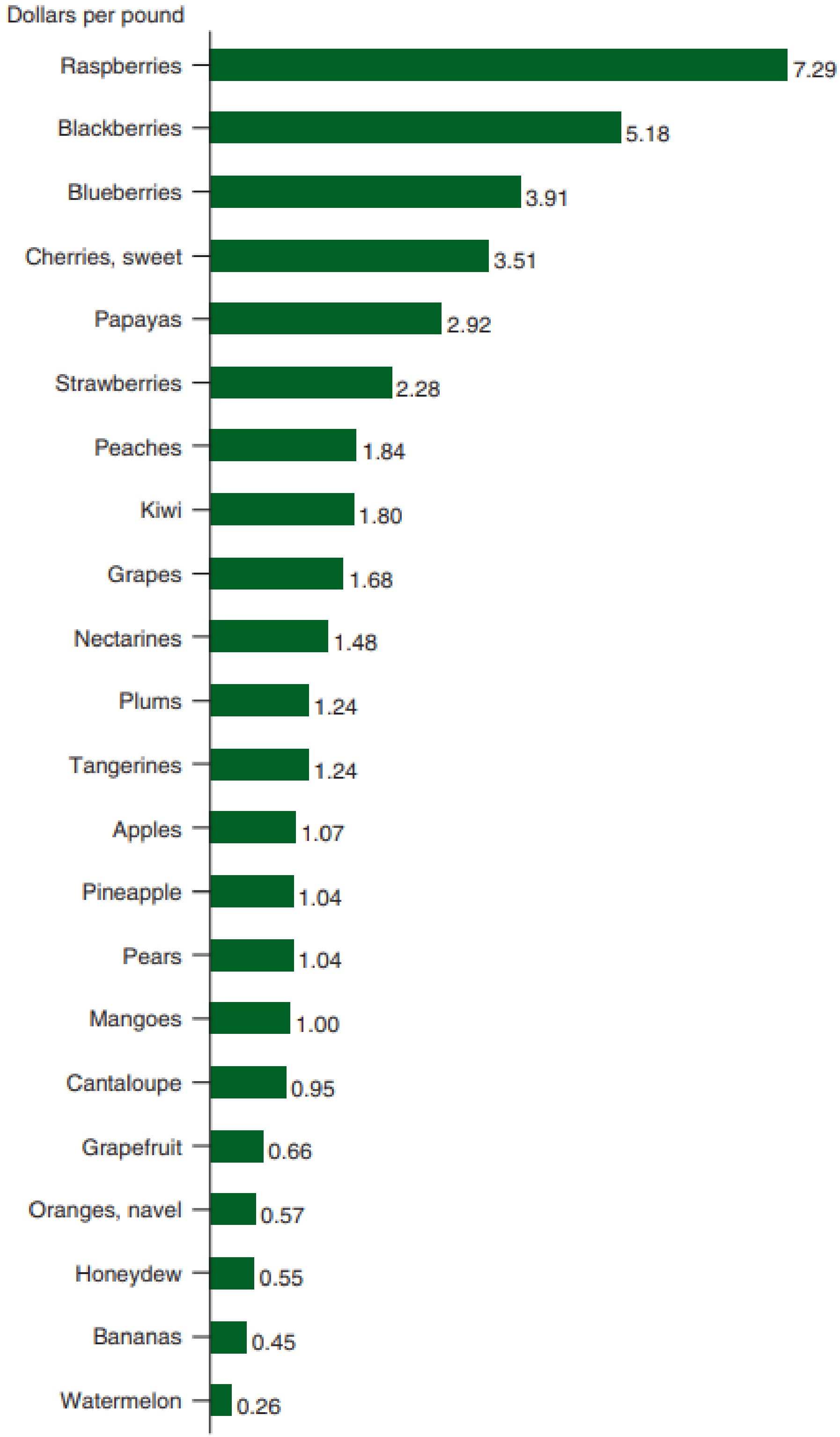
Considering the land use scenarios only account for one quarter of an acre, the benefits are on a small scale. Often, educational programs are developed on a district, or even State level, and involve multiple schools. Increasing adoption rates statewide can be brought about by initiatives and policies that generate significant impact. In California,



Note: Prices are for vegetables sold in a prepackaged container, such as in a bag or clamshell, and vegetables sold on a count basis, such as iceberg lettuce and cauliflower priced per head.

Source: USDA, Economic Research Service analysis of 2008 Nielsen Homescan data.

Figure 20. Fresh vegetable retail prices (USDA, 2011c).



Note: Prices are for fruit sold in a prepackaged container, such as in a bag or clamshell, and fruit sold on a count basis, such as melons and oranges sold per piece of fruit.

Source: USDA, Economic Research Service analysis of 2008 Nielsen Homescan data.

Figure 21. Fresh fruit average retail prices (USDA, 2011c).

Assembly Bill 1535 institutionalized school gardens as instructional tools, and resulted in an increase of 2000 school gardens throughout the State. By 2003, there were 3000 school gardens in California, which was approximately one third of all schools (Smith, 2008). Considering the success of school gardens, analyzing the cumulative results highlights the potential benefits of widespread adoption of food forests in schools.

Using a spreadsheet, I calculated the net ecosystem services of converting a quarter acre lawn to the model food forest of the same area. I selected lawns as the baseline for comparison because of the makeup of land use in California schools and the ease of conversion. Based on the number of public schools in California, I calculated the sum of net ecosystem services statewide for lawn to food forest conversion rates from zero to 100% of schools. I selected California public schools to use as a case study because of favorable conditions that could support widespread adoption of food forests in California public schools. In addition to ecosystem services, I conducted a similar analysis applied to the 30 year NPV results of the CBA to compare the overall cumulative financial benefits with increasing food forest adoption rates.

Educational Benefits

Educational benefits are not included in the CBA as their benefits are difficult to monetize. Instead, I conducted a qualitative review through curriculum mapping using the GAP ESD learning objectives. To evaluate the correlation of GAP ESD to permaculture food forests in schools, I developed a curriculum design tool to align each SDG to topics and activities that can be explored from within the food forest ecological learning environment curriculum (Table 12). Each SDG was ranked in relevance from zero to three as follows: (0) not relevant; (1) indirectly related, or can be integrated through complementary systems or programs; (2) easily related to curriculum; (3) core concept directly related to curriculum.

Chapter III

Results

The aim of my analysis was to evaluate the feasibility of implementing food forests in schools by comparing the CBA results to a raised bed school garden and lawn of similar area. Cost is often a determining factor in decision making, and a school that is considering implementing a school garden may want to consider a food forest instead based on financial performance, in addition to other criteria. Lawn was selected as the baseline so that interested parties could utilize the comparative results to build a case for converting lawns to food forests in schools as part of the greening of schoolyards. The food forest model is based on the hypothetical permaculture food forest design for Castillero Middle School in San Jose, CA. Actual values would vary according to site and species selected.

Castillero Middle School Food Forest Design

The permaculture food forest design for Castillero Middle School was used to model ecosystem services for the cost benefit analysis. The design consisted of seven maps that are essential to permaculture design. The Castillero food forest can serve as an example food forest that incorporates permaculture design considerations and highlights appropriate species that could be used in California schools. The base map was used as the starting point for all other maps and includes dimensions and general layout (Figure

22). The contour lines created in google earth were used to help layout the swales on contour (Figure 23).

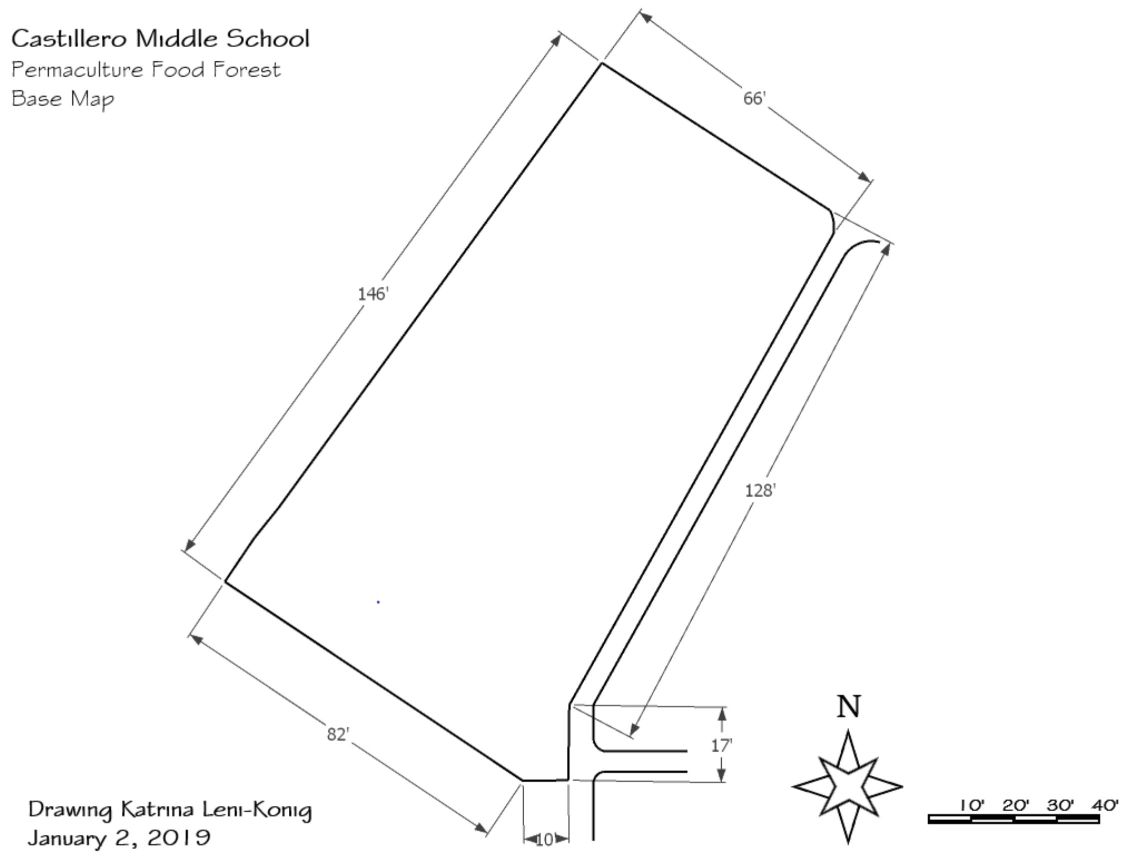


Figure 22. Castillero Middle School food forest base map with dimensions.

The sector map included the contour lines, water flow, wind direction, solar resources, and other considerations such as neighbors, and paved access (Figure 24). The spacing of swales was determined based on the recommended logarithmic distribution (Table 7). The berm and swales map also included main pathways, although it is likely that additional small pathways would be created for access, such as stepping stones (Figure 25). I redefined zones of use in a way that would be applicable to schools, incorporating

Figure 23. Castillero Middle School food forest contour line map created in Google Earth.

the main objects of design with examples of sample patch themes and design elements that could enhance a school food forest for student engagement by adding interest and educational value (Table 8). In the zone map, I applied these redefined zones of use to the Castillero Middle School food forest design (Figure 26).

Table 7. Logarithmic distribution of swales for Castillero food forest design.

Swale	Equation	Distance from Base (ft)
Base	-	0
2	$\log_7(2)*146$	52
3	$\log_7(3)*146$	82
4	$\log_7(4)*146$	104
5	$\log_7(5)*146$	121
6	$\log_7(6)*146$	134

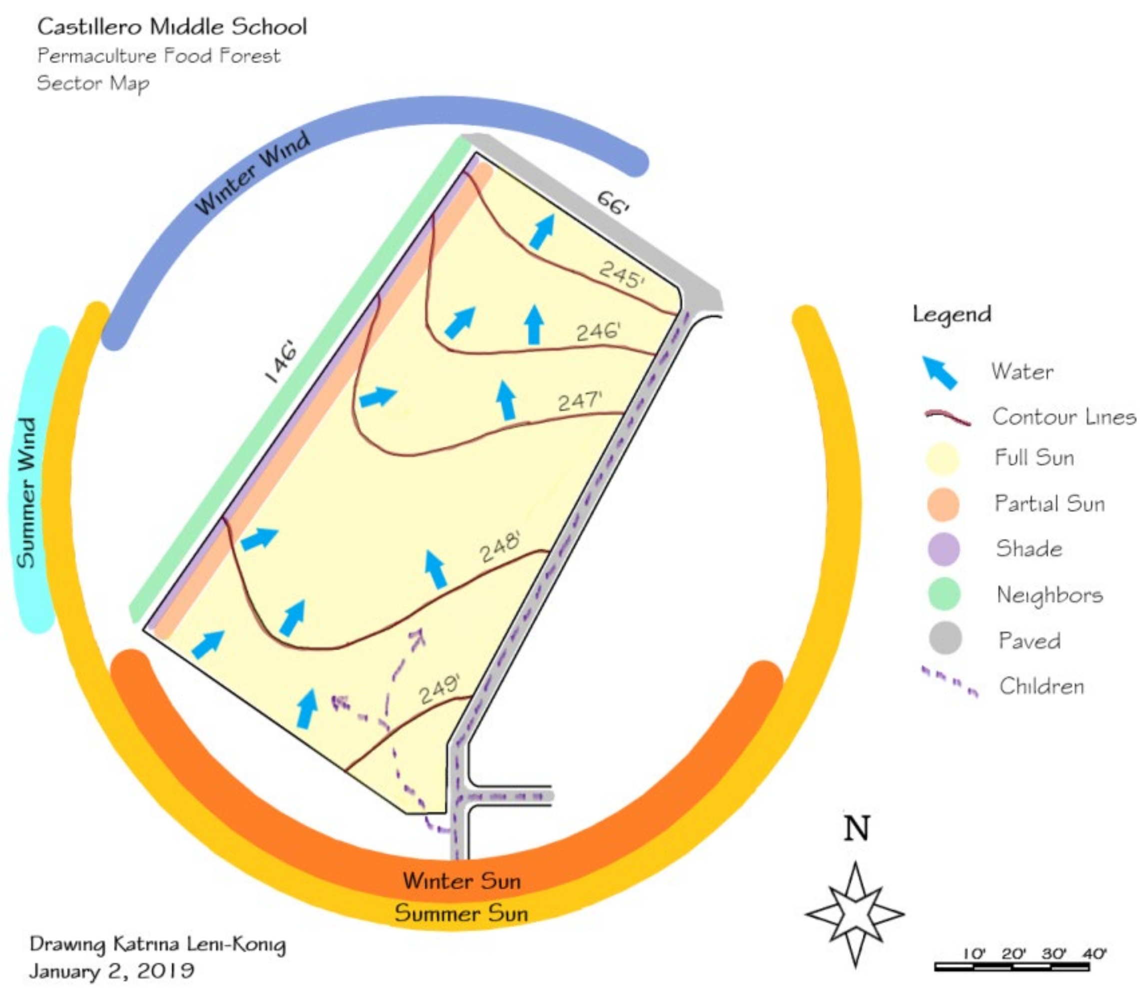


Figure 24. Castillero Middle School food forest sector map.

Table 8. Zones of use for permaculture food forests in schools

Zones	Use	Main Objects of Design	Sample Patch Themes/Design Elements
Zone 0	Highly Intensive	Outdoor classroom	Earthbench, outdoor kitchen, picnic tables, log circle, chalkboard, potting tables, solar oven, cob pizza oven
Zone 1	Highly Intensive	Tool shed, compost, annuals	Mandala garden, salad bar, tea garden, edible flowers, herb spiral, pizza garden, potato towers
Zone 2	Intensive	Perennial vegetables, small trees and shrubs, chicken coop, greenhouse, domestic production	Chicken coop guild, berry patch, medicinal, three sisters, grafted trees, trellised species, tree collards
Zone 3	Extensive	Larger nut and fruit trees, and agriculture	Fruit and nut tree guilds, fertility plants, shade tolerant perennial and self-propagating edibles, pond
Zone 4	Semi Wild	Wild-harvesting, forage, pasture, forestry, native habitat	Native habitat restoration, endemic species habitat, wild edibles, nectary meadow, drought tolerant native garden

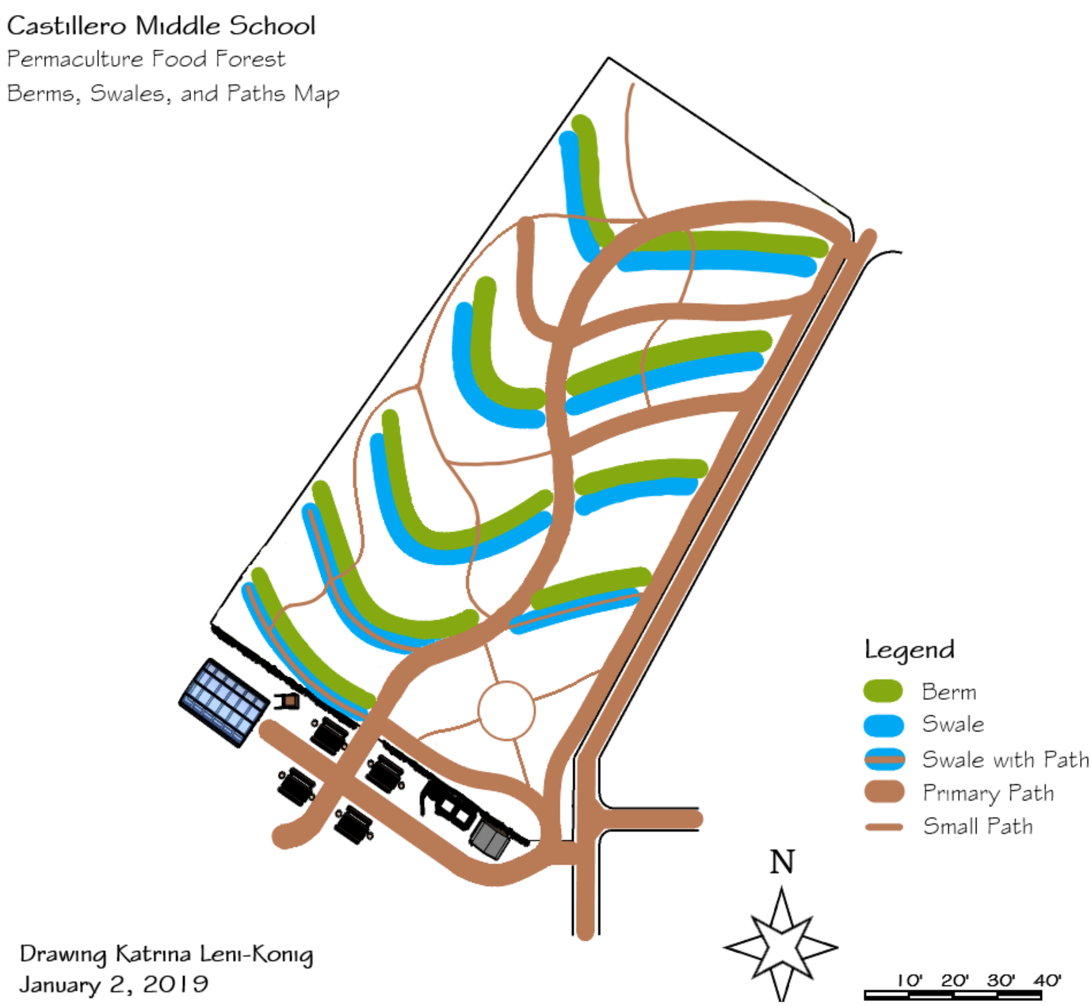


Figure 25. Castillero Middle School food forest swales, berms, and paths.

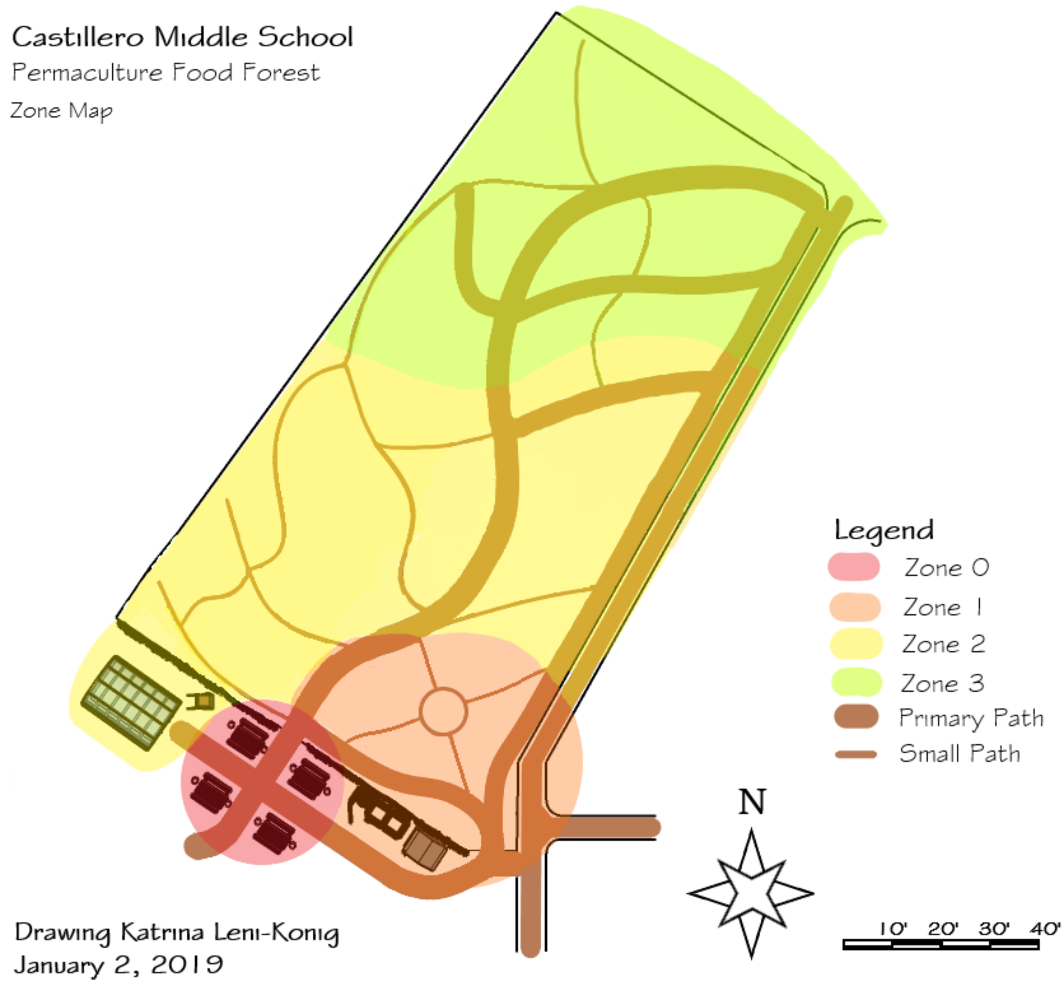


Figure 26. Castillero Middle School food forest zones.

Finally, I laid out the plant species that are used in the iTree food forest analysis in the planting plan (Figure 27). I incorporated graphical information into the planting plan to highlight considerations that are important to placement in food forest design such as: whether it is an evergreen species, casts dense shade not conducive to understory planting, and light requirements. Many plant species were not available in iTree. For example, there were very few dwarf species. As such, I incorporated four dwarf apple trees which would likely provide similar results as any other pome fruit, such as pear or quince, and four citrus trees that could be replaced by different varieties. The sun garden mandala incorporated permaculture keyhole bed design, and was included for planting perennial vegetables that require full sun, such as tree collards, asparagus, and an herb spiral. The productivity of the sun garden mandala was included as part of the understory. I did not delineate all plants in the understory, and only used area of the understory for calculation purposes.

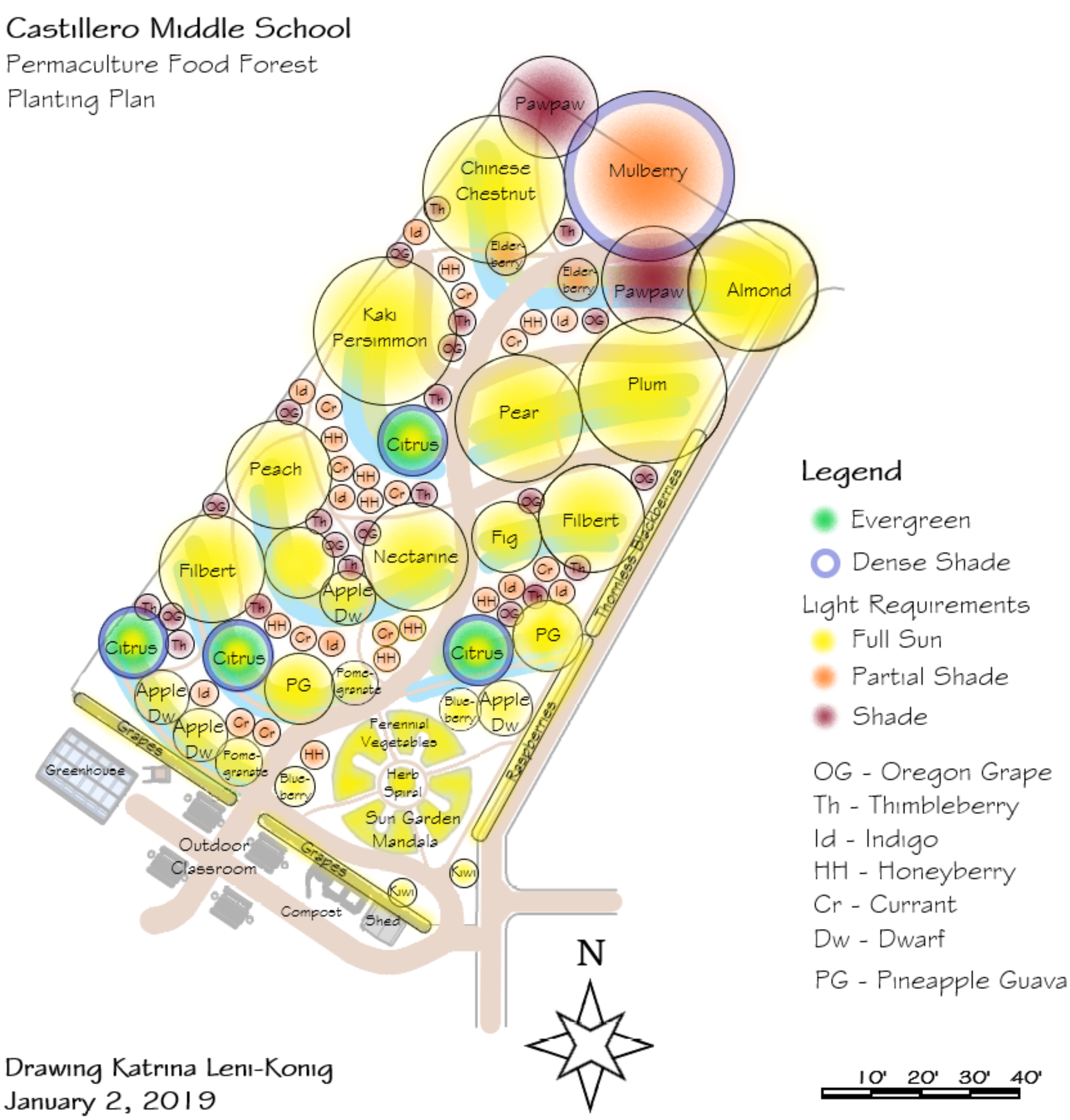


Figure 27. Castillero Middle School food forest planting plan.

Ecosystem Services

Ecosystem services analyzed included carbon storage, carbon sequestration, avoided runoff, pollution removal, and food production. I calculated results for the following land use scenarios over a lifetime of 30 years: food forest with 60% understory (food forest), food forest without understory, raised bed garden, and existing lawn baseline scenario. The baseline scenario demonstrated the net benefits of converting lawns to other land use scenarios. The results of the food forest without understory added transparency to the value of the understory. To demonstrate the potential of widespread adoption, I also calculated results at an adoption rate of 33% in CA, based on the results of Assembly Bill 1535 that resulted in gardens in approximately one third of all schools in California.

Comparing the Ecosystem Services of Land Use Scenarios

As expected, the results showed that the food forest with 60% understory provided the greatest ecosystem services in comparison to the other land use scenarios, with total benefits at year 30 reaching $10,856 per year with food production, and $1,228 without considering food production (Table 9). The ecosystem services benefits increased year over year for the food forest land use scenarios, while the raised bed garden and lawn remained constant. In considering a food forest at year 30, the food forest with 60% understory outperformed all other land use scenarios except with regards to the value of food production from the raised bed. In all scenarios in which food production applied, the value of food production was much higher than the value of all other ecosystem services combined, and the raised bed garden outperformed all other land use scenarios

(Figure 28). The raised bed garden initially produced more food than the food forest; however, as trees mature, the food forest surpassed the raised bed garden in food production yields (Figure 29). While the raised bed produced 4,901 lb of food with a value of $10,341 per year, the mature food forest with 60% understory produced slightly more food at 5,280 lb with a lesser value of $9,628 due to the lower cost of fruit compared to vegetables (Table 9). While lawns did provide some ecosystem services, the benefits of converting a lawn to a food forest were significant; the baseline comparison of a food forest with 60% understory resulted in a cumulative value of $261,274 in net ecosystem services over thirty years, $255,853 of which was food production.

Carbon storage values for the raised bed and lawn were zero because there was no accumulated stored biomass as a result from routine harvesting and mowing, respectively

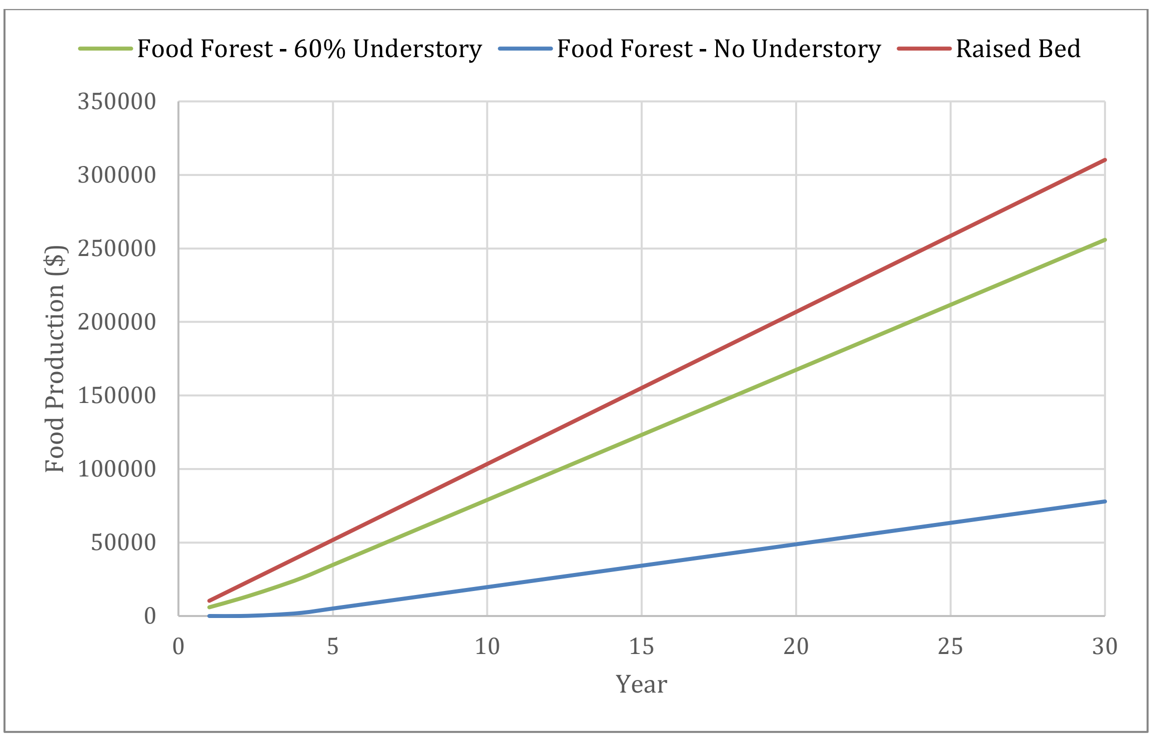


Figure 28. Summation of the annual value of food production for Castillero Middle School by land use scenario.

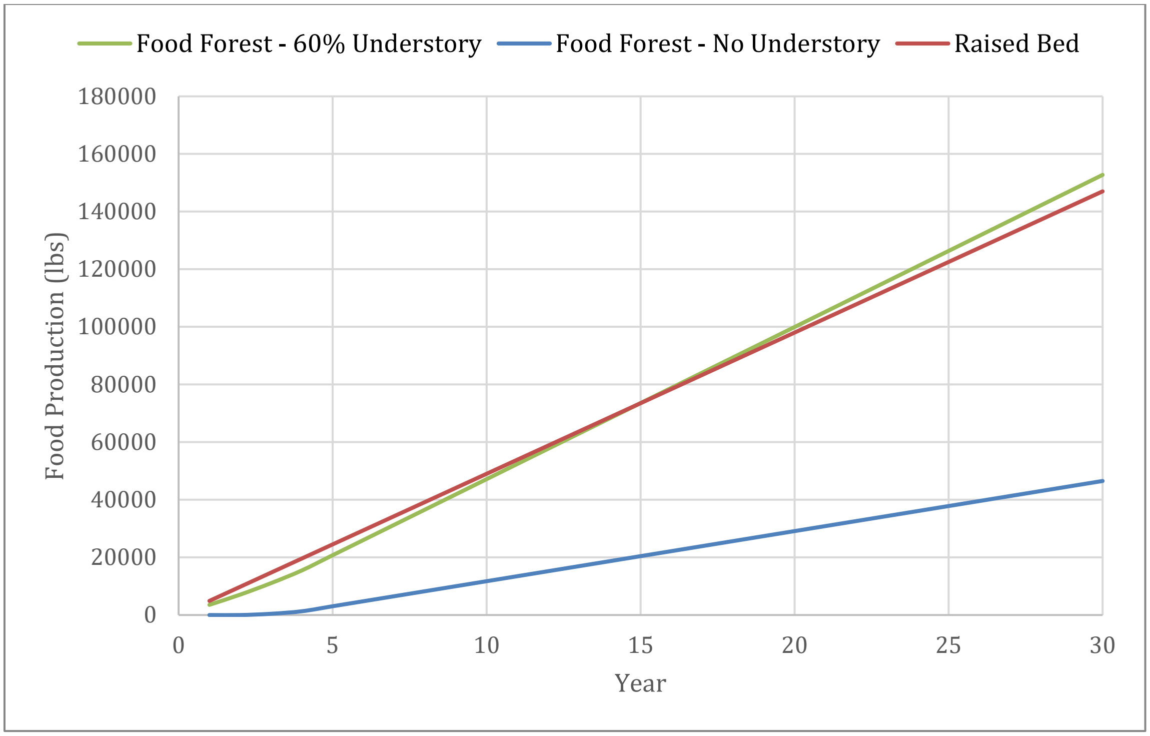


Figure 29. Summation of the annual pounds of food production by land use scenario.

(Figure 30). Carbon storage in the food forests, both with and without understory, accelerated at the same rate, because the biomass is accumulated in the fruit trees and the understory is modeled after the raised bed garden (Figure 30). The carbon stored in the food forest is not a cumulative value, rather it is the value of the biomass in the stand at any given time, with the food forest with 60% understory reaching 7.8 tons after thirty years of growth (Table 9).

The raised bed garden and lawn sequester carbon at the same rate each year; this is not converted into stored biomass due to harvest and lawn maintenance (Figure 31). In comparison, the food forest sequesters carbon at an increasing rate each year as the trees mature. The same is true for avoided runoff (Figure 32) and air pollution removal (Figure 33), where the food forest cumulative ecosystem services accelerate over time and the raised bed and lawn increase at a constant rate. Air pollution removal is plotted based on

Table 9. Ecosystem services results summary including baseline comparison by land use.

Land Use Scenario	**Carbon Storage**		**Gross Carbon Sequestration**		**Avoided Runoff**		**Pollution Removal**	**Food Production**		**Benefits Total**	**Benefits Total (No Food)**
Annual ecosystem services results at year 30											
	(ton)	**($)**	**(ton/yr)**	**($/yr)**	**(ft³/yr)**	**($/yr)**	**($/yr)**	**(lbs/yr)**	**($/yr)**	**($/yr)**	**($/yr)**
Food Forest - 60% Understory	7.80	1,012	0.87	113.4	215.4	14.39	87.96	5,280	9,628	10,856	1,228
Food Forest - No Understory	7.72	1,002	0.71	92.6	173.3	11.58	69.42	1,739	2,156	3,332	1,176
Raised Bed Garden	0.00	0	0.22	28.8	58.4	3.90	25.73	4,901	10,341	10,400	58
Lawn - Baseline	0.00	0	0.08	10.1	80.0	5.35	19.19	0	0	35	35
Cumulative ecosystem services results over 30 years											
	(ton)	**($)**	**(ton/30 yrs)**	**($/30 yrs)**	**(ft³/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**(lbs/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**
Food Forest - 60% Understory	7.80	1,012	16.8	2,179	4,663	312	1,918	152,748	255,853	261,274	5,421
Food Forest - No Understory	7.72	1,002	12.0	1,557	3,400	227	1,362	46,518	77,918	82,066	4,148
Raised Bed Garden	0.00	0	6.6	864	1,751	117	772	147,030	310,233	311,986	1,753
Lawn - Baseline	0.00	0	2.3	303	2,401	160	576	0	0	1,039	1,039
Cumulative ecosystem services results over 30 years for 3456 schools, 33% adoption rate											
	(ton)	**($)**	**(ton/30 yrs)**	**($/30 yrs)**	**(ft³/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**(lbs/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**
Food Forest - 60% Understory	26,958	3,497,943	58,062	7,532,341	16,115,160	1,076,918	6,628,228	527,911,699	884,252,096	902,987,526	18,735,429
Food Forest - No Understory	26,681	3,462,726	41,473	5,380,925	11,752,192	785,569	4,705,950	160,771,259	269,291,858	283,627,028	14,335,170
Raised Bed Garden	0	0	22,810	2,985,025	6,052,996	404,363	2,667,756	508,148,913	1,072,194,206	1,078,251,349	6,057,143
Lawn - Baseline	0	0	8,071	1,047,043	8,297,208	554,443	1,989,671	0	0	3,591,157	3,591,157
Baseline Comparison: net value of converting lawns to new land use scenario											
Net annual ecosystem services results at year 30 - converting existing lawn											
	(ton)	**($)**	**(ton/yr)**	**($/yr)**	**(ft³/yr)**	**($/yr)**	**($/yr)**	**(lbs/yr)**	**($/yr)**	**($/yr)**	**($/yr)**
Food Forest - 60% Understory	7.80	1,012	0.79	103.3	135.4	9.04	68.77	5,280	9,628	10,821	1,193
Food Forest - No Understory	7.72	1,002	0.63	82.5	93.3	6.23	50.23	1,739	2,156	3,297	1,141
Raised Bed Garden	0	0	0.14	18.7	-21.6	-1.45	6.54	4,901	10,341	10,365	24
Lawn - Baseline	0	0	0	0	0	0	0	0	0	0	0
Net cumulative ecosystem services results over 30 years - converting existing lawn											
	(ton)	**($)**	**(ton/30 yrs)**	**($/30 yrs)**	**(ft³/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**(lbs/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**
Food Forest - 60% Understory	7.80	1,012	14.5	1,876	2,262	151	1,342	152,748	255,853	260,235	4,382
Food Forest - No Understory	7.72	1,002	9.7	1,254	1,000	67	786	46,518	77,918	81,027	3,109
Raised Bed Garden	0	0	4.3	561	-649	-43	196	147,030	310,233	310,947	714
Lawn - Baseline	0	0	0	0	0	0	0	0	0	0	0
Cumulative ecosystem services results over 30 years for 3456 schools, 33% adoption rate											
	(ton)	**($)**	**(ton/30 yrs)**	**($/30 yrs)**	**(ft³/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**(lbs/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**	**($/30 yrs)**
Food Forest - 60% Understory	26,958	3,497,943	49,991	6,485,298	7,817,952	522,474	4,638,557	527,911,699	884,252,096	899,396,369	15,144,272
Food Forest - No Understory	26,681	3,462,726	33,402	4,333,882	3,454,984	231,126	2,716,279	160,771,259	269,291,858	280,035,871	10,744,013
Raised Bed Garden	0	0	14,739	1,937,982	-2,244,212	-150,081	678,085	508,148,913	1,072,194,206	1,074,660,192	2,465,986
Lawn - Baseline	0	0	0	0	0	0	0	0	0	0	0

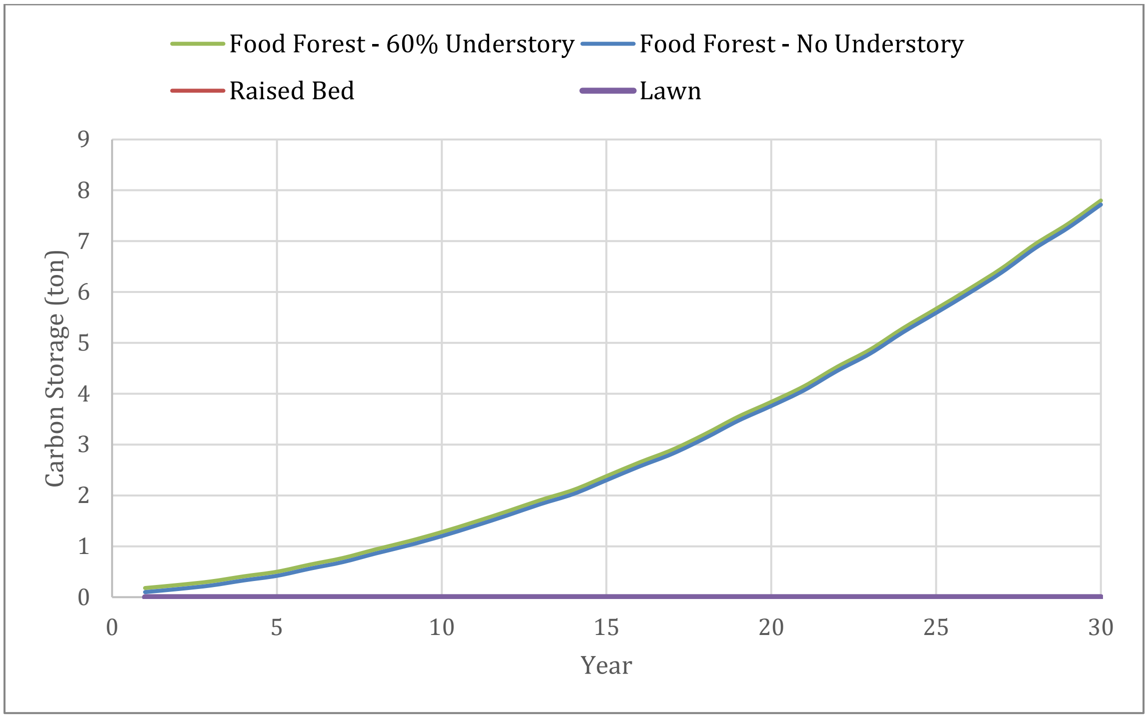


Figure 30. The accumulation of carbon storage by land use scenario.

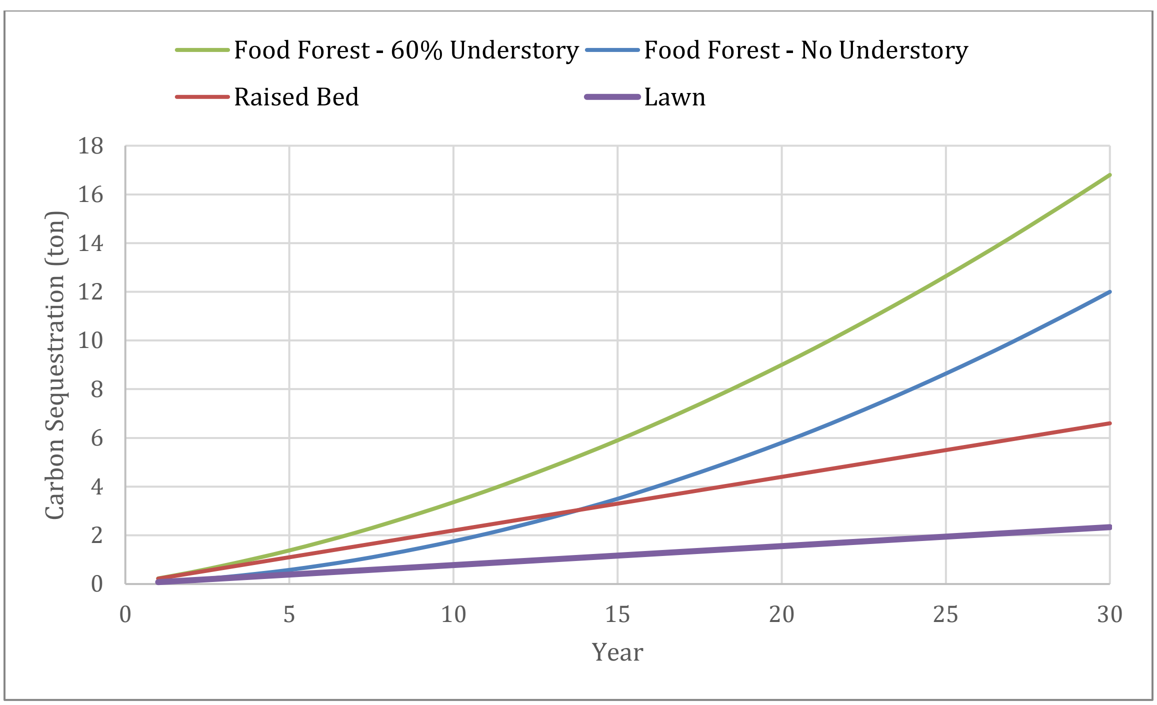


Figure 31. Summation of the annual tons of carbon sequestration by land use scenario.

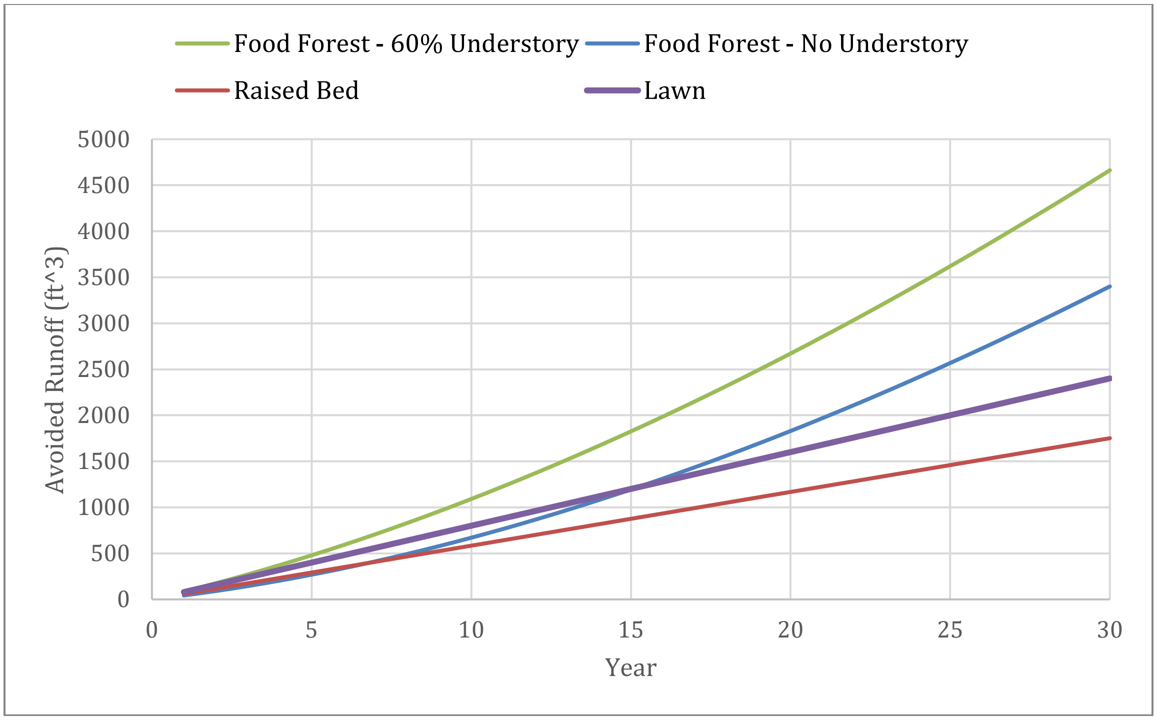


Figure 32. Summation of the annual cubic feet of avoided runoff by land use scenario.

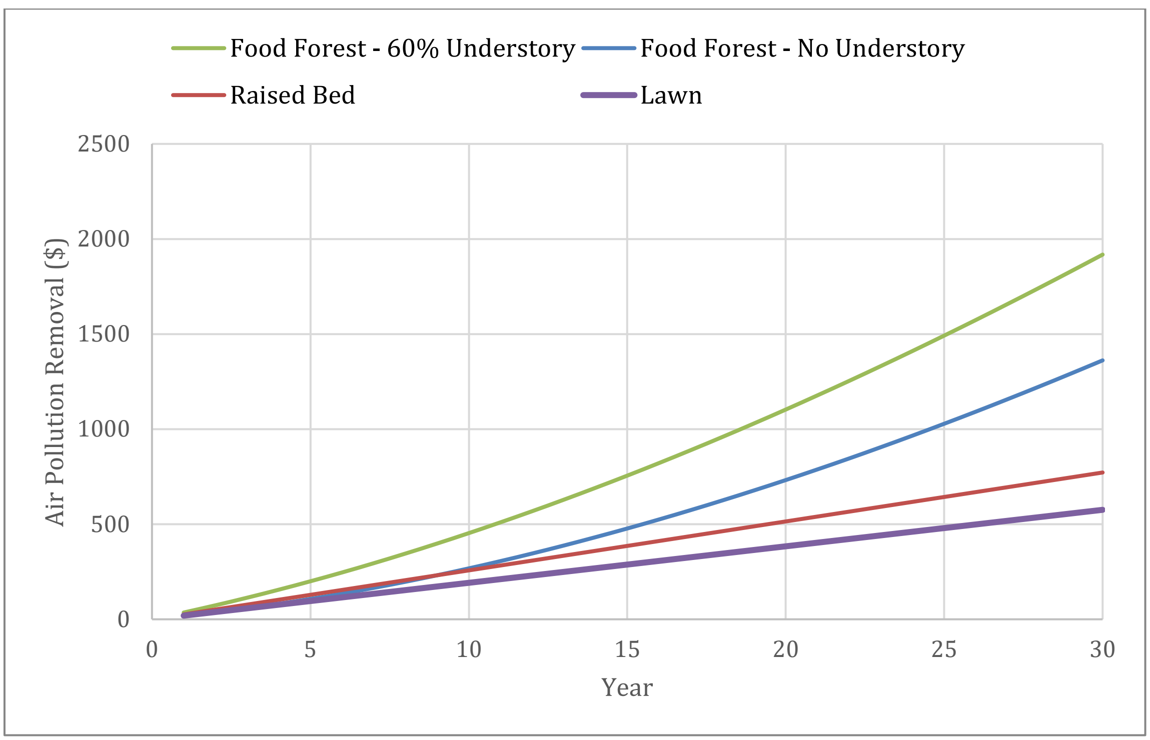


Figure 33. Summation of the annual value of air pollution reduction for Castillero Middle School by land use scenario.

The value to consolidate the results for the various air pollutants considered. In the case of all ecosystem services, less carbon storage, the raised bed garden initially provides greater ecosystem services than the food forest without understory. This is also true for the lawn avoided runoff, where the food forest without understory provides comparably less avoided runoff until approximately year 15 (Figure 32).

In considering the proportion of the cumulative ecosystem services for the food forest over thirty years, the percent contribution of carbon storage (19%), carbon sequestration (45%), and pollution removal (40%) make up a significant amount of the benefits, with avoided runoff at only 6% (Figure 34). In the case of the raised bed garden with zero carbon storage, the percent contribution of carbon sequestration (49%) and pollution removal (44%) make up the majority of the benefits, with avoided runoff only at 7% (Figure 35). The value of food production was not included because the value of all other ecosystem services is proportionally much less in comparison for both scenarios.

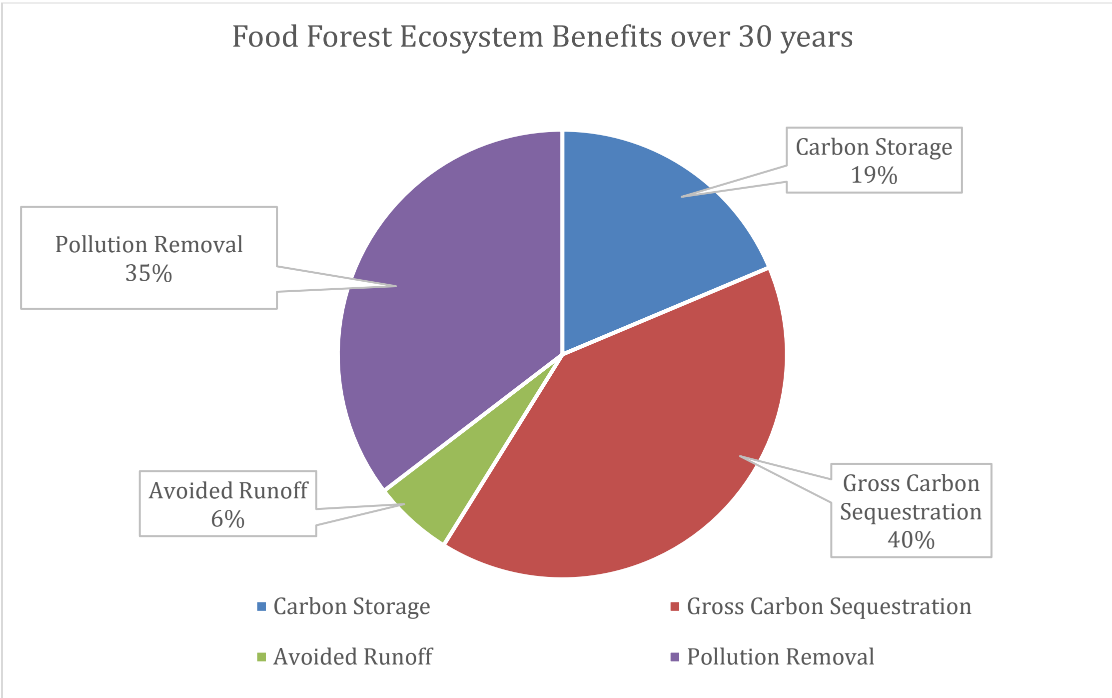


Figure 34. Percentage of ecosystem services value for Castillero Middle School food forest over thirty years.

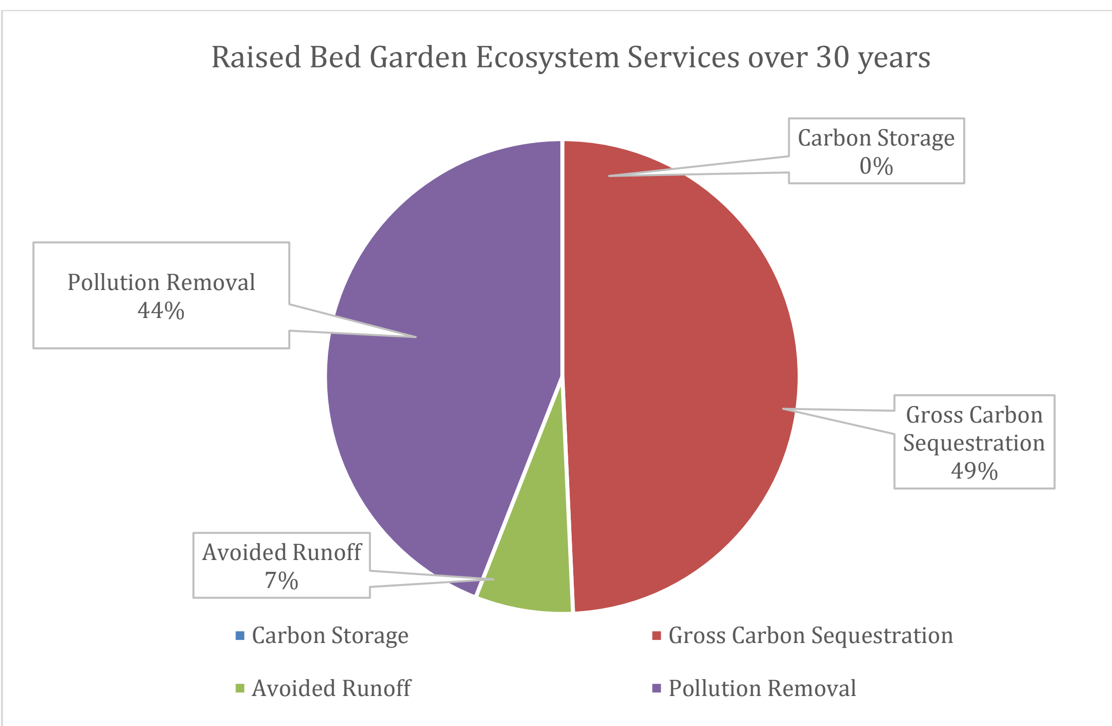


Figure 35. Percentage of ecosystem services value for a raised bed garden over thirty years.

The Value of Ecosystem Services with Increasing Adoption Rates in California

While there are significant ecosystem service benefits generated by a single food forest, there are currently 10,368 schools in California. With increased adoption, food forests in schools could provide significant benefits to the state. While achieving 100% adoption is not likely, with a 33% adoption rate in 3,456 schools, the cumulative benefits over 30 years reaches close to one billion dollars for the food forest with 60% understory; when considering food production only, the total value is $902,987,526 (Table 9). The raised bed exceeds one billion dollars, reaching $1,078,251,349.

Without considering food production, the ecosystem services provided by food forests in 33% of schools in California over 30 years is valued at $18,735,429. When compared to the baseline land use scenario of lawns, the net benefit results are similar compared to the minimal ecosystem services generated from lawns; in 3,356 schools lawns would have a cumulative value of only $3,591,157 over 30 years (Table 9).

By analyzing results for increasing adoption rates in California Schools, I demonstrated the potential significance of the ecosystem services generated by integrating food forests in schools on a mass scale. These benefits increase linearly with % of schools adopting food forests equivalent to the case study middle school. Again, without considering the value of food production, the food forest scenario offers significantly greater ecosystem benefits over all other land use scenarios with increasing adoption rates (Figure 36). When considering the value of food production, the raised bed outperformed the food forest, but the actual pounds of food produced is less than that of the food forest (Figure 37).

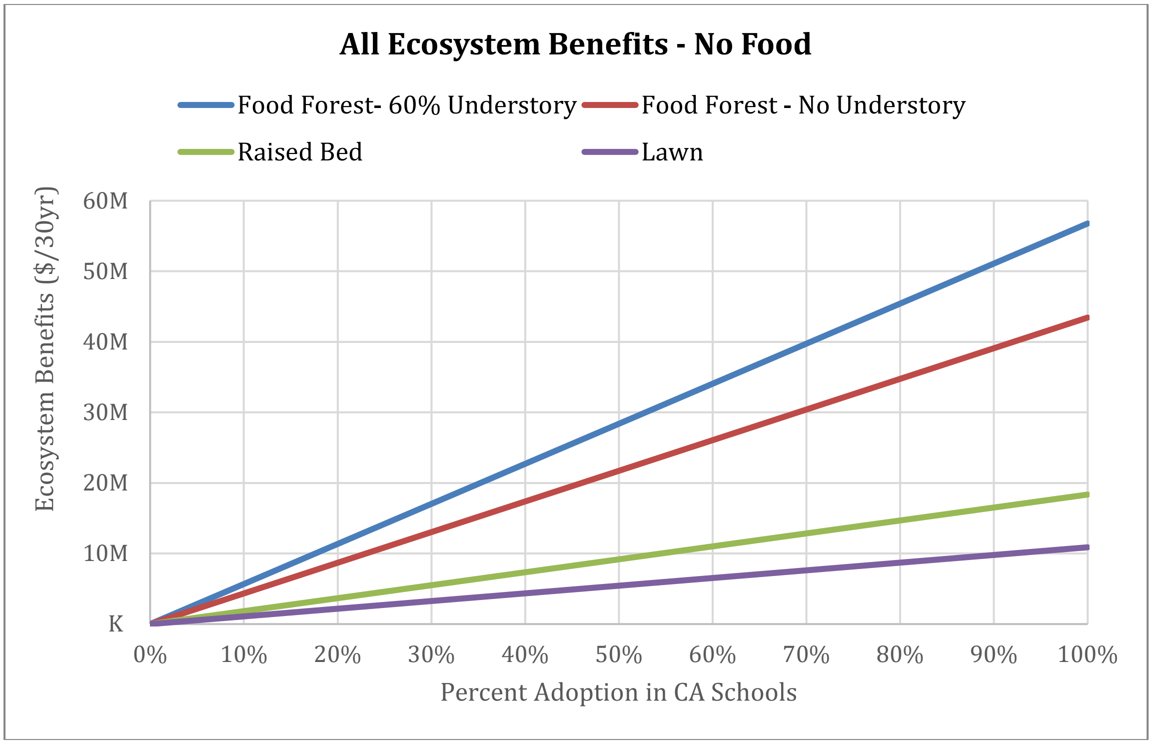


Figure 36. Cumulative value of ecosystem services with increasing adoption rates by land use scenario, food production not included.

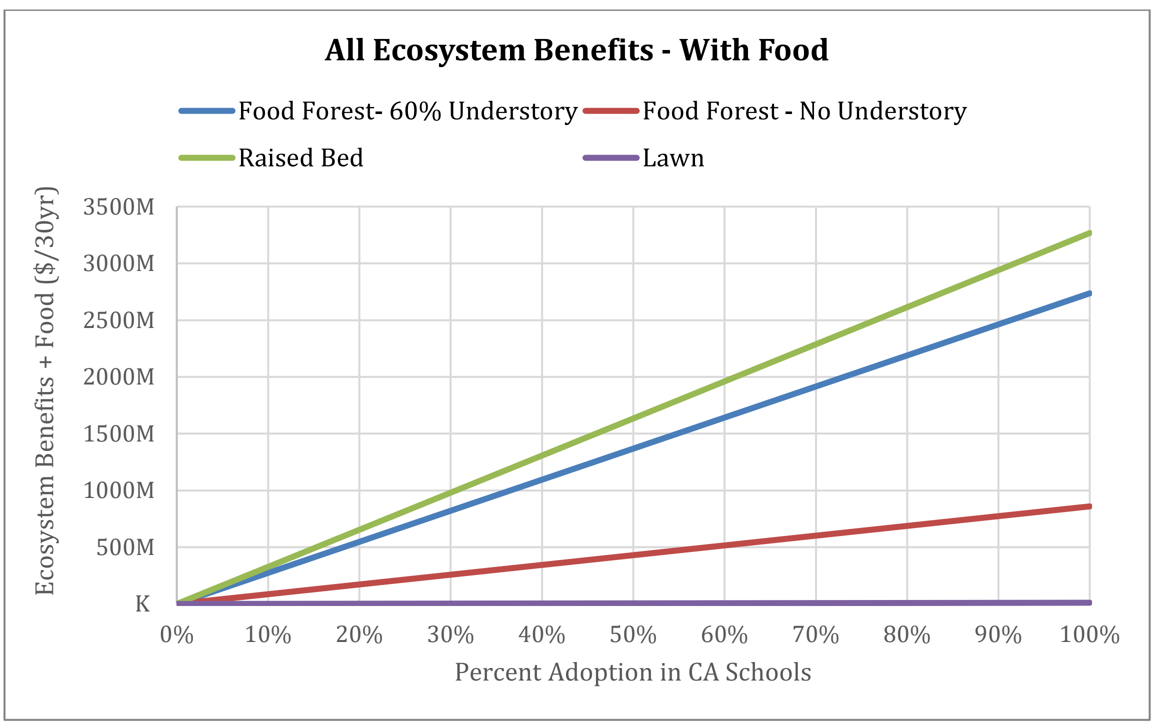


Figure 37. Cumulative value of ecosystem services with increasing adoption rates by land use scenario, food production not included.

Cost Benefit Analysis

The CBA included the financial appraisal of ecosystem services to evaluate the environmental benefits of each land use scenario. The food forest scenario again outperformed all other scenarios, with an NPV of $159,845 based on the NPV of all ecosystem services benefits including food production less all costs (Table 10). In addition, conversion of the baseline lawn scenario to a food forest offered significant benefits with an NPV of $167,384. Benefits of such conversion were net positive, both

Table 10. Cost benefit analysis net present value results by land use scenario.

Land Use Scenario	NPV	NPV (No Food)	NPV (Food Only No costs)	NPV - 33% Adoption (3456 Schools)
Food Forest (60% Understory)	$159,845	-$4,613	$164,459	$552,425,523
Food Forest (No Understory)	$31,348	-$4,344	$35,692	$108,339,474
Raised Bed Garden	$93,714	-$67,173	$160,887	$323,875,049
Lawn (Baseline)	-$7,539	-$7,539	$0	-$26,054,430
Conversion: Lawn to Food Forest (60%U)	$167,384	$2,926	$164,459	$578,479,953
Conversion: Lawn to Raised Bed Garden	$101,253	-$59,634	$160,887	$349,929,479

with and without the consideration of food production. In considering the impact of widespread adoption, if 33% of California schools (3,456 schools) converted lawns to food forests, benefits could reach an NPV of $578,479,953 over 30years. Increasing percent adoption further increases NPV (Figure 38).

The value of food production offered significant monetary benefit, but the analysis is also included as a means to ensure the food forest is able to generate comparable food production value as compared to the raised bed garden. Due to the significant difference in initial cost of each scenario, I calculated the NPV of food production without costs to compare food production benefits independently. Food production in the food forest (NPV $164,459) and raised bed garden (NPV $160,887) were nearly identical, with food forests slightly outperforming the raised bed garden (Table 10). A raised bed garden (NPV $93,714) resulted in greater NPV as compared to the food forest with no understory scenario (NPV $31,348) due to higher food production yields (Table 10). The understory is a significant part of food production, with vegetable food production at 3,541 pounds per year in the understory far exceeding the 1,739 pounds per year of fruit produced by the trees and shrubs at maturity. Results for the food forest without understory demonstrated the value of the understory to the food forest ecosystem. Therefore, it is important to consider the understory food productivity as a key part of the food forest.

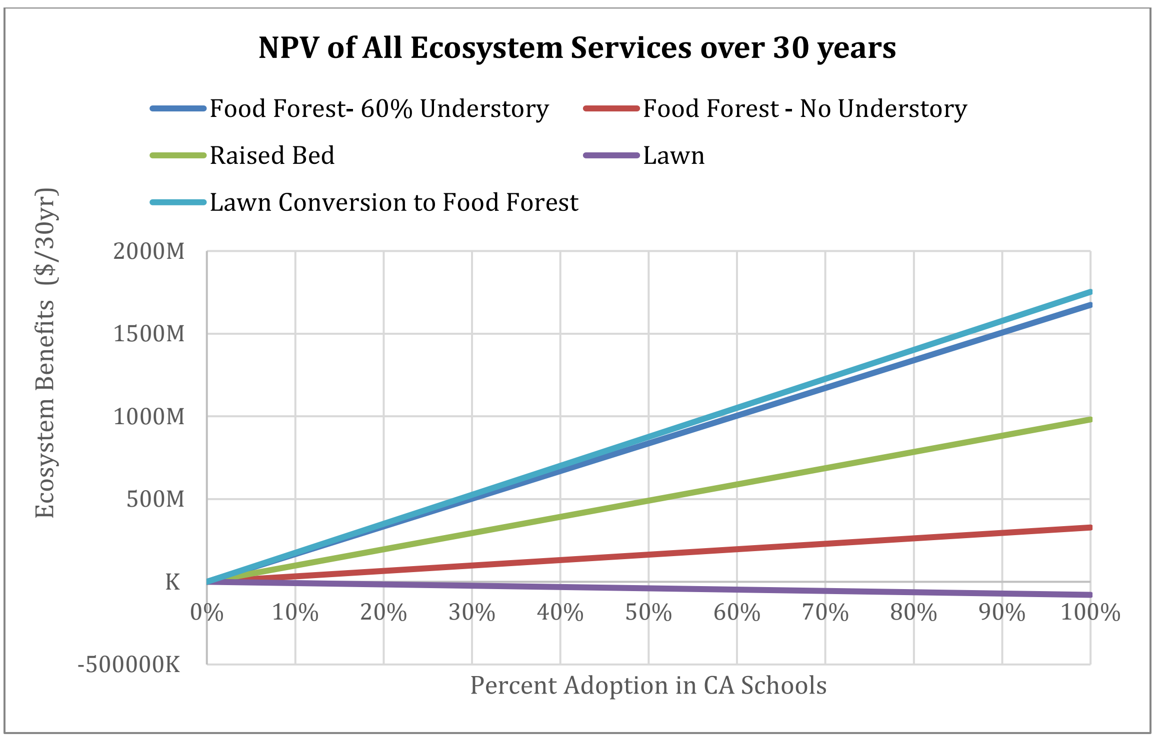


Figure 38. Net present value of land use scenarios with increasing adoption rates in California schools.

Interestingly, without considering food production, the NPV for all land use scenarios is negative (Table 10), as the costs outweigh the financial benefit of environmental ecosystem services alone. Still, the food forest scenario results in lower costs as compared to the other land use scenarios (Table 11). The CBA also reflects that food forests require less ongoing maintenance as compared to a raised bed garden once established, as there is no need to replant year after year. Ongoing maintenance is often a challenge for school gardens, so minimizing maintenance using permaculture techniques can enhance long term success. Due to high initial costs, and greater ongoing costs, the raised bed garden is the most expensive. As for lawns, maintenance is labor intensive and requires extensive inputs resulting in significant annual costs. It is assumed that lawn maintenance is not free because lawns will not be managed by volunteers or educational programs built into curriculum.

Table 11. Itemized initial and ongoing costs used in CBA for each land use scenario.

	Food Forest Costs			**Raised Bed Costs**		**Lawn Costs**	
Itemized costs	Year 1	Year 2	>Year 2	Year 1	>Year 2	**Itemized Costs**	≥ Year 1
Replacement rate	0%	10%	5%	0%	0%	*Annual Cost ($0.0385/sqft)*	$419
Tree cost ($30 each)	$720	$60	$30	$0	$0	*Existing Lawn*	$0
Shrub cost ($10 each)	$1,010	$100	$50	$0	$0		
Transplants ($1 each)	$667	$66	$33	$924	$924		
Ground Cover Seed Cost	$100	$50	$25	$0	$0		
Irrigation Equipment	$1,650	$100	$100	$1,650	$100		
Fencing	$1,000			$1,000			
Water	$19	$19	$19	$11	$11		
Compost & Amendments	$720	$150	$150	$720	$150		
Soil test	$150			$43,316			
Free Mulch	$0	$0	$0	$0	$0		
Volunteer Labor	$0	$0	$0	$0	$0		
Total Costs	**$6,036**	**$545**	**$407**	**$47,621**	**$1,185**		**$419**

ESD Curriculum Design Tool

The curriculum design tools demonstrated that the SDGs aligned well with the food forest curriculum, earning an average relevance score of 2.35 out of a maximum score of 3. Of the 17 SDGs, eight are core concepts directly related to the food forest ecological learning environment, seven are easily related, two are indirectly related (score of 1), and none are irrelevant based on the relevance scoring criteria (Table 12).

Table 12. Relevance scoring criteria for the ESD curriculum design tools.

Score	Relevance
0	Not relevant
1	Indirectly related, or can be integrated through complementary systems or programs
2	Easily related
3	Core competency or concepts directly related

The two most relevant cognitive, socio-emotional, and behavioral GAP ESD learning objectives for each SDG are highlighted to substantiate the relevance of food forest learning topics and activities (Table 13). In addition, the food forest ecological learning environment provides excellent context for developing all key competencies, with an average relevance of 2.625 out of 3 (Table 14). In Table 14, the relevance is explained with a description of how these key competencies are developed and reinforced in correlation with the food forest curriculum. This same approach to curriculum mapping can be applied to other educational projects that also seek to integrate ESD.

Table 13. Curriculum design tool: mapping food forest curriculum to SDGs by applying ESD learning goals and objectives.

SDGs	Curriculum Correlation		Education for Sustainable Goals Learning Objectives (Select Two)		
	Relevance	Learning Topics and Activities	Cognitive	Socio-Emotional	Behavioural
1. End poverty in all its forms everywhere					
1 NO POVERTY	2	- Act to address issues of poverty within their community by enhancing access to healthy nutritious food. - Assess the food forest, a form of agroforestry, as a strategy to reduce poverty, provide food security, and enhance climate resilience, locally and globally, as suggested by FAO. - Debate controversial topics linked to poverty and agriculture including agrarian reform, The Green Revolution, GMOs, subsidies, and foreign aid.	4. The learner understands how extremes of poverty and extremes of wealth affect basic human rights and needs. 5. The learner knows about poverty reduction strategies and measures and is able to distinguish between deficit-based and strength-based approaches to addressing poverty.	1. The learner is able to collaborate with others to empower individuals and communities to affect change in the distribution of power and resources in the community and beyond. 3. The learner is able to show sensitivity to the issues of poverty as well as empathy and solidarity with poor people and those in vulnerable situations.	1. The learner is able to plan, implement, evaluate and replicate activities that contribute to poverty reduction. 5. The learner is able to propose solutions to address systemic problems related to poverty.
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture					
2 ZERO HUNGER	3	- Leverage the food forest to end hunger within their local community. - Develop and apply skills in sustainable agriculture. - Examine world hunger, malnutrition, obesity and issues related to food justice, food waste, and unequal distribution of resources. - Advocate for the development of sustainable food systems, locally, and globally.	1. The learner knows about hunger and malnutrition and their main physical and psychological effects on human life, and about specific vulnerable groups. 5. The learner understands the need for sustainable agriculture to combat hunger and malnutrition worldwide and knows about other strategies to combat hunger, malnutrition and poor diets.	4. The learner is able to reflect on their own values and deal with diverging values, attitudes and strategies in relation to combating hunger and malnutrition and promoting sustainable agriculture. 5. The learner is able to feel empathy, responsibility and solidarity for and with people suffering from hunger and malnutrition.	1. The learner is able to evaluate and implement actions personally and locally to combat hunger and to promote sustainable agriculture. 5. The learner is able to change their production and consumption practices in order to contribute to the combat against hunger and the promotion of sustainable agriculture.
3. Ensure healthy lives and promote well-being for all at all ages					
3 GOOD HEALTH AND WELL-BEING	3	- Develop a connection to nature in order to understand and experience the benefits of time outdoors, and staying active through green exercise. - Promote good health and well-being for themselves, their families, and others. - Evaluate benefits of food forests and urban tree canopy as it relates to public health through reduced air pollution, carbon sequestration (climate change mitigation), connection to nature, and food production.	3. The learner understands the socio-political-economic dimensions of health and wellbeing and knows about the effects of advertising and about strategies to promote health and well-being. 5. The learner knows relevant prevention strategies to foster positive physical and mental health and well-being, including sexual and reproductive health and information as well as early warning and risk reduction.	3. The learner is able to encourage others to decide and act in favour of promoting health and well-being for all. 4. The learner is able to create a holistic understanding of a life of health and well-being, and to clarify related values, beliefs and attitudes.	1. The learner is able to include health promoting behaviours in their daily routines. 4. The learner is able to publicly demand and support the development of policies promoting health and well-being.
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all					
4 QUALITY EDUCATION	3	- Apply ESD within the context of the food forest through the integration of the SDGs. - Promote sustainable development through the sustainable management and local impact of the food forest, and empower others to do the same. - Question what is quality education, and what impact can quality education and ESD have on the world.	4. The learner understands the important role of culture in achieving sustainability. 5. The learner understands that education can help create a more sustainable, equitable and peaceful world.	1. The learner is able to raise awareness of the importance of quality education for all, a humanistic and holistic approach to education, ESD and related approaches. 5. The learner is able to engage personally with ESD.	4. The learner is able to promote the empowerment of young people. 5. The learner is able to use all opportunities for their own education throughout their life, and to apply the acquired knowledge in everyday situations to promote sustainable development.

5. Achieve gender equality and empower all women and girls					
5 GENDER EQUALITY	2	- Challenge traditional perceptions of gender roles by distributing food forest management tasks that reinforce gender equality. - Identify and reflect upon their own gender biases as applied to work within the food forest. - Compare gender biases within their own culture with respect to global norms in agriculture.	1. The learner understands the concept of gender, gender equality and gender discrimination and knows about all forms of gender discrimination, violence and inequality and understands the current and historical causes of gender inequality. 3. The learner understands levels of gender equality within their own country and culture in comparison to global norms (while respecting cultural sensitivity), including the intersectionality of gender with other social categories such as ability, religion and race.	1. The learner is able to recognize and question traditional perception of gender roles in a critical approach, while respecting cultural sensitivity. 4. The learner is able to reflect on their own gender identity and gender roles.	1. The learner is able to take the measure of their surroundings to empower themselves or others who are discriminated against because of their gender. 5. The learner is able to plan, implement, support and evaluate strategies for gender equality.
6. Ensure availability and sustainable management of water and sanitation for all					
6 CLEAN WATER AND SANITATION	3	- Apply sustainable water management methods within the food forest, and test methods and species for drought tolerance. - Determine food forest water ecosystem services such as reduced runoff, stormwater control, improved water quality, and rainwater harvesting. - Evaluate agroforestry with respect to drought tolerance, climate resilience, and water resources around the world. - Measure virtual water of the food forest products, and compare virtual water of different diets.	1. The learner understands water as a fundamental condition of life itself, the importance of water quality and quantity, and the causes, effects and consequences of water pollution and water scarcity. 4. The learner understands the concept of "virtual water."	1. The learner is able to participate in activities of improving water and sanitation management in local communities. 2. The learner is able to communicate about water pollution, water access and water saving measures and to create visibility about success stories.	2. The learner is able to contribute to water resources management at the local level. 3. The learner is able to reduce their individual water footprint and to save water practicing their daily habits.
7. Ensure access to affordable, reliable, sustainable and clean energy for all					
7 AFFORDABLE AND CLEAN ENERGY	1	- Design and build clean energy systems within the food forest such as: greenhouse, solar oven, solar water pump, wind mill, human power. - Validate solar energy as a resource for heat, electricity, and make the connection to the productivity of the food forest via photosynthesis. - Evaluate appropriate technologies for affordable clean energy, and consider challenges to widespread adoption (i.e. solar ovens).	1. The learner knows about different energy resources – renewable and non-renewable – and their respective advantages and disadvantages including environmental impacts, health issues, usage, safety and energy security, and their share in the energy mix at the local, national and global level. 5. The learner knows about harmful impacts of unsustainable energy production, understands how renewable energy technologies can help to drive sustainable development and understands the need for new and innovative technologies and especially technology transfer in collaborations between countries.	3. The learner is able to cooperate and collaborate with others to transfer and adapt energy technologies to different contexts and to share energy best practices of their communities. 4. The learner is able to clarify personal norms and values related to energy production and usage as well as to reflect and evaluate their own energy usage in terms of efficiency and sufficiency.	1. The learner is able to apply and evaluate measures in order to increase energy efficiency and sufficiency in their personal sphere and to increase the share of renewable energy in their local energy mix. 2. The learner is able to apply basic principles to determine the most appropriate renewable energy strategy in a given situation.

8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all					
8 DECENT WORK AND ECONOMIC GROWTH	**2**	- Develop entrepreneurial projects from food forest products and consider alternative business models such as: cooperatives, certified B corporations, and nonprofits. - Compare how traditional and alternative economic models and indicators can hinder/support the transition to sustainable agriculture. - Investigate the benefits and challenges of fair trade, and organic certification. - Collaborate with farm workers to ensure fair wages and safe working conditions.	1. The learner understands the concepts of sustained, inclusive and sustainable economic growth, full and productive employment, and decent work, including the advancement of gender parity and equality, and knows about alternative economic models and indicators. 5. The learner understands how innovation, entrepreneurship and new job creation can contribute to decent work and a sustainability-driven economy and to the decoupling of economic growth from the impacts of natural hazards and environmental degradation.	1. The learner is able to discuss economic models and future visions of economy and society critically and to communicate them in public spheres. 2. The learner is able to collaborate with others to demand fair wages, equal pay for equal work and labour rights from politicians and from their employer.	1. The learner is able to engage with new visions and models of a sustainable, inclusive economy and decent work. 4. The learner is able to plan and implement entrepreneurial projects.
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation					
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	**2**	- Investigate the economic, social, and environmental impacts of industrialized agriculture. - Calculate and compare food miles for diets from industrialized versus sustainable agriculture. - Develop an alternative to industrialized agriculture by supporting the success of the food forest. - Collaborate with local partners, raise funding, and propose innovative solutions to market challenges to demonstrate the viability of sustainable agriculture.	1. The learner understands the concepts of sustainable infrastructure and industrialization and society's needs for a systemic approach to their development. 2. The learner understands the local, national and global challenges and conflicts in achieving sustainability in infrastructure and industrialization.	4. The learner is able to recognize and reflect on their own personal demands on the local infrastructure such as their carbon and water footprints and food miles. 3. The learner is able to find collaborators to develop sustainable and contextual industries that respond to our shifting challenges and also to reach new markets.	2. The learner is able to evaluate various forms of industrialization and compare their resilience. 4. The learner is able to access financial services such as loans or microfinance to support their own enterprises.
10. Reduce inequality within and among countries					
10 REDUCED INEQUALITIES	**2**	- Inquire into the root cause of food deserts, food waste, and unequal access to healthy foods within their local community. - Investigate inequalities related to the distribution of resources and the impacts of climate change in regards to food security globally. - Leverage the food forest and develop a strategy to reduce inequalities within their local food system.	3. The learner understands that inequality is a major driver for societal problems and individual dissatisfaction. 4. The learner understands local, national and global processes that both promote and hinder equality (fiscal, wage, and social protection policies, corporate activities, etc.).	4. The learner becomes aware of inequalities in their surroundings as well as in the wider world and is able to recognize the problematic consequences. 5. The learner is able to maintain a vision of a just and equal world.	2. The learner is able to identify or develop an objective indicator to compare different groups, nations, etc. with respect to inequalities. 4. The learner is able to plan, implement and evaluate strategies to reduce inequalities.
11. Make cities and human settlements inclusive, safe, resilient and sustainable					
11 SUSTAINABLE CITIES AND COMMUNITIES	**3**	- Collaborate with local community to increase sustainable agriculture and increase the number of food forests, fruit trees, and community gardens. - Participate in local governance meetings and committees to support sustainable development initiatives as motivated by ESD and the SDGs. - Design, implement and evaluate community-based sustainability projects of the food forest. - Adjust their lifestyle, get to know the local ecosystem, and connect with their community in order to support sustainable development. - Tour permaculture communities to experience the possibilities for sustainable human settlements.	4. The learner knows the basic principles of sustainable planning and building, and can identify opportunities for making their own area more sustainable and inclusive. 5. The learner understands the role of local decision-makers and participatory governance and the importance of representing a sustainable voice in planning and policy for their area.	4. The learner is able to contextualize their needs within the needs of the greater surrounding ecosystems, both locally and globally, for more sustainable human settlements. 5. The learner is able to feel responsible for the environmental and social impacts of their own individual lifestyle.	1. The learner is able to plan, implement and evaluate community-based sustainability projects. 2. The learner is able to participate in and influence decision processes about their community.

12. Ensure sustainable consumption and production patterns					
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	3	- Identify and adjust individual food consumption patterns in order to align with sustainable consumer choices. - Transform the food forest into a closed loop system as much as possible by planning and implementing strategies to reduce external inputs and outputs. - Develop sustainable food production skills through experience in the food forest. - Propose food waste reduction strategies. - Promote sustainable production and consumption.	1. The learner understands how individual lifestyle choices influence social, economic and environmental development. 4. The learner knows about strategies and practices of sustainable production and consumption.	1. The learner is able to communicate the need for sustainable practices in production and consumption. 5. The learner is able to feel responsible for the environmental and social impacts of their own individual behaviour as a producer or consumer.	3. The learner is able to promote sustainable production patterns. 5. The learner is able to challenge cultural and societal orientations in consumption and production.
13.Take urgent action to combat climate change and its impacts					
13 CLIMATE ACTION	3	- Work to reduce the carbon footprint and enhance carbon sequestration of the food forest by building soils and increasing biomass. - Evaluate the carbon footprint of different diets, and adjust their own diet to be more climate friendly. - Evaluate, propose, and implement strategies for climate resilient agriculture within the food forest.	3. The learner knows which human activities – on a global, national, local and individual level – contribute most to climate change. 5. The learner knows about prevention, mitigation and adaptation strategies at different levels (global to individual) and for different contexts and their connections with disaster response and disaster risk reduction.	1. The learner is able to explain ecosystem dynamics and the environmental, social, economic and ethical impact of climate change. 2. The learner is able to encourage others to protect the climate.	1. The learner is able to evaluate whether their private and job activities are climate friendly and – where not – to revise them. 5. The learner is able to support climate-friendly economic activities.
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development					
14 LIFE BELOW WATER	1	- Trace the local watershed through maps and site visits in order make the connection between the terrestrial and marine aquatic systems. - Develop water runoff reduction strategies to prevent erosion, and enhance water interception within the food forest in order reduce pollution and enhance the quality of the local watershed. - Incorporate marine life when analyzing sustainable diets, and make adjustments to consumption in order to support sustainable fisheries.	1. The learner understands basic marine ecology, ecosystems, predator-prey relationships, etc. 4. The learner understands threats to ocean systems such as pollution and overfishing and recognizes and can explain the relative fragility of many ocean ecosystems including coral reefs and hypoxic dead zones. etc.	2. The learner is able to show people the impact humanity is having on the oceans (biomass loss, acidification, pollution, etc.) and the value of clean healthy oceans. 4. The learner is able to reflect on their own dietary needs and question whether their dietary habits make sustainable use of limited resources of seafood.	1. The learner is able to research their country's dependence on the sea. 3. The learner is able to identify, access and buy sustainably harvested marine life, e.g. ecolabel certified products.
Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss					
15 LIFE ON LAND	3	- Evaluate and enhance the ecosystem services of the food forest. - Experience the human nature connection first hand by working to regenerate land and biodiversity via the food forest. - Develop skills in sustainable soil management, work to regenerate soil, and understand the importance to the planet. - Develop ecoliteracy and experience the local ecosystems by participating in regenerative land practices.	3. The learner is able to classify the ecosystem services of the local ecosystems including supporting, provisioning, regulating and cultural services and ecosystems services for disaster risk reduction. 4. The learner understands the slow regeneration of soil and the multiple threats that are destroying and removing it much faster than it can replenish itself, such as poor farming or forestry practice.	3. The learner is able to connect with their local natural areas and feel empathy with nonhuman life on Earth. 4. The learner is able to question the dualism of human/nature and realizes that we are a part of nature and not apart from nature.	2. The learner is able to effectively use their voice effectively in decision-making processes to help urban and rural areas become more permeable to wildlife through the establishment of wildlife corridors, agro-environmental schemes, restoration ecology and more. 4. The learner is able to highlight the importance of soil as our growing material for all food and the importance of remediating or stopping the erosion of our soils.

16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels					
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	2	- Evaluate food systems and climate change through the justice lens. - Through ESD experienced within the context of the food forest, students are equipped with the knowledge, skills, and key competencies necessary to promote peaceful and inclusive societies for sustainable development. - Plan an initiative within their local community that promotes peaceful and inclusive societies and take a stand for justice for all.	4. The learner understands the importance of individuals and groups in upholding justice, inclusion and peace and supporting strong institutions in their country and globally. 5. The learner understands the importance of the international human rights framework.	2. The learner is able to debate local and global issues of peace, justice, inclusion and strong institutions. 3. The learner is able to show empathy with and solidarity for those suffering from injustice in their own country as well as in other countries.	3. The learner is able to collaborate with groups that are currently experiencing injustice and/or conflicts. 4. The learner is able to become an agent of change in local decision-making, speaking up against injustice.
17. Strengthen the means of implementation and revitalize the global partnership for sustainable development					
17 PARTNERSHIPS FOR THE GOALS	2	- Identify and establish key partnerships globally. - Build relationships with other schools globally that are engaged in ES and learn from their perspectives. - Participate in knowledge sharing by developing a web based presence to log food forest activities, share lessons learned, and gather information from others. - Develop partnerships at the local, global, and national levels.	2. The learner understands the importance of global multi-stakeholder partnerships and the shared accountability for sustainable development and knows examples of networks, institutions, campaigns of global partnerships. 4. The learner recognizes the importance of cooperation on and access to science, technology and innovation, and knowledge sharing.	4. The learner is able to create a vision for a sustainable global society. 5. The learner is able to experience a sense of belonging to a common humanity, sharing values and responsibilities, based on human rights.	1. The learner is able to become a change agent to realize the SDGs and to take on their role as an active, critical and global and sustainability citizen. 2. The learner is able to contribute to facilitating and implementing local, national and global partnerships for sustainable development.

Table 14. Curriculum design tool: correlating food forest curriculum to key competencies for sustainability.

Key Competencies for Sustainability		Curriculum Correlation	
		Relevance	Description
Systems thinking	The abilities to recognize and understand relationships; to analyse complex systems; to think of how systems are embedded within different domains and different scales; and to deal with uncertainty.	3	Food forests serve as a complex ecosystem where children can apply systems thinking at many scales such as: soil biology, nutrient cycling, plant-pollinator relationships, food webs, local food systems, and global food systems.
Anticipatory	The abilities to understand and evaluate multiple futures – possible, probable and desirable; to create one's own visions for the future; to apply the precautionary principle; to assess the consequences of actions; and to deal with risks and changes.	3	Students can make decisions about how to sustainably manage the food forest in order to develop the best outcome for the future. They can evaluate multiple futures, consider the tradeoffs between short-term versus long term benefits, apply the precautionary principle when implementing changes, and assess the consequences of their actions as observed by the resulting productivity of the food forest.
Normative	The abilities to understand and reflect on the norms and values that underlie one's actions; and to negotiate sustainability values, principles, goals, and targets, in a context of conflicts of interests and trade-offs, uncertain knowledge and contradictions.	2	Food is a central aspect of our lives and our individual consumption patterns can have a great impact on economic, social, and environmental sustainability at the micro, meso, and macro scale. By raising awareness, students are challenged to reflect upon their own norms and values, and how this is reflected in their food consumption. In addition, choices in land use become apparent.
Strategic	The abilities to collectively develop and implement innovative actions that further sustainability at the local level and further afield.	3	By managing the food forests, students are directly benefiting their community through sustainable agriculture, enhancing their local food system and providing ecosystem services. Students can design innovative ways to extend their impact, both locally and abroad.
Collaboration	The abilities to learn from others; to understand and respect the needs, perspectives and actions of others (empathy); to understand, relate to and be sensitive to others (empathic leadership); to deal with conflicts in a group; and to facilitate collaborative and participatory problem solving.	3	In the food forests, students are working together outside the confines of the classroom and are interacting in a significantly more complex and dynamic environment that demands greater levels of collaboration, problem solving, empathy, and leadership.
Critical thinking	The ability to question norms, practices and opinions; to reflect on own one's values, perceptions and actions; and to take a position in the sustainability discourse.	2	In the food forests, students engage in practices that inherently challenge the norms of agricultural production and consumption resulting in opportunities to reflect and think critically about one's own position, and society as a whole, with regards to sustainability.
Self-awareness	The ability to reflect on one's own role in the local community and (global) society; to continually evaluate and further motivate one's actions; and to deal with one's feelings and desires.	2	By engaging in a project that enhances the sustainability of one's own community, students cultivate a sense of self within the context of their local community. Students are also empowered to take action by gaining skills and experience through participation in the betterment of their community. Students are pushed outside of their comfort zone, enhancing self awareness through personal growth.
Integrated problem-solving	The overarching ability to apply different problem-solving frameworks to complex sustainability problems and develop viable, inclusive and equitable solution options that promote sustainable development, integrating the above mentioned competences.	3	The food forest offers a rich context for real-world application of integrated problem-solving on the micro, meso, and macro scales. Students can apply problem-solving frameworks to any of the SDGs within the context of the food forest, developing solutions to promote sustainable development within their community, and understanding relevance within a global context.

Chapter IV

Discussion

My research assessed food forests as a new model for use in schools by evaluating how they perform as compared to traditional raised bed school gardens. In addition to my primary research, I examined my results to generate additional data to analyze the impact of alternative input values, and site considerations. Overall, I found that the results drawn from my primary analysis are in line with results from these additional scenarios. Most importantly, as a result of my simulations, I was able to approximate expected values of ecosystems services per acre for food forests, raised bed garden, and lawn for a site in San Jose, CA.

Ecosystem Service Benefits per Acre

Estimates of ecosystem service benefits per acre can be used to compare food forests, raised bed gardens, and lawns (Table 15). These values are specific to San Jose, CA, and actual values would vary based on species selection and site conditions. I utilized values from year fifteen for the food forest because the food forest would be mature and it is midway through the 30 year lifetime applied in my analysis. Further investigations could be conducted to verify these simulated values by taking site measurements of actual food forests and raised bed gardens over time. While every food forest will have a different variety of plant species, it is likely that species selection could be optimized for ecosystem service benefits, and could be an interesting investigation.

Table 15. Approximate rates of ecosystem services per acre per year by land use scenario for San Jose, CA.

Land Use Scenario	Carbon Storage (ton/ac)	Carbon Storage ($/ac/yr)	Gross Carbon Sequestration (ton/ac)	Gross Carbon Sequestration ($/ac/yr)	Avoided Runoff (ft^3/ac)	Avoided Runoff ($/ac/yr)	Pollution Removal ($/ac/yr)	Food Production (lbs/yr)	Food Production ($/ac/yr)	Benefits Total ($/ac/yr)
Food Forest (year 15)	10	1,234	2	287	623	42	256	21,120	38,511	40,330
Raised Bed Garden	0	0	1	115	234	16	103	19,604	41,364	41,598
Lawn	0	0	0	40	320	21	77	0	0	139

Raised Bed Garden Considerations

The initial costs of installing a raised bed garden were significantly higher than that of a food forest due to the cost of materials required for raised bed construction. If these materials were donated, the NPV of the raised bed garden would be more comparable to that of the food forest with an NPV of $135,768 as compared to $159,845 for the food forest. Food productivity of the food forest is slightly higher than that of a raised bed garden (Table 15). However, if we were to account for the difference in value of vegetables as compared to fruits, with median values of $2.11 per pound, and $1.24 per pound, respectively, raised bed gardens would be nearly identical, and actually outperform the overall benefits of food forest by a small margin if costs of raised bed construction materials are not considered, with an NPV of $177,551 as compared to $177,513. However, including cost of the raised bed construction materials, this is reduced to an NPV of $135,496.

Lawns

To validate the results of the lawn model I developed in iTree, I compared results to air pollution reduction values attributed to grasslands in the United States. I found the results to be comparable, and performed my analysis based on results from iTree (Table 16).

Table 16. Air pollution removal results from iTree as compared to grasslands results from study (Gopalakrishnana, Hirabayashib, Zivc, & Bakshi, 2018).

	From iTree	Conversions			from Gopalkrishnan
	lbs/0.25ac/yr	lbs/ac/yr	g/m2/yr	ton/.25ac/yr	g/m2/yr
CO	0.583	2.332	0.26	0.0002915	na
NO2	1.436	5.744	0.64	0.000718	0.36
O3	5.813	23.252	2.61	0.0029065	2.93
PM2.5	0.018	0.072	0.01	0.000009	0.04
SO2	0.082	0.328	0.04	0.000041	0.16

While lawns have a bad reputation for environmental impact, after researching ecosystem services of turfgrass, I found that the carbon sequestration values far exceeded my expectations, ranging from 25.4 to 204.3 g C/m^2/yr as a result of management practices. In this analysis, I applied the average of the maximum and minimum, at 69.8 g C/m^2/yr, or 0.078 tons per quarter acre per year. If we apply the higher value for carbon sequestration, rates would be 0.23 tons per quarter acre per year. This is equivalent to the food forest at year 1 with 0.23 tons per quarter acre per year. However, the food forest sequestration rates increase year over year, reaching 0.87 tons per quarter acre year by year thirty, far exceeding sequestration of lawns over time. In addition, diverse ecosystems, and ecosystems of many layers, such as food forests, offer an array of environmental benefits beyond what is captured in this analysis.

Research Limitations

While food forests in schools could provide numerous ecosystem services, my research targeted only five: carbon sequestration, avoided runoff, air pollution reduction, food production, and education. Benefits to public health related to food production are not evaluated in this study, but could likely be another direct benefit. In addition, my research is specific to California, utilizing agricultural data available for the region, and creating a food forest design applicable to California's Mediterranean climate. Actual values will vary based on species and site selection. Many of the values in the iTree model resort to default values built into the software, and tend to be approximations based on data available. Greater accuracy would require actual measurements in the field.

My analysis assumes that off campus carbon emissions and air pollution resulting from ongoing maintenance would be similar for each land use scenario, and therefore negligible; many of the people that would participate in ongoing maintenance would be on school grounds regardless of land use scenarios. In addition, my current methodology neglects emissions of volatile organic compounds.

Conclusions

My analyses demonstrated that food forests in schools would provide greater ecosystem services as compared to raised bed school gardens while upholding food production and enhancing opportunities for education for sustainable development. Food forests in schools would significantly enhance ecosystem services and financially outperform raised bed school gardens through reduced maintenance costs, environmental benefits, and comparable food productivity. In addition, the aggregate benefits of converting lawns to food forests in California schools could result in a significant amount of carbon sequestration, air pollution reduction, avoided runoff, and food production for the state of California. By implementing policies to promote food forests in schools, it is reasonable to consider that one third of all California schools could convert lawns to food forests, or expand their existing gardens to incorporate more perennial trees and shrubs. If 33% of California schools converted a quarter acre lawn to food forest, after 30 years, it would result in 49,991 tons of carbon sequestration, 7,817,952 cubic feet of avoided runoff, and a value of $4,638,557 for pollution removal. In addition, the food forests would have produced 527,911,699 pounds of healthy food for youth. By year 30, these food forests would amount to 26,958 tons of carbon storage in the form of woody biomass resulting from 49,991 tons of total carbon sequestration from the atmosphere. Some of the carbon sequestered is lost each year in leaf biomass because many of the trees in the food forest are deciduous, resulting in less carbon stored each year than sequestered. Total carbon sequestration is greater than the carbon stored in the food forest at year thirty because it is a cumulative value of carbon removed from the atmosphere over the duration of thirty years.

By implementing food forests, schools would experience all of these benefits while enhancing opportunities to cultivate the human nature connection and develop ESD by offering a rich ecological learning environment in the transition to greener schoolyards. By correlating food forest curriculum to ESD learning objectives and key competencies, I was able to document the educational value and also provide educators with a template to develop their own ESD curriculum. Overall, these results provide educators and other decision makers with information and tools that can support initiatives to grow food forests and promote ESD in their community.

Cultural Social Responsibility and Regenerative Conservation Ethic

In the process of developing my thesis, I came to understand that what we need in order to achieve global sustainability is a shift in worldview that supports a regenerative as opposed to extractive relationship with the earth. What this requires is a cultural shift at a magnitude and pace like never before. I define “Cultural Social Responsibility” as the ideas, customs, and social behavior of a society that supports a balance of environmental, economic and social imperatives through a “regenerative conservation ethic” and prioritizes services to ecosystems (S2E). I define “regenerative conservation ethic” as a proactive focus on regenerating the health of the natural world that leverages a circular economy of renewable materials and energy to support a sustainable society. Education that supports Cultural Social Responsibility as a potential outcome could be the impetus for the necessary widespread cultural shift towards humans as environmental stewards.

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