Economic Opportunities for Biomass Harvest of Invasive Giant Reed (Arundo Donax L.) in Southern California as Feedstock for the Pulp and Paper Industry

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Economic Opportunities for Biomass Harvest of Invasive Giant Reed (*Arundo donax* L.) in Southern California as Feedstock for the Pulp and Paper Industry

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A Thesis in the Field of Sustainability and Environmental Management
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Abstract

This study investigates commercial opportunities in southern California for removing Giant Reed (*Arundo donax* L.) biomass and selling it to pulp and paper manufacturing operations. *Arundo donax* is an invasive non-native grass that threatens riparian zones by increasing risk of wildfire, sediment trapping, and flood damage. It consumes greater water resources than native vegetation and has demonstrated a detrimental impact on wildlife and human infrastructure. Studies have shown *Arundo* to be a superior source of non-wood fiber for several pulping processes, including the manufacture of kraft paper. *Arundo* fiber has lower cooking and bleaching requirements and produces a higher quality pulp than most traditionally used hardwoods. Plantation agriculture of *Arundo* has proven to be profitable outside of California, but runs the risk of escape and invasion into wildlands. This study utilized an economic appraisal approach to determine the feasibility of an enterprise specializing in the direct sale of wild harvested *Arundo* biomass to pulp mills. I hypothesized that the direct sale of biomass as a pulpwood commodity would fully offset the cost of removal from the wild and generate a profit. The study area covered California coastal watersheds from the Salinas River in Monterrey County in the north to the Tijuana River in the south and utilized existing *Arundo* distribution data. Pulp mills in California and Mexico were mapped to determine the closest mill for biomass delivery. Cost estimating for harvest, processing, and transport were conducted using machine rate methods utilized in the forestry sector. These were weighed against market index prices for hardwood chips. A

sensitivity analysis of variable firm sizes and the effect of transport distance and chip price on profitability determined that an optimal operation consists of a ground crew running a disk chipper and a skid-steer harvester. A transport fleet of tractor-trailers towing chip vans would be the optimal equipment to deliver *Arundo* chips to the mill. The feasibility study revealed that a business operation that harvests, chips, and transports *Arundo* biomass would not likely be profitable on its own. An operation of this size would be able to clear 35 acres of *Arundo* per year and generate estimated revenue of $460,000 at the mill. This value equals roughly 10 – 20% of overall restoration costs. Although not independently profitable, incorporating direct sale of biomass into current restoration efforts could provide a nearly $5,000 per acre subsidy and solve the logistical challenge of responsibly disposing of *Arundo* biomass.

Acknowledgments

I would first like to thank my research advisor and thesis director, Professor Mark Leighton, PhD of the Sustainability Program at the Harvard Extension School. Despite being a distance student, Professor Leighton was always willing to offer guidance and encouragement during the research and writing process. He helped to strengthen my writing and analysis while allowing it to fully remain my own work. His professional insights and expertise were invaluable to the development of my own critical thinking about the subject.

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Finally, I must express my continued gratitude to my parents, family, and friends, who have remained coaches and mentors throughout my years of study and during the process of researching and writing this thesis. Special thanks to Dr. Francisco Escobedo for scholastic counsel and Mark Hedderson for generous financial support. Without my community, this accomplishment would not have been possible. Thank you from the bottom of my heart.

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List of Abbreviations

AAI	Average annual investment
BDMT	Bone dry metric ton
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CEQA	California Environmental Quality Act
ET	Evapotranspiration
FRCS	Fuel Reduction Cost Simulator
GCW	Green *Arundo* chip weight (US t)
GVW	Gross vehicle weight
IUCN	International Union for Conservation of Nature
IRR	Internal rate of return
LSA	Lake or Streambed Alteration
M&R	Maintenance and repair
MC	Moisture content of green *Arundo* biomass (50%)
MR	Machine rate
NPV	Net present value
PMH	Productive machine hour
PH	Profitable haul distance
QAL	Qualified Applicator's License
SMH	Scheduled machine hour

Chapter I

Introduction

Biological invasion is the process by which a species enters a new environment, establishes itself there and begins to disturb the balance of existing populations. In the United States, environmental damages and losses due to invasive species are valued at approximately $120 billion per year (Pimentel, Zuniga, & Morrison, 2005). These estimates can be considered conservative because they exclude monetary values of losses in biodiversity, ecosystem services, and extinction of native species (Cororaton, Orden, & Peterson, 2009). Species have always spread and become established in new locations due to natural processes, such as wind, ocean currents, or even continental shifting. These natural movements, however, are limited by a relatively low natural rate. Species are introduced by people much more widely, in greater numbers, and on shorter timescales than the natural rate of introduction. Some of these introduced species display a high potential for invasiveness due to characteristics such as rapid growth and reproduction, high dispersal ability, and tolerance of a wide range of environmental conditions. The determining factor of an introduced species being considered "invasive" is if it causes, or has the ability to cause, harm to the environment, economies, or human health (U.S.DA, 2014). Not all introduced species become invasive, however, the ones that do have the potential to disrupt the ecosystem to a point where significant biodiversity may be lost.

Invasive species follow a predictable pattern on their way to harming the ecosystems in which they invade. Emerton and Howard (2008) described this pattern in four stages: introduction, establishment, naturalization, and invasion. Introduction and establishment are achieved when a species is capable of surviving and reproducing without assistance in a novel ecosystem (Emerton & Howard, 2008). Naturalization is characterized by population growth and an expanded distribution without any measurable negative impact to the surrounding populations. Invasion finally takes place when the introduced species continues to spread to the disadvantage of existing populations.

Invasive species can eliminate endemic species through direct competition or by altering ecological processes and resource abundance. In the U.S. roughly 42% of threatened or endangered species are at risk primarily because of the effects of over 50,000 invasive species (Pimentel et al., 2005).

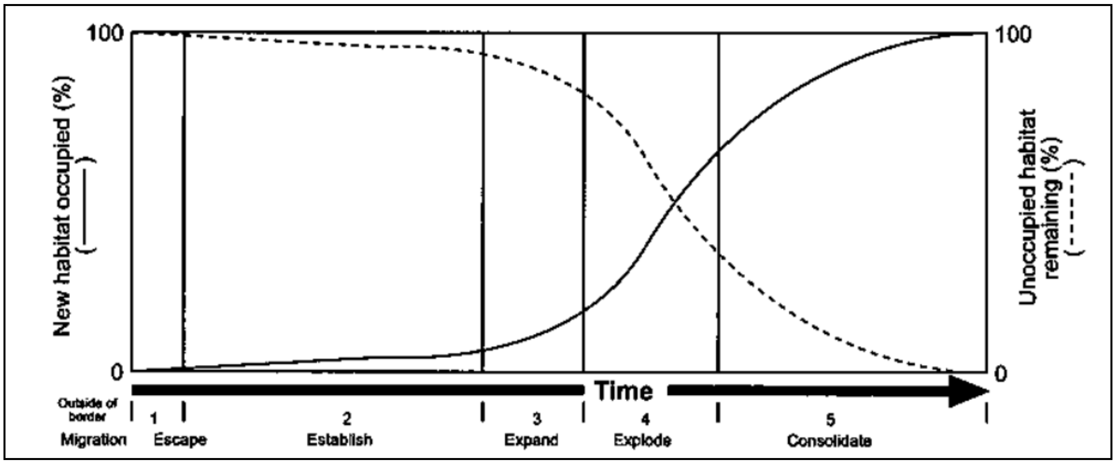


Figure 1. Phases of invasion over time (Williams, 2003).

Control of invasive species is inherently difficult. Figure 1 shows a conceptual invasion model that identifies the point at which a weedy plant species rapidly expands and begins to occupy a majority of the habit. Williams (2003) refers the “explosion” phase of invasion as the point at which the percent of habitat occupied is equal to that of the unoccupied habitat. It is clear that the most cost effective control of invading species takes place during the earliest stages of establishment. The United States Department of the Interior spends approximately $100 million annually on invasive species prevention, early detection and rapid response, control and management, research, outreach, international cooperation and habitat restoration (U.S. Fish & Wildlife Service, 2010). After the "explosion" phase, control costs and environmental damage are much higher than before.

Invasive species may alter disturbance cycles which further support their continued spread. Common models used to determine the invasiveness of species often do not accurately account for changes to the entire ecosystem, but merely quantify a species' ability to outcompete native species for shared resources (Thiele, Isermann, Kollmann, & Otte, 2011). In California, annual oat grass (*Avena fatua*) contributes to an increased fuel load that raises the likelihood of wildfires in chaparral ecosystem (Brooks et al., 2004). This increased fire frequency further encourages the spread of the oat grass, creating a positive feedback loop in which native species end up permanently eradicated (Brooks et al., 2004). When an invasive plant species alters abiotic processes, it has the potential for wide ranging and permanent change to the entire system.

Prevention is almost always cheaper and more effective than containment or eradication of existing invasive species. Under the guiding principles of the Convention on Biological Diversity, party countries are instructed to enact practices that prevent, contain, or eradicate invasive species that threaten ecosystems (United Nations Environment Program, 1992). Policy decisions are guided by economic models that weigh the detrimental impact of invasive species against the cost of control (Emerton &

Howard, 2008). Invasive species control measures fit into four general categories: mechanical, chemical, biological, and integrated. Mechanical removal refers to physical removal by hand, controlled burning, or the use of machinery. Mechanical methods are often more labor and time intensive, but provide greater precision. Chemical control involves the use of pesticides and herbicides to kill a target species, but run the risk of harm to non-target plant or animal life and the release of toxic pollutants into the environment. In 2000 and 2001, pesticide expenditures to treat invasive species were over $30 billion globally (Keily, Donaldson, & Grube 2004). Biological control typically refers to introducing parasites or predators to an area where a species has established and begun to spread due in part to a lack of natural controls. This is often the most cost effective approach due to relatively low long-term costs once biocontrols are introduced (Bell, 1997). Precautions against introducing additional pests and a lack of knowledge or availability of biological control species elsewhere often limit the ability to employ a biological approach. An integrated approach involves the combination of two or more of the previously mentioned methods. Biological control is commonly used to reduce established populations, while mechanical or chemical methods would be used on outlying populations or along the advancing edges to curb the spread of the invasive population (Emerton & Howard, 2008). In many cases, cooperation between public agencies and private stakeholders is important if effective control is to be achieved.

Invasive species removal is costly due to necessarily high energy, labor, and time input. A critical issue, then, for invasive species management is directing limited resources towards efforts that will maximize environmental benefit. A simple economic framework has been developed for setting targets for invasive species removal by identifying the point at which a maximized net benefit of removal is reached (Gren, 2008). Net benefit is the difference between total benefit and total cost of implementing various invasive species control programs.

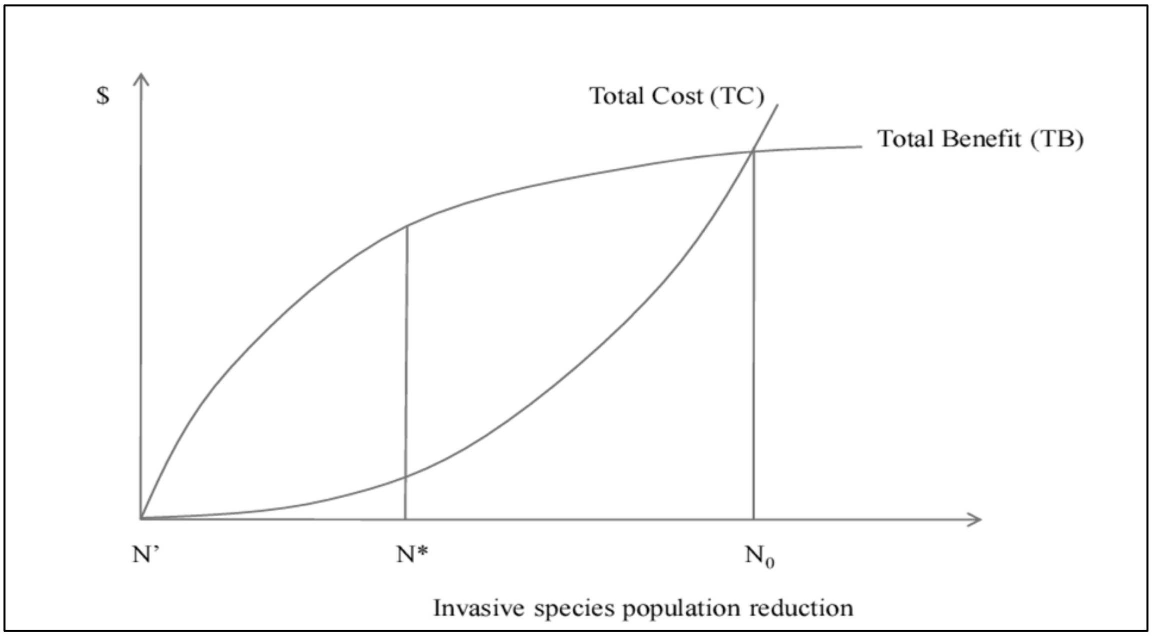


Figure 2. Net benefit curve for setting invasive species management goals (Gren, 2008).

Figure 2 diagrams the process for identifying the maximized net benefit of an invasive species control programs. The total benefit (TB) curve and the total cost (TC) curve are shown. The horizontal axis is the reduction of invasive species population, while the vertical axis is in dollars. The TB curve illustrates diminishing benefits past a certain point of reduction in invasive species population. The TC curve shows an increasing cost as removal efforts intensify. Along the horizontal axis, point N' has a value of zero, meaning no reduction in species population is achieved. The curves TB and TC intersect at point N_0, beyond which total cost exceeds total benefits implying that invasive species reduction isn't cost effective and should not be implemented. Between points N’ and N_0, reduction measures should be implemented because benefits exceed costs. The point on the horizontal axis where the benefit most exceeds cost of management is at N*. This is the point of greatest net benefit. Many studies attempt to estimate the costs and benefits of various control measures of invasive species, but relatively few of them look at the degree to which net benefit is maximized (Cororaton et al., 2009).

For invasive species management to be successful it is necessary to identify the point of greatest net benefit, during implementation phases as well as subsequent monitoring periods. Documented eradication attempts indicate that it generally costs as much to control the last remaining 1-10% of an invasion as it does to control the initial 90-99% (Myers, Savoie, & van Randen, 1998). Restoration efforts can be made most effective when informed by accurate economic and financial assessment.

Research Significance and Objectives

Invasive plants threaten sensitive habitats and nearby human settlements through displacement of native plants and animals and disruption of ecosystem services. Although many restoration techniques are well understood and technically straightforward, invasive species removal is often implemented at a slower pace than the rate of invasion. Invasive plant removal programs are expensive to manage and implement, often requiring specialized equipment and large workforces in remote locations. If direct sale invasive plant biomass were technically feasible and profitable, then restoration efforts could be widely increased.

The overall goal of this study is to determine the degree to which ecological restoration can be subsidized by direct sale of invasive species as a commodity. To achieve this goal, the study defined the following objectives:

- Develop an analytical framework for considering invasive plant species as a consumable resource.
- Determine a methodology for evaluating the profit potential of selling invasive species biomass to industry.
- Develop a protocol for prioritizing invasive species removal projects based on their profitability.

Background

In the American Southwest, and more specifically the state of California, invasive species are of special concern. The California Floristic Province, an area covering almost 300,000 km^2 from Southern Oregon to Northern Baja California Mexico, contains over 7,000 plant species, subspecies, and varieties of which over 2,000 are found nowhere else on earth (Hickman, 1993). The California Floristic Province is an internationally designated biodiversity hotspot with roughly 10% of the vegetation remaining in a relatively pristine condition (Conservation International, 2011). Not surprisingly, this high biodiversity is threatened by invasive plant species. More than 10% of plant biomass growing spontaneously in the state is exotic, comprising over 3,000 non-native species (Dowell & Krass, 1992).

Riparian zones are the interface zone between rivers and streams and the surrounding banks, floodplain, and upland area. Particularly important in arid Southern

California, an estimated 90% of historic riparian habitat has been lost to agriculture, urban development, and flood control (Katibah, 1984). Typical native riparian plant species include *Salix* (willows), *Baccharis salicifolia* (mulefat), and *Populus* (cottonwoods) which provide nesting habitat for an array of wildlife including the federally-designated threatened and endangered birds, the least Bell's vireo (*Vireo bellii pusillus*) and the willow flycatcher (*Empidonax traillii eximus*) (Zembal, 1990). These riparian ecosystems are adapted to specific flood-dominated disturbance cycles that maintain varying stages of ecological succession and a relatively high level of biodiversity. Riparian systems in Southern California have been degraded due to the introduction of invasive species, particularly tamarisk (*Tamarix* spp.) and giant reed (*Arundo donax*). In 2000, by The Invasive Species Specialist Group a specialist group of the Species Survival Commission of the World Conservation Union (IUCN) listed *Arundo donax*, as one of the top 100 invasive species in the world having successfully invaded most warm regions with a Mediterranean type climate (Lowe, Browne, Boudjelas, & De Porter, 2004).

Giant Reed (*Arundo donax*)

Arundo donax is a tall bamboo-like member of the grass family. Its origin is unclear due to longstanding dispersal by humans, although its native distribution appears to have extended from Southeast Asia to the Mediterranean Basin, evidenced in part by the presence of insect herbivores associated with the plant in these regions. (Perdue 1958; Kirk, Widmer, Campobasso, Carruthers, & Dudley, 2003). In California, *Arundo* appears to have been introduced for building materials and erosion control in the 1700s, and it was dominant along parts of the Los Angeles River as early as the 1820s (Robbins, Bellue, & Ball, 1951).

Arundo is one of the fastest growing plants in the world, up to 10 cm per day and reaching heights of 10 m tall when mature (Perdue, 1958). It rapidly expands outward to form monotypic stands along riparian floodplains and terraces (Rieger & Krieger 1989). It typically grows on bare soil with abundant water recourses, such as river beds, banks, islands, and floodplains. Upon introduction, it rapidly invades riparian areas, often dominating native vegetation and forming dense monotypic stands. *Arundo* produces a long plume-like flower that has never been observed to contain viable seeds. It is speculated that environmental conditions necessary to stimulate sexual reproduction are highly specific and not frequently encountered (Ahmad, Spencer, & Jasieniuk, 2008). Reproduction, therefore, is exclusively asexual through vegetative cloning of stems and rhizomes which separate during rain events and colonize land downstream (Else & Zedler, 1996). *Arundo* is present in almost every stream and river system in coastal southern California (Giessow et al., 2011).

Ecological Impacts of *Arundo* Invasion

Arundo donax threatens abiotic and biotic elements in the riparian ecosystems in which it gets introduced. Abiotic effects include: altered water flow, reduced water availability, increased sediment trapping, and increased fire frequency (Giessow et al., 2011). Studies of evapotranspiration rate (ET) show that *Arundo* transpires 20 – 40mm of water per day (Giessow et al., 2011). In one day, *Arundo* transpires roughly 10% of total annual precipitation in Southern California (NASCE, 1995). Increased wildfire disturbance and frequency are caused by *Arundo* biomass altering the vegetative canopy. Annual growth is roughly 400% higher than native riparian vegetation (Giessow et al., 2011). The tall, well-ventilated stand structure burns readily and transports fire into the crown of riparian forests (Brooks et al. 2004). After a wildfire, *Arundo* will resprout and spread faster than native vegetation (Figure 3). One year after a wildfire along the Santa Clara River, *Arundo* showed a 24% increase in relative cover resulting in a monotypic stand of 99% relative cover (Ambrose & Rundel, 2007).

Figure 3. *Arundo* regrowth at 6 - 12 inches one week after total canopy burn (Valen, 2014).

These abiotic influences on ecosystem functioning result in detrimental conditions for native species and improved conditions for the growth of *Arundo* leading to runaway growth and eventual conversion to monotypic stands.

In riparian zones, dense stands of *Arundo* eliminate understory vegetation and threaten the wildlife that depends on native shrubs, and annual herbs. *Arundo* provides no known habitat or forage value in Southern California (Giessow et al., 2011). The stems and leaves contain an array of inorganic noxious chemicals that reduce herbivory by most insects and grazers (Jackson & Nunez, 1964). Invertebrate composition was compared for aerial and ground dwelling arthropod populations in 100% *Arundo*, 100% native vegetation dominated by willow, and mixed stands along a stream in central California. Native vegetation supported twice the levels of aerial insects as the *Arundo* stands (Herrera & Dudley, 2003). The change of vegetation structure due to *Arundo* invasion reduces habitat value for those species whose diets are largely composed of riparian arthropod species, in particular many bird species. In addition, riparian systems are the primary corridors for wildlife to travel through urban landscapes, but dense stands of *Arundo* negatively impact passage.

Riparian Habitat Restoration and *Arundo* Removal Methods

Ecological restoration involves the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, 2004). Typical restoration projects follow a four step process: planning, implementation, monitoring, and evaluation (McDonald, Gann, Jonson, & Dixon, 2016).

In the project planning and design phase, stakeholder engagement efforts gain input from land and water managers, industry interest, and local communities. Existing regional conservation plans and projects are assessed in order to align project goals with the larger external context. An ecosystem baseline is established including existing native and non-native species present, those presumed to be absent, abiotic conditions, and drivers of damage or destruction. Targets, goals, and objectives are then developed to guide action and provide metrics for determining restoration success. Funding sources are identified and labor contracts are selected.

Riparian restoration projects are scheduled so that they have the least possible impact on sensitive species. Intensive restoration activities, such as vegetation removal and use of power equipment, are typically only permitted for implementation outside of the breeding seasons for sensitive species: February 15th through September 15th (County of San Diego, 1997). Migratory birds typically arrive and begin nesting in May and continue through July (Faber, Keller, Sands, & Massey, 1989).

Once the project has been designed and scheduled, extensive permits and permissions are required in order to work in riparian habitats. An encroachment permit may be required if the project area includes rivers, waterways, or floodways within or adjacent to federal and state authorized flood control projects (Griggs, 2009). The California Department of Fish and Wildlife must be informed of any restoration project that could significantly alter a stream, lake, or river through a submitted Lake or Streambed Alteration (LSA) notification (California Department of Fish and Wildlife, 2017). A LSA Agreement may be deemed necessary if the project might “substantially change or use any material from the bed, channel, or bank of, any river, stream, or lake”

(California Fish & Game Code, 2004). The federal Clean Water Act may require a permit from the Army Corps of Engineers if a restoration project discharges into wetlands, streams, rivers, and other U.S. waters (Clean Water Act of 1972). Additionally, the Regional Water Quality Control Board may require a Water Quality Certification and a determination on water discharge requirements (Clean Water Act of 1972). Depending on the funding source, projects must comply with the National Environmental Protection Act (NEPA) or the California Environmental Quality Act (CEQA). If a project takes place on federal land, it typically requires NEPA compliance. Funding from a state program, such as the Wildlife Conservation Board or Department of Water Resources Flood Protection Corridor Program, necessitates CEQA compliance (Griggs, 2009). NEPA or CEQA will typically require an archaeological survey or disclosure of known archaeological or cultural resources within or near the project area. County land use ordinances or voluntary neighbor agreements with adjoining private property may also be essential elements in granting permission for a project (Griggs, 2009). A Pesticide Use Permit is typically required for applying herbicide and requires application by personnel with a Qualified Applicator's License (QAL) along with mandatory documentation and reporting to the County Agricultural Commissioner, and California Department of Pesticide Regulation.

The implementation phase involves undertaking planned actions in such a way that no further or lasting damage is caused to the ecosystem. Removal of invasive species and prevention of their reintroduction and spread is a critical step in successful riparian habitat restoration (Griggs, 2009). A variety of methods are used to control *Arundo* depending on size and density of the stand, the type of terrain and the distance from other recourses and habitat types. Effective treatment of established *Arundo* requires killing the root mass (Bell, 1997). This almost inevitably requires the application of a systemic herbicide. Glyphosate, the active ingredient in RoundUp®, has proven to effectively kill *Arundo* when applied at specific times of the year and at appropriate concentrations (Spencer et al., 2008).

Best management practices call for a foliar application of a 2-5% percent solution of glyphosate mixed with a surfactant approved for aquatic ecosystems at a rate of 0.5 - 1 Liter/hectare applied post-flowering and pre-dormancy, when the plant is most actively translocating nutrients to the root, usually between August and November (Bell, 1997). To reduce the volume of herbicide used and lessen the risk of non-target application, a cut-stem treatment may be employed in sensitive habitats (Figure 4). Recently cut stems are treated within two minutes with a concentrated herbicide.

Figure 4. Ground crew worker applying herbicide to recently cut *Arundo* stems (ACE, 2015).

Cut-stem treatment has a higher labor cost and relies on more precise planning. Wide distributions of pure stands (>80% canopy cover) of *Arundo* or a mix with salt cedar (*Tamarix ramosissima*) have found the most cost effective methods to be aerial application of herbicide by helicopter, allowing for an application of up to 50 hectares per day (Figure 5)(Bell, 1997).

Figure 5. Standing *Arundo* biomass being prepared for foliar herbicide application (Giessow et al., 2010).

In less dense areas, or in those prohibitive of helicopter application, herbicide is typically applied by vehicle-based spray tanks or by hand. A similar method to cut-stem treatment involves removing all aboveground biomass and waiting 3-6 weeks for vegetative growth to about one meter tall. At this point a foliar spray of herbicide is applied (Bell, 1997). Dead canes that have previously been sprayed with herbicide are easier to remove and process and do not have the same potential for rooting in place as freshly-cut stalks.

Arundo biomass is typically removed by burning, heavy machinery, or hand cutting with chainsaws (Figure 6). Biomass removal is prescribed on sites where *Arundo* stand density prevents recovery of native vegetation, or where cut stalks might create blockages during flood events (Bell, 1997).

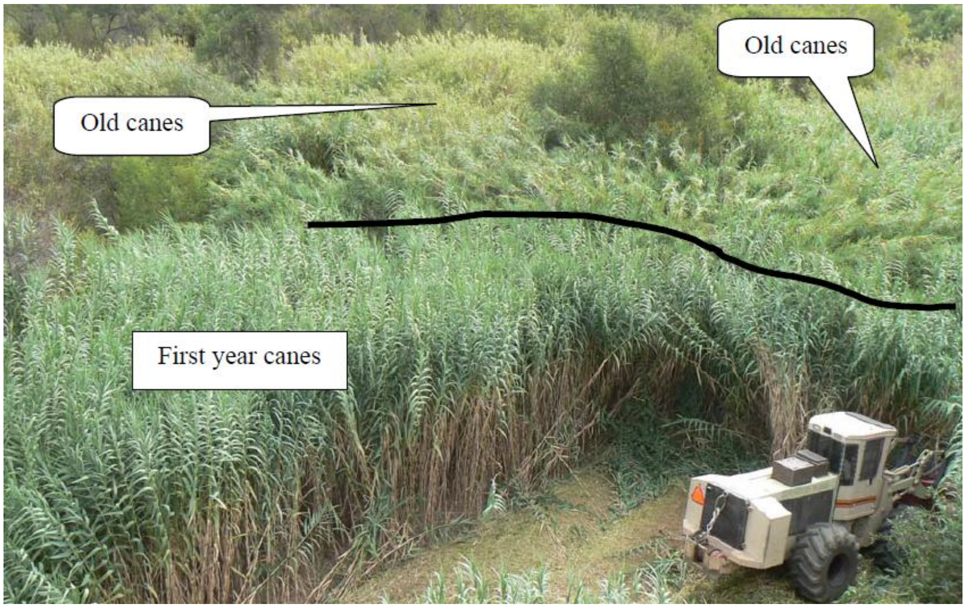


Figure 6. One year old *Arundo* stand being cleared by farm-style tractor for fuel break (Giessow et al., 2011).

Prescribed burns are cost-effective but can easily threaten native vegetation and are not practiced in urban areas. Chipping is costly but is the most efficient method for transporting biomass offsite. Transporting biomass by vehicle has been considered prohibitively expensive and only done as a last resort. Additionally, many landfills will not accept *Arundo* biomass (Quinn, Endres, & Voigt, 2014).

Once invaders such as *Arundo* and *Tamarisk* are eradicated, natural flood disturbance patterns lead to the rapid establishment of native species such as *Salix,* *Populus,* and *Baccharis*. Native plant recruitment can be successful with imported plant material and supplemental irrigation, but once established usually provide lesser habitat value as those naturally established plant communities (Bell, 1997). A comprehensive program of invasive species eradication that allows natural processes to influence the reestablishment of native plant species is the most cost effective method for restoring coastal riparian zones (Bell, 1997). Riparian species, adapted to periodic disturbance are limited not by their capacity to regenerate but by their ability to compete with invaders (Bell, 1997). Revegetation, while still commonly practiced, is considered by some to be redundant in areas where flood regimes and native species are present (Bell, 1997). In these circumstances, introduction of native plant material is only encouraged when necessary to introduce missing species or quickly close up strategic corridors (Bell, 1997).

Study Area

The study area covered 9 counties and 31 distinct coastal watersheds from Santa Cruz County in the north to the US-Mexican Border in the south (Figure 7). The total area covers roughly 22,000 square miles with an estimated population of 19 million people as of 2016 (U.S. Census Bureau, 2017). Coastal southern California has a Mediterranean climate, with hot and dry summers and mild winters. Average annual rainfall ranges from 10 -20 inches per year on the coast and up to 30 inches in coastal mountain ranges (NASCE, 1995). *Arundo* is documented to be distributed along 8,907 acres of coastal riparian corridor (Giessow, et al., 2011). These areas are wild and semi-wild drainages in close proximity to urban infrastructure. I estimated total standing biomass by multiplying *Arundo* distribution by mean stand density of 70%, mean above ground dry biomass of 69.14 US t/ac, and then adding 24% to account for estimated moisture content (Table 1).

Table 1. *Arundo* distribution and estimated standing biomass by watershed.

County	Density (ac)	Biomass (US t)
Orange	2,707	232,111
Ventura	1,499	128,513
San Diego	1,475	126,421
Monterrey	1,332	114,204
Los Angeles	197	16,873
Santa Barbara	36	3,069
San Luis Obisbo	10	849
San Benito	8	694
Santa Cruz	0.3	26
Total	7,264	622,761

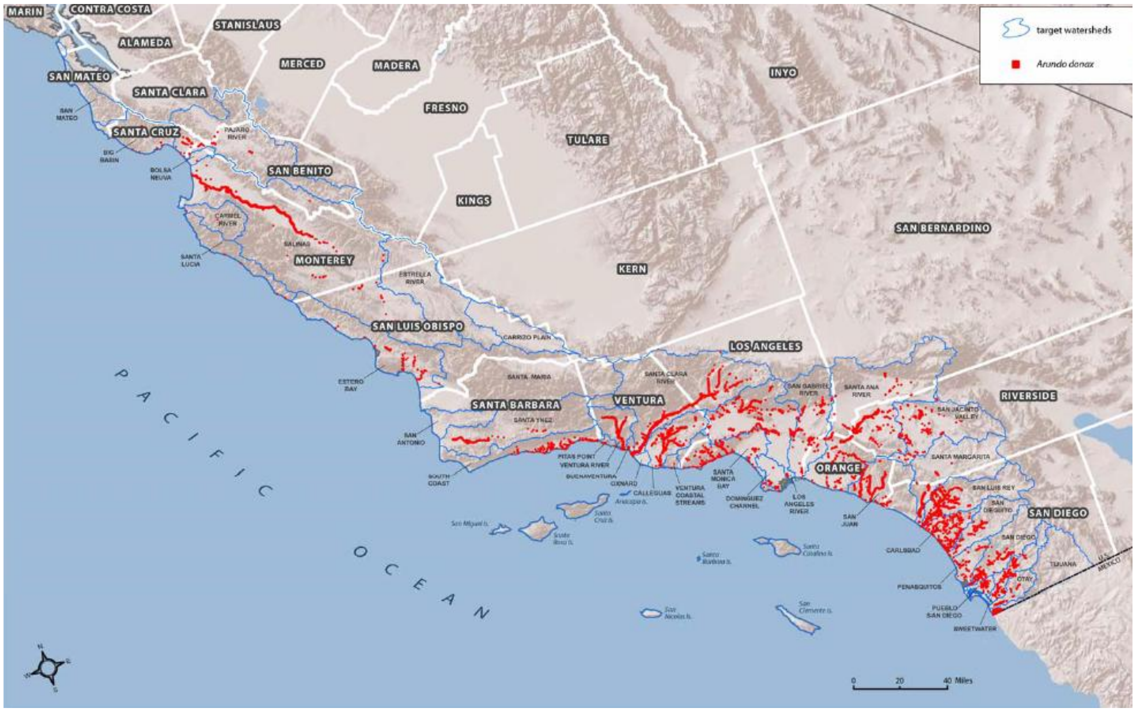


Figure 7. Distribution of *Arundo* within the study area (Giessow et al. 2011).

The vast majority of standing *Arundo* biomass is in the southern portion of the study area. The four southernmost counties, San Diego, Orange, Los Angeles, and Ventura, contain roughly 80% of the total biomass (Figure 8). Monterrey County contains the largest concentration *Arundo* of the five northern counties with roughly 115,000 US t of biomass or 18% of the total population. The four other northern counties, Santa Barbara, San Luis Obispo, San Benito, and Santa Cruz, cumulatively make up the remaining 1% of standing *Arundo* biomass within the study area.

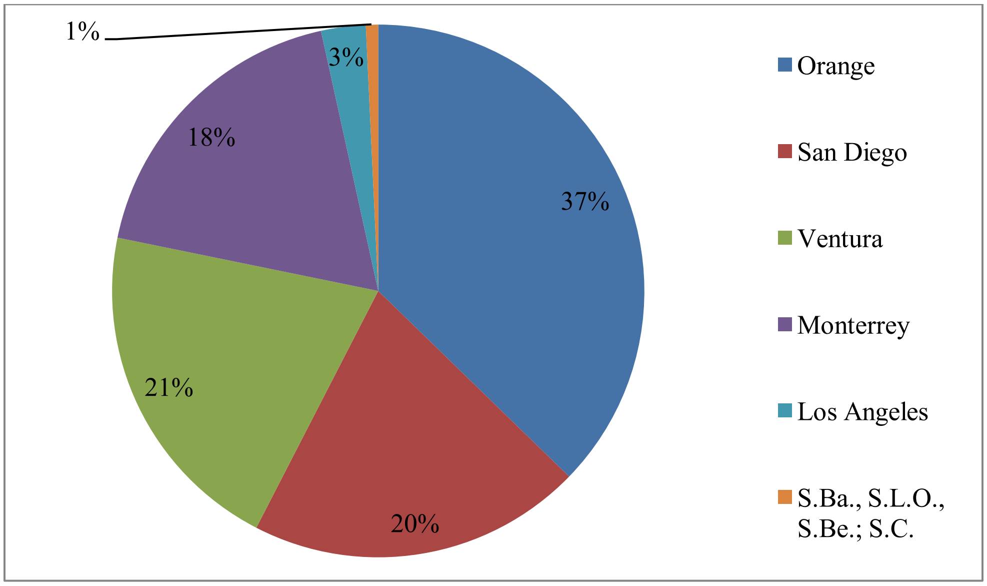


Figure 8. Proportional distribution of *Arundo* biomass by southern California county.

Economic Analysis of *Arundo donax*

A cost benefit analysis (CBA) is the most commonly used decision-making framework for assessing the desirability of a given action or intervention. CBAs use a monetary valuation of costs and benefits, which are then expressed as a ratio. This allows the impacts of invasive species, such as *Arundo*, to be synthesized into a common measure expressed in a dollar value.

Cost-benefit analysis usually accompanies a feasibility study (technical, financial, legislative, and organizational) of the project in which the CBA usually becomes the final synthesis (European Commission, 2009). There are three main parts of a CBA: technical analysis, financial analysis, and economic analysis. The first step of conducting a CBA involves placing the project within a context. A technical analysis is carried out to ensure the feasibility of the project (Irvin, 1978). The project often considers at least three alternatives: the "do nothing" alternative, the "do minimum" alternative, and the "do something" alternative (European Commission, 2009). The second step, the financial analysis, provides all the necessary data regarding inputs and outputs, their relative prices, and how they are distributed over time. This typically includes cash flows and the financial return on the initial investment. The third step, the economic analysis, combines values from the previous steps and incorporates externalities. The CBA typically concludes by presenting three basic measures of worth: net present value, benefit-cost ratio, and internal rate of return (Emerton & Howard, 2008).

Net present value (NPV) is the sum of discounted net benefits, calculated as benefits minus costs. A course of action is generally considered worthwhile if the NPV is positive. The benefit-cost ratio (BCR) is the ratio between total benefits and costs and shows the extent to which benefits exceed costs. A BCR that is greater than one signifies an action that is overall beneficial. Internal rate of return (IRR) is the discount rate at which a project's NPV becomes zero. An IRR above the discount rate means that the project generates returns in excess of those which could be expected from alternative investments (Irvin, 1978). If the IRR is lower than the rate of financial return, then the project would typically be more convenient for a private investor than for a public operator (European Commission, 2009).

Previous CBAs of *Arundo* Control Programs

Multiple CBAs have examined the potential net economic benefit of *Arundo* control programs, all of which show a positive benefit to cost ratio for removal. The water savings benefit of removing *Arundo* along the Rio Grande River in Texas showed a net benefit of four to eight times greater than the cost of removal (Seawright et al., 2009). Broader CBAs covering multiple factors on the Santa Clara and Santa Margarita watersheds in California found benefit to cost ratios of 3.9:1 and 1.1:1 respectively (Giessow et al., 2011).

The most thorough CBA to date for *Arundo donax* removal was conducted in 2011 by the California Invasive Plant Council for the State Water Resources Control Board (Giessow et al., 2011). Budget estimates from over 50 *Arundo* control projects in 11 Southern California watersheds were averaged to determine an overall removal cost of $25,000 per acre (Table 2). This is valuation was based on over fifty projects within nine watersheds and was subdivided into $5,000 for management and $20,000 for implementation. The subdivision was based on both written data and personal knowledge of typical cost subdivisions in proposals and reports. Program management activities included management of contractors, obtaining right of entry agreements, and permitting, among other activities. Implementation costs included, but were not limited to, treatment, biomass reduction, and re-vegetation. A 2-4:1 benefit to cost ratio was found for *Arundo* removal within the study area (Giessow et al., 2011).

Table 2. Existing program costs used to generate cost basis for Arundo control by watershed within the study area (Giessow et al., 2011).

Watershed	Treated net acres	Expenditure	Cost per acre
Calleguas	1.4	-	-
Carlsbad	98.7	$ 1,500,000	$ 15,201
Estero Bay	1.2	-	
Los Angeles River	16.3	$ 250,000	$ 15,379
Penasquitos	2.2	-	-
Salinas	106.4	$ 500,000	$ 4,700
San Diego	56.2	$ 1,000,000	$ 17,198
San Dieguito	89.8	$ 1,500,000	$ 16,701
San Juan	13.1	$ 250,000	$ 19,025
San Luis Rey	612.4	$ 7,500,000	$ 12,246
Santa Ana	1006.9	$ 40,000,000	$ 39,724
Santa Clara	0.3	-	-
Santa Margarita	684.7	$ 10,000,000	$ 14,605
Santa Monica Bay	0.3	-	-
South Coast	7.8	-	-
Sweetwater	5.7	-	-
Tijuana	41.1	$ 1,500,000	$ 36,496
Ventura River	117.4	$ 7,500,000	$ 63,909
Total	2861.9	$ 71,500,000	$ 24,983

Giessow et al. (2011) chose to use the mean rate of $25,000/ac as the estimated removal cost per acre. The median rate of $16,704/ac could just have easily been chosen. One project had a per acre cost of $63,000 while the rest were all less than half of that value; as low as $4,700 per acre. The projects, implemented over a period of 15 years, were taken as straight costs, without any discounting or depreciation over time. Although flawed, the Giessow cost estimate is the standard used for determining budgets for new projects and conducting economic analysis *Arundo* biomass removal (Quinn et al., 2014).

Benefits were calculated over a ten year period of *Arundo* eradication project implementation (Giessow et al., 2011). Estimates on future recruitment of *Arundo* over time have are also missing, although they have been incorporated in other CBA's for *Arundo* removal assessment (Seawright et al., 2009). More accurate system harvest estimates could be utilized with methodology familiar to forestry woody biomass harvest planning.

The CBA approach has a few major drawbacks when it comes to analyzing *Arundo* removal projects. The primary disadvantage of the CBA is the inherent difficulty in quantifying the benefits of *Arundo* removal in terms of a monetary value. While removal costs, and any potential gains from sale of biomass, exist as a dollar value, the environmental benefits of invasive species removal are inherently difficult to quantify. For example, Giessow et al. valued the reduced fire risk achieved from removing *Arundo* biomass as $2,500 per acre (2011). This value was taken as an arbitrary, albeit conservative, estimate of the valuation of *Arundo's* degradation of habitat during wildfire events. A second drawback is that a positive NPV and greater cost benefit ratio answer whether or not a given project should be undertaken, but CBA does not readily compare alternative interventions against one another (Tuominen et al., 2015).

Cost Effectiveness Analysis (CEA)

Cost effectiveness analysis (CEA) is an alternative method to CBA that quantifies benefits as a physical outcome per cost of achieving said outcome (European Commission, 2009). Ecological restoration and invasive species removal programs may be highly effective at meeting objectives, such as biomass reduction, and yet may not provide a good value for money. CEA can rank a set of possible interventions with similar objectives according to maximum desired result per unit cost.

A cost-effectiveness analysis will typically contain four main steps (European Commission, 2009). First, program objectives are determined. Next, public sector costs of the program are assessed. Thirdly, the impact of the program is measured. Finally, the cost per unit output and outcome are assessed, through the simple division of costs by outputs (European Commission, 2009). The final result of the CEA is a cost-effectiveness ratio that can be used as a single criterion for selecting invasive species removal program actions. CEA is preferred over CBA when the benefits or negative impacts of an analysis are typically non-monetary and difficult to value (Tuominen et al., 2015). CEA was therefore used as one method of evaluating the feasibility of using *Arundo* biomass in the pulp and paper industry.

Arundo donax Biomass as Pulp and Paper Supply Source

Among non-wood alternative crops, *Arundo* has proven to be a potentially valuable biomass and fiber crop for ethanol production, pulp and paper manufacturing, and wastewater treatment (Perdue, 1958; Quinn et al., 2014; Jakubowski, Casler, & Jackson, 2010). Plantation-style agriculture has proven an efficient means by which to harvest *Arundo* biomass. There exists, however, the potential for the plant to escape cultivation and invade previously pristine riparian systems. Quinn et al. (2014) conducted a simple assessment of harvesting *Arundo* biomass in wild ecosystems for ethanol production and deemed economically and technologically unfeasible. This is in large part due to the high costs of tooling ethanol production facilities to receive *Arundo* biomass and the high cost of long distance transport of biomass to relatively few existing facilities (Quinn et al., 2014).

In 1920, Wiedermann studied the papermaking potential of *Arundo* and determined that pulping yields were higher than typical non-wood fiber, yielding pulp strength similar to hardwood kraft species. Unbleached *Arundo* pulp was considerably bright, resulting in easy bleaching to high brightness levels (Wiedermann, 1920). Considerable efforts were made in the 1940s and 1950s in Hungary and Italy to cultivate and utilize *Arundo* in pulp and paper manufacture (Perdue, 1958). Despite its acceptable qualities, technological difficulties in the cultivation and harvesting of *Arundo* have prevented it from being more widely used (Lewis & Jackson, 2002). However, the Nile Fiber Pulp and Paper Company found that many of the attributes of *Arundo* pulp are suitable for direct substitution for hardwoods in existing kraft mills without major equipment changes (Lewis & Jackson, 2002). This thesis research took a new look at this neglected, but promising, alternative use for *Arundo* biomass.

Research Questions, Hypotheses, and Specific Aims

This research addresses a series of questions: Is it possible to completely fund the restoration of riparian habitats and make a profit by selling *Arundo donax* biomass to industry? The biofuel sector has closely examined wild stands of *Arundo* to determine if it could be successfully utilized. What does an analysis using similar methods reveal the profit potential of working within the pulp and paper supply chain? Further, if a wild harvest operation is not successful enough to fully fund itself, to what extent would it subsidize efforts that are already taking place? Ultimately, this study is aimed at determining whether or not selling *Arundo* biomass is a viable alternative to both benefit the environment and generate revenue.

The primary hypothesis examined in this research is that it is economically cost effective to fund the removal of *Arundo* by selling the vegetative biomass as a feedstock for the pulp and paper industry. The following specific research aims were pursued to test the hypothesis:

1. Determine the operational logistics, harvest costs, and profit estimates for a business that harvests wild *Arundo* and sells the biomass as a pulp and paper commodity.
2. Quantify potential cost savings to current restoration efforts by selling discarded *Arundo* biomass.
3. Develop a protocol for prioritizing *Arundo donax* removal projects based on the relative profitability of removal projects.

Chapter II

Methods

An initial technical analysis estimated the operational logistics, market prices, and production costs that would determine the profitability of an *Arundo donax* removal operation that employs the direct sale of biomass to paper mills. This information informed a financial appraisal of a hypothetical *Arundo* removal business. Sensitivity studies were conducted for optimal firm size and the effect of chip price and transport distance on profitability. A final economic analysis was performed in order to determine the overall benefit of selling *Arundo* biomass toward the goal of eliminating it completely within the study area.

Operational Logistics

Due to the sensitive nature of riparian habitats and the small diameter of individual *Arundo* canes, I determined that the ideal hypothetical harvest operation would utilize minimal heavy equipment (Giessow et al., 2011). The preferred operation consists of ground crews performing manual felling with chainsaws. Ground crews of 16 or fewer individuals would be organized into work teams each containing five or less individuals in which one worker cuts with a chainsaw, while the other team members pull, haul, and stack the cut *Arundo* cane (San Diego River Conservancy, 2009) (Figure 9).

Figure 9. Typical *Arundo donax* removal ground crew (ACE, 2015).

Wheeled skid-steer loaders equipped with grapple attachments would transport the cut *Arundo* canes from the felling location to a staging area (Figure 10).

Figure 10. Wheeled skidsteer to be operated with a grapple attachment (Ritchie Bros. Auctioneers, 2009).

Cut and stacked *Arundo* canes would then be processed by a commercial chipper that shoots chipped biomass into the transport vehicle. The two primary chipper configurations for the forestry sector are disc chippers and drum chippers (Figure 11). Although more expensive to own and operate, disc chippers are the most common types of chippers used to make wood chips for the pulping process due to their ability to be adjusted in order to create uniform chips of a specified size (Hellström, 2010).

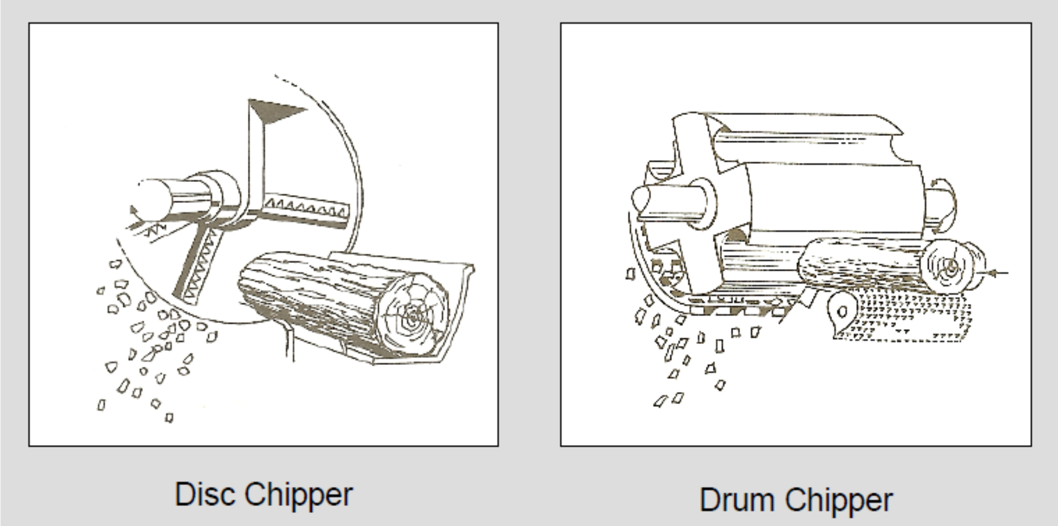


Figure 11. Disc and drum chipper configurations (RE Consulting, 2007).

When full, tractor units would connect to the chip vans and the chipped biomass would be hauled to the pulp mill. A set out truck, operated by a front line supervisor, stages the chipper and chip trailers so that biomass processing may continue with minimal interruptions.

Biomass harvesting, chipping, and transport operations were considered as separate production systems in order to identify the critical functions and bottlenecks in productivity (Table 3).

Table 3. Production systems, personnel, and their associated equipment types.

Harvest System		Chipping System		Transport System	
Equipment	Personnel	Equipment	Personnel	Equipment	Personnel
Chainsaw	5	Set out Truck	1	Tractor unit	1
Skidder	1	Chipper	2	Chip van	-
Set out truck	1				

Market Price Considerations

There is no existing market for bulk quantities of chipped *Arundo* biomass. When used as a feedstock for kraft paper, *Arundo* chips, cut to 7/8 inch length, cook more rapidly, require less chemical additives, and display no significant difference in rejects than both hardwood and softwood chips (Lewis & Jackson, 2002). Chipped *Arundo* “gate price”, or the price paid at the pulp mill, was estimated using the global price for hardwood chips reported by the FOEX Index.

FOEX Indexes Ltd. compiles wood and biomass price listings obtained directly from woodchip vendors, monthly prices from public sources, and data received from Wood Resources International (FOEX, 2017). International prices are recorded in US dollars per bone dry metric ton (BDMT). Although green *Arundo* canes can contain over 50% moisture content, kraft trials have shown moisture content or presteaming treatment to be have an insignificant effect on kraft cooking of chipped *Arundo* biomass (Williams & Biswas, 2010; Lewis & Jackson, 2002). Moisture content in green *Arundo* chips was therefore ignored in price estimates. Hardwood chip commodity price ($/BDMT) was multiplied by the constant 0.907185 to convert to U.S. dollars per short ton ($/US t). *Arundo* chips were estimated to sell at an average price of $151.84 ($/US t).

Production System Costs

The ideal organizational structure for an *Arundo* biomass removal operation reflected typical crew sizes and equipment utilized in woody biomass harvest operations for fuel or bioenergy applications (Keefe, Anderson, Hogland, & Muhlenfeld, 2014). Production costs were determined according to the “machine rate” method for cost estimation of logging operations (U.S. Forest Service, 2017; Miyata, 1980). Separate machine rates (MR) were calculated for each equipment type as the sum of fixed, variable, and labor costs described as a dollar value cost per hour of equipment operation.

Fixed costs, or ownership costs, accumulate with the passage of time, rather than rate of work (FAO, 1992). Operating costs are the variable costs associated with running each piece of equipment. Labor costs are additional variable costs that describe the costs required to keep machine operators on the job (Miyata, 1980). Once determined, equipment machine rates were totaled for each system and divided by the system production rate (US t/PMH) to determine the cost of production ($/US t) for each type of equipment (U.S. Forest Service, 2017). The summary table outlines the comprehensive production system cost calculations (Table 4).

Table 4. Comprehensive production system costs.

Preliminary Data	Harvest System		Chipping System		Transport System	
Equipment Variables	Chainsaw	Setout Truck	Skidder	Chipper	Tractor Unit	Chip Van
Scheduled Machine Hour	832	832	832	832	1456	1456
Utilization Rate	65%	25%	65%	75%	79%	79%
Productive Machine Hour	541	208	541	624	1144	1144
Retail Price	$ 520	$ 38,600	$ 50,000	$ 75,000	$ 150,000	$ 30,000
Sales Tax	$ 43	$ 3,185	$ 4,125	$ 6,188	$ 12,375	$ 2,475
Salvage Value	$ 113	$ 8,347	$ 10,782	$ 16,208	$ 32,246	$ 6,312
Economic Life (yr)	5	10	4	5	10	10
Initial Equipment Investment	$ 563	$ 41,736	$ 53,909	$ 81,042	$ 161,231	$ 31,560
Average Annual Investment	$ 383	$ 26,711	$ 37,736	$ 55,108	$ 103,188	$ 20,198
Depreciation	$ 90	$ 3,339	$ 10,782	$ 12,967	$ 12,898	$ 2,525
Interest	$ 15	$ 1,068	$ 1,509	$ 2,204	$ 4,128	$ 808
Insurance	$ 10	$ 668	$ 943	$ 1,378	$ 2,580	$ 505
Property Tax	$ -	$ -	$ 943	$ 1,378	$ 2,580	$ 505
Ownership Cost	$ 115	$ 5,075	$ 14,178	$ 17,926	$ 22,185	$ 4,343
Tire Unit Price	$ -	$ 175	$ 300	$ 175	$ 500	$ 500
Tire Life (hrs)	-	3000	3000	3000	5000	5000
Number of Tires	-	4	4	4	10	8
Tire Cost ($)	$ -	$ 49	$ 216	$ 146	$ 1,144	$ 915
M & R Rate	700%	75%	90%	100%	100%	0%
M & R Cost	$ 630	$ 2,504	$ 9,704	$ 12,967	$ 12,898	$ -
Fuel Type	Gasoline	Gasoline	Diesel	Diesel	Diesel	-
Consumption Rate (gal/hr)	2.5	0.6	2.8	2.3	6.7	-
Consumption Rate (mpg)	-	15.5	-	-	6	-
Average Speed (mph)	-	10	-	-	40	-
Fuel Cost	$ 4,117	$ 409	$ 4,611	$ 4,370	$ 23,223	$ -
Lubricant Cost	$ 1,515	$ 150	$ 1,697	$ 1,608	$ 8,546	$ -
Operating Cost	$ 6,262	$ 3,112	$ 16,228	$ 19,091	$ 45,812	$ 915
Crew Size	5	1	1	2	1	-
Wages	$ 17.72	$ 27.71	$ 20.18	$ 17.72	$ 21.17	$ -
Benefits	$ 8.51	$ 13.30	$ 9.69	$ 8.51	$ 10.16	$ -
Labor Cost	$ 109,098	$ 34,121	$ 24,849	$ 43,639	$ 45,619	$ -
Indirect Costs	$ 11,548	$ 4,231	$ 5,525	$ 8,066	$ 11,362	$ 526
Annual Cost	$ 127,023	$ 46,539	$ 60,780	$ 88,722	$ 124,978	$ 5,784
Machine Rate ($/PMH)	$ 235	$ 224	$ 112	$ 142	$ 109	$ 5

Preliminary Data

Specific determinations and assumptions were made about the hypothetical *Arundo* biomass production systems in order to calculate equipment and labor costs. Annual work time, referred to as scheduled machine hours (SMH), was determined by calculating the total number of working hours outside of the bird nesting season in southern California riparian habitats (Table 5).

Table 5. Riparian habitat work season from September 15th - February 15th.

	Calendar days	Weekend days	Holidays	Work days
September	16	5	0	11
October	31	9	1	21
November	30	8	2	20
December	31	10	1	20
January	31	8	2	21
February	15	4	0	11
Total				104

Federal holidays from (U.S. Postal Service, 2017).

Harvest and chipping operations worked standard 8 hour days. Drivers, however, were scheduled to drive for 11 hours out of a 14 hour shift per 24-hour day (Code of Federal Regulations, 2017). Work hours (SMH) were further divided into productive and nonproductive time (Wenger, 1984). Productive machine hours (PMH) are defined as the time spent by a machine performing its primary task as well as time spent on support activities, such as refueling or loading and unloading trailers. Nonproductive time was assumed to include delays such as scheduled and unscheduled maintenance or a halt in production due to management issues such as bottlenecks in production caused by mismatched equipment processing speeds (Wegner, 1984). The ratio of productive time to scheduled time is utilization. Average utilization rates (UR) were taken from Brinker, Kinard, Rummer, & Lanford, (2002) for the harvest and chipping systems. The transport system UR was set at 79%, determined by dividing the drive hours per day into the total transport shift length. Equipment UR was multiplied by the annual SMH in order to determine the annual productive machine hours for each equipment type (Table 6).

Table 6. Annual maximum productive machine hours (PMH) per equipment type.

Equipment	SMH	UR	PMH
Chainsaw	832	65%	541
Skidder	832	65%	541
Set Out Truck	832	25%	208
Chipper	832	75%	624
Tractor Unit	1456	79%	1144
Chip Van	1456	79%	1144

The initial investment for each piece of equipment was calculated as the retail price plus sales tax, minus the cost of tires (Table 7). Equipment list prices were obtained from dealers and manufacturers during the spring of 2017. All equipment was assumed to be purchased within the study area in California. Sales tax was estimated as 8.25%: the average sales tax rate among all counties within the study area (Walczak & Drenkard, 2017). Annual tire costs are variable, dependent upon use of equipment, and were therefore subtracted from the initial investment. Initial equipment investment costs ranged from $560 for a chainsaw up to $160,000 for a single tractor unit.

Table 7. Initial investment per unit by equipment type.

Equipment	Retail Price	Sales Tax	Tire Cost	Total
Chainsaw	$ 520	$ 43	$ -	$ 563
Skidder	$ 50,000	$ 4,125	$ 216	$ 53,909
Set Out Truck	$ 38,600	$ 3,185	$ 49	$ 41,736
Chipper	$ 75,000	$ 6,188	$ 146	$ 81,042
Tractor Unit	$ 150,000	$ 12,375	$ 1,144	$161,231
Chip Van	$ 30,000	$ 2,475	$ 915	$ 31,560

(Caterpillar 2015; Kelly Blue Book 2017; Jackson et al., 2010)

The preliminary estimates required to determine equipment costs include the initial investment, salvage values, equipment life, and average annual investment (Table 8). Salvage values were described as the dollar amount that equipment can be sold for at the time of disposal (Miyata, 1980). All salvages values were estimated as 20% of purchase price (Brinker et al., 2002). Economic life estimates, in years, were determined by dividing useful life hours specified by the manufacturer by the annual scheduled machine hours (SMH) for the entire operation (Caterpillar, 2015). An average annual investment value (AAI) was determined for each equipment type in order to estimate insurance and taxes (Bushman, 1988). AAI was calculated as follows:

$$AAI = \frac{(P - S)(N + 1)}{(2N) + S}$$

Where P = initial investment; S = salvage value; & N = economic life in years.

Table 8. Preliminary data for equipment machine rate estimation.

Equipment	Initial Investment	Salvage Value	Economic Life (yrs)	AAI
Chainsaw	$ 563	$ 113	5	$ 383
Skidder	$ 53,909	$ 10,782	4	$ 37,736
Set Out Truck	$ 41,736	$ 8,347	10	$ 26,711
Chipper	$ 81,042	$ 16,208	5	$ 55,108
Tractor Unit	$ 161,231	$ 32,246	10	$103,188
Chip Van	$ 31,560	$ 6,312	10	$ 20,198

Ownership Costs

Fixed ownership costs were calculated as the sum of interest, insurance, taxes, and depreciation (Table 9). Interest is defined as the rental amount charged by a lender for the use of money (Thuesen, Fabrycky, & Thuesen, 1977). An interest rate of 4 percent, annual percentage rate (APR) was selected as an estimate based upon the current average interest rate on a 30-year fixed mortgage (Bankrate, 2017). Equipment liability and comprehensive insurance coverage costs vary by locality, equipment type, and size of operation, but a standard 2.5% of AAI was used for estimation purposes (Miyata, 1980). An additional property tax rate of 2.5% of AAI was charged on heavy equipment, excluding chainsaws and pickup trucks (Miyata, 1980).

Depreciation, defined as the reduction in value of a piece of equipment over time, was computed using a straight line methodology that assumes equipment value reduces at a constant rate for each year over its economic life (Miyata, 1980). This decline in value is not an “out-of-pocket” cost in the sense that a cash payment is made. It simply reflects a loss in value over time. Straight line depreciation was calculated as follows:

$$Depreciation\ (D) = \frac{P - S}{N}$$

Where P = initial investment; S = salvage value; and N = economic life in years.

Table 9. Annual ownership costs per unit by equipment type.

Equipment	Type	Interest	Insurance	Property Tax	Depreciation	Total
Chainsaw	Light	$ 15	$ 10	$ -	$ 90	$ 115
Skidder	Heavy	$ 1,509	$ 943	$ 943	$ 10,782	$14,178
Set Out Truck	Light	$ 1,068	$ 668	$ -	$ 3,339	$ 5,075
Chipper	Heavy	$ 2,204	$ 1,378	$ 1,378	$ 12,967	$17,926
Tractor Unit	Heavy	$ 4,128	$ 2,580	$ 2,580	$ 12,898	$22,185
Chip Van	Heavy	$ 808	$ 505	$ 505	$ 2,525	$ 4,343

Operating Costs

Equipment operating costs are variable costs that typically change in direct proportion to hours of operation or use (Miyata, 1980). Some operating costs, however, such as fuel consumption, can be within the control of the operator or owner. Total operating costs were determined as the sum of the costs of tires, fuel, lubricants and oil, and maintenance and repair. Annual tire costs, initially subtracted from initial equipment investment, were calculated as follows:

$$Tire\ cost\ = \frac{P_t \times\ Q\ \times PMH}{N_t}$$

Where P_t = tire unit price; Q = tire quantity; PMH = productive machine hour; and N_t = tire life (Table 10).

Table 10. Tire costs per unit by equipment type.

Equipment	PMH	Unit Price	Quantity	Life (hrs)	Tire Cost
Chainsaw	541	$ -	$ -	-	$ -
Skidder	541	$ 300	$ 4	3000	$ 216
Set Out Truck	208	$ 175	$ 4	3000	$ 49
Chipper	624	$ 175	$ 4	3000	$ 146
Tractor Unit	1144	$ 500	$ 10	5000	$ 1,144
Chip Van	1144	$ 500	$ 8	5000	$ 915

Fuel costs were determined by multiplying fuel price per gallon, fuel consumption rate and productive machine hours (Table 11). Light equipment was priced using gasoline while heavy equipment utilized diesel fuel. Fuel prices were taken from values published by the U.S. Energy Information Administration (2017) for the state of California. Fuel consumption rate estimates were provided by equipment manufacturers (Art's Lawnmower Shop, 2017; Caterpillar, 2015; Kelly Blue Book, 2017; Jackson et al., 2010). For the transportation system, fuel costs are a significant part of the machine rate, each tractor unit requiring roughly 5 times greater annual fuel expenses than every other piece of equipment. Lubricant costs included the cost of engine oil, hydraulic oil, and other lubricants and was estimated using a standard 36.8% percent of annual fuel costs (Brinker et al., 2002).

Table 11. Fuel costs per unit by equipment type.

Equipment	Fuel Type	Price ($/gal)	Consumption (gal/hr)	PMH	Fuel Cost	L & O Cost
Chainsaw	Gasoline	$ 3.05	2.5	541	$ 4,117	$ 1,515
Skidder	Diesel	$ 2.93	2.8	541	$ 4,440	$ 1,634
Set Out Truck	Gasoline	$ 3.05	0.6	208	$ 409	$ 150
Chipper	Diesel	$ 2.93	2.3	624	$ 4,208	$ 1,549
Tractor Unit	Diesel	$ 2.93	6.7	1144	$ 22,361	$ 8,229

Maintenance and repair (M&R) estimates were taken from Wenger (1984) as percentages of equipment depreciation (Table 12). Chainsaw M&R were estimated at 700% of depreciation. Chip vans were not assigned a value for maintenance and repair. All other equipment types ranged from 75% to 100% of depreciation for M&R costs.

Table 12. Annual maintenance and repair (M&R) costs per unit by equipment type.

Equipment	Depreciation	M & R (%)	M & R Cost
Chainsaw	$ 90	700%	$ 630
Skidder	$ 10,782	90%	$ 9,704
Set Out Truck	$ 3,339	75%	$ 2,504
Chipper	$ 12,967	100%	$ 12,967
Tractor Unit	$ 12,898	100%	$ 12,898
Chip Van	$ 2,525	0%	$ -

The chip van, lacking an engine, was not assigned estimates for fuel or lubricants. Only tire replacement costs of $915 per year were accounted for chip van operating costs. Total annual operating costs per equipment type were calculated as the sum of all aforementioned operating costs (Table 13).

Table 13. Annual operating costs per unit by equipment type.

Equipment	Tires	Fuel	L & O	M & R	Total
Chainsaw	$ -	$ 4,117	$ 1,515	$ 630	$ 6,262
Set Out Truck	$ 49	$ 409	$ 150	$ 2,504	$ 3,112
Skidder	$ 216	$ 4,611	$ 1,697	$ 9,704	$16,228
Chipper	$ 146	$ 4,370	$ 1,608	$12,967	$19,091
Tractor Unit	$1,144	$23,223	$ 8,546	$12,898	$45,812
Chip Van	$ 915	$ -	$ -	$ -	$ 915

Labor Costs

Labor costs are variable costs that were accounted separately from operating costs because employees were assumed to be paid for an entire workday regardless of whether or not specific pieces of equipment were operating at a given time. Employee wages, benefits, and labor burden were multiplied by the annual working hours (SMH) to calculate equipment labor costs (Table 14). Position title and wages were determined for each equipment type as described by the Bureau of Labor Statistics (2015) for the state of California. Benefits and labor burden percentage were calculated as 48% of hourly wages (Stone, 2008).

Ground crew workers, operating chippers, bundling and stacking biomass, and feeding the chipper, were given an hourly wage and benefit rate of $26.23. Equipment operators operating skid steers and performing in-field equipment troubleshooting received $29.87 in hourly wages and benefits. First-line supervisors, operating set out trucks and overseeing crew operations, earned $41.01 in hourly wages and benefits. Driver wages and benefits were $31.33 per hour (Bureau of Labor Statistics, 2015).

Table 14. Annual labor costs per unit by equipment type.

Equipment	Position	Wage	Benefits	Quantity	SMH	Total ($/yr)
Chainsaw	Ground Crew Worker	$ 17.72	$ 8.51	5	832	$ 109,098
Set Out Truck	First-Line Supervisor	$ 27.71	$ 13.30	1	832	$ 34,121
Skidder	Equipment Operator	$ 20.18	$ 9.69	1	832	$ 24,849
Chipper	Ground Crew Worker	$ 17.72	$ 8.51	2	832	$ 43,639
Tractor Unit	Driver	$ 21.17	$ 10.16	1	1456	$ 45,619

Total annual equipment costs per unit type were determined as the sum of ownership, labor, and operating costs (Table 15). An additional 10% indirect cost was added to each piece of equipment to account for miscellaneous expenses (U.S. Forest Service, 2017). The chainsaw, with an operator plus four additional ground crew workers, and the tractor unit, had the highest annual per unit equipment cost at $127,000 and $125,000 respectively. The chipper, skidder, and set out truck had annual equipment costs of roughly $90,000, $60,000, and $45,000 respectively.

Table 15. Total annual equipment costs per unit by equipment type.

Equipment	Ownership	Operating	Labor	Indirect	Total
Chainsaw	$ 115	$ 6,262	$109,098	$ 11,548	$127,023
Set Out Truck	$ 5,075	$ 3,112	$ 34,121	$ 4,231	$ 46,539
Skidder	$ 14,178	$ 16,228	$ 24,849	$ 5,525	$ 60,780
Chipper	$ 17,926	$ 19,091	$ 43,639	$ 8,066	$ 88,722
Tractor Unit	$ 22,185	$ 45,812	$ 45,619	$ 11,362	$124,978
Chip Van	$ 4,343	$ 915	$ -	$ 526	$ 5,784

Machine rates, describing the hourly costs of operating each type of equipment ($/hr), were calculated by dividing total annual equipment costs by annual productive machine hours (Table 16). Each chainsaw had a machine rate of $235/hr. The set out truck, skidder, and chipper machine rates were $224, $112, and $142 dollars per hour respectively.

Table 16. Machine rates for all equipment types in all production systems.

Equipment	Annual Cost	PMH	Machine Rate
Chainsaw	$ 127,023	541	$ 235
Skidder	$ 60,780	541	$ 112
Set Out Truck	$ 46,539	208	$ 224
Chipper	$ 88,722	624	$ 142
Tractor Unit	$ 124,978	1144	$ 109
Chip Van	$ 5,784	1144	$ 5

Transport System Logistics

There are a number of common configurations for the transport of chipped woody biomass. The optimum configuration is the transport system with the least costs associated with transporting a given amount of biomass. Two primary transport configurations are chip vans and set out bins, each of which have various carrying capacities (Figure 12).

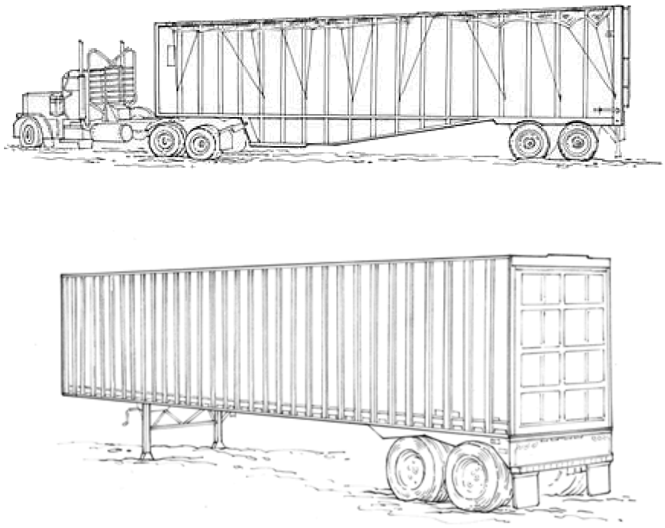


Figure 12. Diagram of high-capacity "possum belly" trailer (above) and standard chip van (below) (Forests and Rangelands, 2017).

Transport system cost estimates were influenced by payload and cycle time. Payload was defined the maximum amount of *Arundo* biomass that could be physically and legally hauled in a single trip. The cycle time was the total time it takes for a chip van to load, drive to the pulp mill, unload the biomass, and return to the harvest location. Total transportation costs for each county were determined by multiplying the available payloads by the cycle time to calculate the total required PMH for the area. Total PMH was then multiplied by the transportation system machine rate ($/PMH) to derive the total transportation cost per county. The profitable haul (PH) distance from the study area to the pulp mill was calculated in order to determine the break-even point at which direct sale of biomass becomes profitable.

Maximum Payload

California road transport laws limit the maximum size and weight of trucks (Table 17). The goal for the biomass transport system is to carry the maximum possible payload, either by weight or by volume, in order to minimize costs (Scion, 2009).

Table 17. California legal weight and size limits (California Vehicle Code, 1982).

Gross Vehicle Weight (lb)	80,000
Width (in)	102
Height (ft)	14
Straight truck (ft)	40
Tractor & Semi-Trailer (ft)	65

A transport vehicle is full when it either “bulks out” or “weighs out”. Bulking out is when the transport vehicle runs out of volume before maximum payload is reached. Weighing out is when the vehicle reaches maximum payload before the truck is full (Scion, 2009). Whether a truck reaches maximum weight or maximum volume first depends on the bulk density of the material being transported. Maximum payload was determined by calculating the maximum payload by weight and maximum payload by volume and selecting the lesser of the two values. Parameters were defined in Table 18 for the following equations:

Table 18. Parameters for determining transportation system maximum payload.

Item	Parameter
Maximum payload	MP
Maxmum payload by weight	MP_w
Gross vehicle weight	GVW
Vehicle tare weight	W_T
Maximum payload by volume	MP_v
Volume of chip container	V
Wet bulk density of *Arundo* chips	WBD

The maximum payload by weight (MP_w) was calculated as follows:

$$MP_w = GVW - T = 40\ US\ t - 17.09\ US\ t$$

$$MP_w = 22.91\ US\ t$$

The legal maximum gross vehicle weight (GVW) in the state of California is 40 US t (California Vehicle Code, 1982). The estimated vehicle tare weight is 17.09 US t (Scion, 2002). Total maximum payload by weight was 22.91 US t. Maximum payload volume (MP_v) was calculated as follows:

$$MP_v = \frac{V \times WBD}{2000} = \frac{3{,}557\ ft^3 \times 12.5 \frac{lb}{ft^3}}{2000}$$

$$MP_v = 22.23\ US\ t$$

The maximum chip van volume was estimated at 132 cubic yards (yd^3) (Scion, 2002) (Table 19).

Table 19. Load space dimensions for possible truck configurations.

Truck Type	Truck				Trailer				Total V (yd^3)
	L (yd)	W (yd)	H (yd)	V (yd^3)	L (yd)	W (yd)	H (yd)	V (yd^3)	
Chip Small	6.3	2.5	2.5	40.2	10.4	2.5	2.5	65.8	106
Chip Large	6.3	2.6	3.1	49.9	10.4	2.6	3.1	81.8	132
Bin Small	6.1	2.5	2.5	38.8	9.1	2.5	2.5	57.5	96
Bin Large	6.1	2.5	3.0	45.5	9.1	2.5	3.0	67.5	113

Where L = length, W = width, H = height, & V = volume (Scion, 2009).

Wet bulk density is a measurement of the weight of green *Arundo* chips within a given volume. As a physical property, bulk density depends on many factors, including material composition, particle shape, particle size distribution, and moisture content (Sokhanhanj et al., 2008). The bulk density of compacted green *Arundo* chips has been measured at 12.5 $\frac{lb}{ft^3}$ (Lewis & Jackson, 2002). Maximum weight and maximum volume values were compared to determine maximum payload (*MP*).

$$MP_w = 22.91\ US\ t > 22.23\ US\ t = MP_v$$

$$MP = 22.23\ US\ t$$

The maximum chip van payload was limited by the lesser value of the maximum payload by volume at 22.23 US t per truck (Table 20).

Table 20. Maximum payload of chip van and set out bin transport configurations.

Truck Type	Tare W (US t)	Max GVW (US t)	MPw (US t)	Truck V (yd3)	MPv (US t)
Chip	17.09	40	22.91	131.74	22.23
Bin	22.05	40	17.95	112.97	19.06

Distance to Pulp Mill

Locations of active pulp mills in California were identified using public data from the U.S. Forest Service (U.S. Forest Service, 2005). California pulp mills are located in the northern part of the state where the majority of commercial logging takes place (Table 21). Several facilities throughout California receive wood chips for alternative uses, including power generation, but these were excluded from this study. Two pulp facilities that manufacture kraft paper were located just south of the US-Mexico border in Mexicali, Baja California.

Table 21. Facilities that receive chipped woody biomass in proximity to the study area.

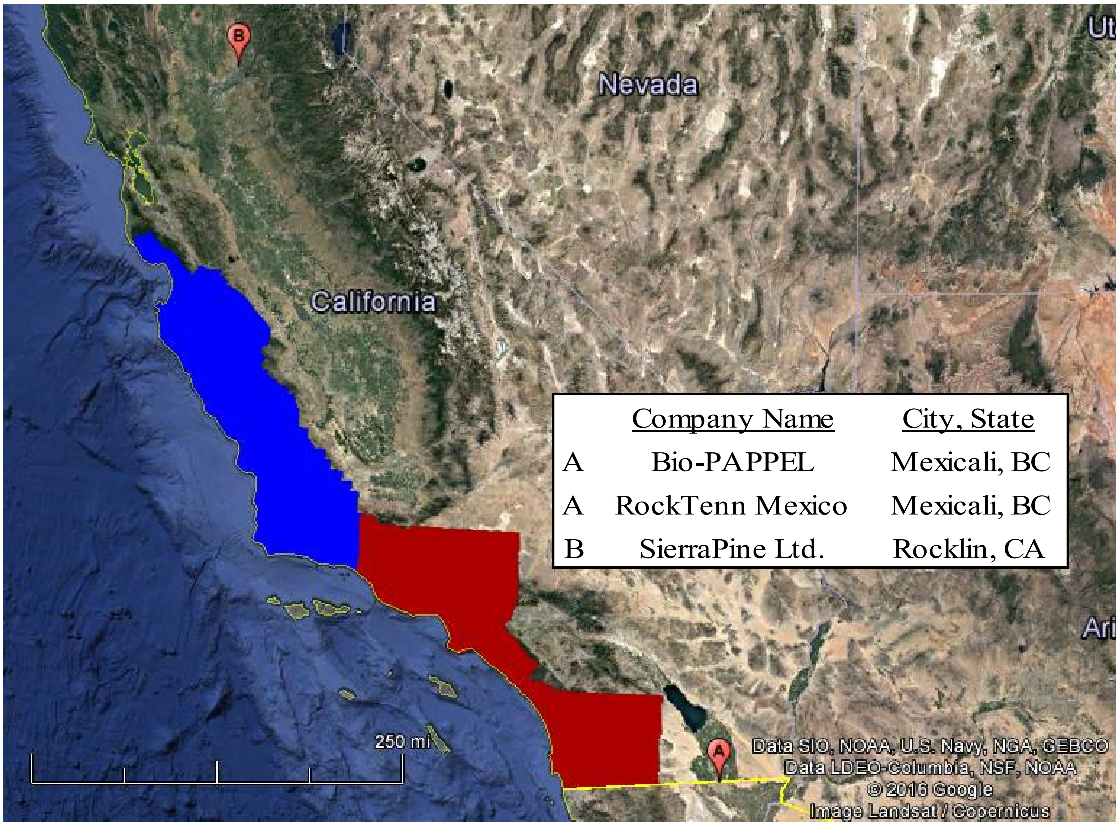
Company Name	Type	City, State
Abitibi-Consolidated Inc.	Pulp	Snowflake, AZ
Stockton Pacific Enterprises	Pulp	Samoa, CA
Shasta Paper Co.	Pulp	Anderson, CA
Masonite Corp.	Pulp	Ukiah, CA
SierraPine Ltd.	Pulp	Rocklin, CA
RockTenn Mexico	Pulp	Mexicali, BC
Bio-PAPPEL	Pulp	Mexicali, BC
SierraPine Particleboard	Particleboard	Martell, CA
Dover Resources	Pellets	Stockton, CA
GreenLeaf Power	Power	Mecca, CA
Merced Power	Power	Merced, CA
Rio Bravo Biomass Power	Power	Fresno, CA
Chowchilla Biomass Power	Power	Chowchilla, CA
Mt. Poso Cogeneration	Power	Bakersfield, CA

Estimated distances from the standing *Arundo* biomass to the closet pulp mill were determined using data from Google Maps (Google, n.d.). The closest city within the specific watershed was entered as the starting destination (Table 22). Known pulp mill locations were then entered in order to determine the shortest driving distance. Watershed driving distances were then averaged by county.

Table 22. Estimated distances from *Arundo* stand to nearest pulp mill.

County	Watershed	Closest City	Mill location	Distance (mi)
Santa Cruz	Big Basin	Santa Cruz	Rocklin, CA	171
San Benito	Pajaro River	Hollister	Rocklin, CA	181
Monterrey	Bolsa Nueva	Moss Landing	Rocklin, CA	190
	Salinas	Salinas	Rocklin, CA	195
	Santa Lucia	Big Sur	Rocklin, CA	290
San Luis Obisbo	Estero Bay	San Luis Obisbo	Rocklin, CA	326
	Santa Maria	Santa Maria	Rocklin, CA	345
Santa Barbara	Santa Ynez	Santa Ynez	Rocklin, CA	375
	South Coast	Santa Barbara	Rocklin, CA	408
Ventura	Pita’s Point	Ventura	Mexicali, BC	303
	Ventura River	Ventura	Mexicali, BC	303
	Buena Ventura	Ventura	Mexicali, BC	303
	Santa Clara River	Santa Clarita	Mexicali, BC	292
	Calleguas	Point Mugu	Mexicali, BC	275
	Ventura Coastal Streams	Point Mugu	Mexicali, BC	275
Los Angeles	Santa Monica Bay	Santa Monica	Mexicali, BC	242
	Dominguez Channel	Long Beach	Mexicali, BC	221
	Los Angeles River	Los Angeles	Mexicali, BC	228
	San Gabriel River	El Monte	Mexicali, BC	215
Orange	Santa Ana River	Corona	Mexicali, BC	182
	San Juan	San Juan Capistrano	Mexicali, BC	181
San Diego	Santa Margarita	Camp Pendleton	Mexicali, BC	166
	San Luis Rey	Oceanside	Mexicali, BC	156
	Carlsbad	Carlsbad	Mexicali, BC	150
	San Dieguito	Rancho Penasquitos	Mexicali, BC	130
	Penasquitos	Del Mar	Mexicali, BC	123
	San Diego	Mission Valley	Mexicali, BC	124
	Pueblo San Diego	San Diego	Mexicali, BC	122
	Sweetwater	Jamacha	Mexicali, BC	112
	Otay	Chula Vista	Mexicali, BC	115
	Tijuana	Imperial Beach	Mexicali, BC	117

Northern counties, from Santa Cruz to Santa Barbara, were closest to the mill in Rocklin, CA, while counties from Ventura south to San Diego were closest to the pulp mill in Mexicali, Baja California (Figure 13). Estimated distances to the nearest pulp mill ranged from 131.5 miles in San Diego County to 391.5 miles in Santa Barbara County.



	Company Name	City, State
A	Bio-PAPPEL	Mexicali, BC
A	RockTenn Mexico	Mexicali, BC
B	SierraPine Ltd.	Rocklin, CA

Figure 13. Pulp mill locations in proximity to the study area.

Cycle Time

Transportation cycle time was calculated as the sum of loading, hauling, unloading, and return times. Parameters for cycle time calculations are listed in Table 23.

Table 23. Parameters for transport system cycle time calculations.

Item	Parameter
Cycle time	t_C
Distance	D
Speed	S
Loading time	t_L
Chipper production rate	PR_c
Maximum payload	MP
Trailer hitch time	t_h
Unloading time	t_U
Dump time	t_D
Waiting time	t_W

Cycle time was expressed with the following equation:

$$t_C = 2\left(\frac{D}{S}\right) + t_L + t_U = 2\left(\frac{D}{40}\right) + 1.98$$

Haul and return times were determined by dividing distance to the pulp mill by average travel speed (Assakkaf, 2003). Average travel speed for a loaded tractor-trailer was estimated at 40 mph (Ford Torrey & Murray, 2014; Hertz, 1991). Loading time was calculated as follows:

$$t_L = \frac{PR_c}{MP} + t_h = \frac{34}{22.23} + 0.17 = 1.70\ hrs.$$

Unloading time was calculated as follows:

$$t_U = t_D \times t_W = 0.03 + 0.25 = 0.28hrs.$$

The number of payloads of standing *Arundo* biomass in each county was calculated by dividing total biomass by the maximum payload (Table 24). Total transportation costs for each county were determined by multiplying the available payloads by the cycle time to derive the total required PMH for the area. Transport PMH by county ranged from 12 transport hours in Santa Cruz County to 115,419 total transport machine hours in Orange County.

Table 24. Transport system logistics and total productive machine hours by watershed.

County	Biomass (US t)	Payloads	Mill Location	Distance (mi)	Cycle Time (hr)	Total PMH
Santa Cruz	26	1	Rocklin, CA	171.0	10.5	12
San Benito	694	31	Rocklin, CA	181.0	11.0	345
Monterrey	114,204	5,137	Rocklin, CA	225.0	13.2	67,962
San Luis Obisbo	849	38	Rocklin, CA	335.5	18.8	716
Santa Barbara	3,069	138	Rocklin, CA	391.5	21.6	2,976
Ventura	128,513	5,781	Mexicali, BC	291.8	16.6	95,796
Los Angeles	16,873	759	Mexicali, BC	226.5	13.3	10,098
Orange	232,111	10,441	Mexicali, BC	181.5	11.1	115,419
San Diego	126,421	5,687	Mexicali, BC	131.5	8.6	48,647

Optimum Firm Size

The optimal firm size of a company in a given industry is that which results in the lowest production costs per unit of output (Canbäck, 2002). The optimum firm size is achieved when the benefits from internal economies of scale, such as specialized equipment, are fully enjoyed without the negative aspects of company size, such as reduction in output and duplication of effort, yet beginning to accrue.

The production rate for a forestry system composed of several machines is limited to the least productive function in the system (Stokes & Hartsough, 1993). Functions within the system are usually balanced by either increasing the quantity, the productivity, or the scheduled machine hours of the limiting function. Balanced systems typically have the lowest cost (Stokes & Hartsough, 1993).

For the *Arundo* harvest system, the production rate increased in a positive correlation to the ground crew size. Additionally, an increased production rate increased the chipper utilization rate toward its maximum average rate of 75% due to reduced waiting time for biomass to become available for processing. A sensitivity analysis was conducted in order to determine the optimum firm size for *Arundo* removal operations. Annual SMH was dictated by the maximum working days outside of the bird nesting season and could not reliably be increased. Many contracts for *Arundo* removal allow up to three separate chainsaw crews into sensitive habitat at any given time (San Diego River Conservancy, 2009). Hypothetical harvest system equipment and crew quantities were stratified from one to three chainsaw ground crews. The quantity of ground crewmembers in each work team was reduced as the total number of teams increased. This is because in a real-world setting the support crew would shift to assist the chainsaw operator that needed the greatest assistance. Multiple work teams would not realistically require four support staff per chainsaw. Five workers were employed for the firm with one ground crew, four workers each for two ground crews, and three workers for three ground crews (Table 25). The chipper utilization rate was adjusted to the nearest 0.25% in order to most closely match the harvest system production rate. Production rates were estimated in short tons per hour (US t/PMH) according to various sources (Behjou et al., 2009; Caterpillar, 2015; Pitts Enterprises, Inc., 2013; Smidt & Mitchell, 2014).

Each chainsaw had an estimated average production rate of 5.62 US t per hour or 3,038 US t annually (Behjou et al., 2009). The chipper productivity was estimated at 34 US t per PMH with an annual maximum production of 21,216 US t (Smidt & Mitchell, 2014). Harvest and chipping system machine rates were calculated as the equipment and labor costs for each firm size. The harvest system machine rate was calculated as the sum of the costs for all chainsaws, added together along with a single skidder. The chipping system contained a single chipper at variable utilization rates added to the machine rate for a single setout truck.

Table 25. Annual production (US t) of *Arundo* biomass at variable firm sizes.

Chainsaw Quantity	1	2	3
Work Crew Size	5	4	3
Chipper UR	11%	22%	32%
Annual Production	3,041	6,082	9,123

The transport system cost per ton of output was determined by configuring the annual transport cost for each county at the various biomass output rates for the three variable firm sizes. Each tractor-unit had a maximum annual PMH of 1,144 hours. The number of trucks required to transport the annual harvest was determined by subtracting an individual tractor-unit PMH from the available annual PMH in each county. The remainder determined the extent to which additional trucks would be required to haul the harvested biomass in each county.

Annual transport cost was calculated as the tractor-unit machine rate multiplied by the number of tractor-units required for biomass transport as follows:

$$Annual\ Transport\ Cost = (T_{MR} \times Q_T) \times (P \times t_C)$$

Where T_{MR} = Tractor-unit machine rate; Q_T = required tractor quantity; P = payloads; and t_c = transport cycle time.

Transport costs were calculated for each county assuming biomass outputs for each of the three variable firm sizes. This value was divided by the biomass harvest in each county in order to determine the transport system production rate ($/US t). Finally, the production rates of the harvest, chipping, and transport systems were added for each county to determine the overall optimal firm size.

Economic Appraisal

An economic appraisal for each county within the study area was performed in order to determine the profitability of removing the standing *Arundo* biomass and selling it to the paper mill. The cost-effectiveness analysis (CEA) approach was followed in order to determine the counties within the study area where *Arundo* biomass output per dollar spent is maximized.

Total costs were the sum of harvest, chipping, and transport system costs at the respective optimal firm size for the county. These costs were added to business-as-usual restoration costs. Business-as-usual restoration costs were estimated using the Giessow et al. (2011) figure of $25,000 per acre of *Arundo* biomass removed: further broken down into $5,000 per acre for project management and $20,000 per acre for project implementation. *Arundo* harvest and chipping system machine rates were included in restoration implementation costs, since those actions are taken in the business-as-usual scenario. Transport system costs were considered as additional costs outside of the restoration effort.

Direct benefits were considered as the gross profit generated from biomass sales at the pulp mill. Total biomass in the county was multiplied by the chip price per ton to derive the dollar value of standing biomass. The extent to which biomass sales subsidized the cost of restoration was calculated by dividing direct benefits by total costs. The subsidy value was expressed as a percentage.

Net profit for three hypothetical firms was calculated by subtracting system costs from gross profit. The three firms were a fully integrated field-to-mill operation, a chipping and transport system, and a transport only operation. Net profit for each firm was divided by total biomass in order to derive a dollar value profit per ton of biomass removed in each county.

The Effect of Distance on Profit Potential

A simple sensitivity analysis was conducted in order to determine the profitability of selling *Arundo* biomass at variable chip prices and over transport distances. Chip price and transport distance variables were constrained by the maximum transport distance in the study area, 400 miles, and the subsequent range of chip prices required to generate a positive net profit. Net profit for each delivered payload was calculated 100 times as a partial derivative of ten hypothetical chip prices and 10 distance values. Chip price ranged from \$0 – \$225 per US t of biomass and distance values ranged from 0 - 450 miles from the pulp mill. Net profit was calculated according to specific parameters and equations (Table 26).

Table 26. Parameters for calculating profitability at variable stand densities and distances to the pulp mill.

Parameter	Variable
Net Profit	P_N
Gross Profit	P_G
Payload (US t)	B
Chip price ($/US t)	P_C
Total production cost	C_T
Harvest system production cost	PC_H
Harvest system average production rate	PR_H
Chipping system production cost	PC_C
Chipping system average production rate	PR_C
Transport system production cost	PC_T
Transport distance	D
Tranport system average production rate	PR_T

The formula for determining net profit was calculated as follows:

$$P_N = P_G - C_T$$

Gross profit was determined as follows:

$$P_G = B \times P_C$$

Total production cost was calculated as follows:

$$C_T = PC_H + PC_C + PC_T$$

Harvest system production rate was calculated as follows:

$$PC_H = B \times PR_H$$

Chipping system production rate was calculated as follows:

$$PC_C = B \times PR_C$$

Transport system production rate was calculated as follows:

$$PC_T = 2\left(\frac{D}{40}\right) + 1.98 \times PR_T$$

Chapter III

Results

For counties within the study area with high densities of *Arundo donax*, the smallest firm size proved to be most profitable. When the biomass exceeded what could be harvested in a single year, the largest firm size was most profitable. In no instance, however, was the revenue gained from the direct sale of *Arundo* biomass enough to completely offset restoration costs. *Arundo* sales did, however, subsidize restoration costs by roughly 40%. Hypothetical enterprises were slightly profitable in certain counties within the study area, especially if they only dealt with biomass transport. Chip price and transport distance were the key factors in determining whether or not *Arundo* biomass sale resulted in a net benefit that could be used to subsidized restoration costs.

Optimum Firm Size

The ideal *Arundo donax* biomass harvest operation consisted of a business that operated at the lowest cost per US t of biomass harvested, chipped, and transported. Harvest operations demonstrated the lowest cost at the firm size that most closely matched the chipper production rate (Table 27). The smallest firm size, consisting of a single chainsaw operator, four additional ground crew laborers, and a one skidder, had an annual cost of $188,000. The largest firm size, three separate chainsaw teams, had an annual cost of $298,000. The chipping system annual cost increased from $103,000 to $145,000 as the utilization rate for the chipper increased from 11% at the smallest firm size to 32% at the three-team firm size. The cumulative cost per ton of biomass removed, however, decreased as the firm size increased. Harvesting and processing costs were lowest at the three-team firm size.

Table 27. Harvest and chipping system machine rates at variable firm sizes.

	1	2	3
Harvest PMH	541	541	541
Harvest System MR	$ 347	$ 493	$ 551
Chainsaw MR	$ 235	$ 381	$ 438
Skidder MR	$ 112	$ 112	$ 112
Annual Cost	$187,803	$266,823	$297,839
Chipping PMH	89	179	268
Chipping System MR	$ 1,152	$ 693	$ 540
Chipper MR	$ 928	$ 469	$ 316
Setout Truck MR	$ 224	$ 224	$ 224
Annual Cost	$103,015	$123,984	$144,952
Annual Biomass Output	3041	6082	9123
Harvest $/US t	$ 62	$ 44	$ 33
Chipping $/US t	$ 34	$ 20	$ 16

Transport system costs for each county increased as the firm size, and annual harvested biomass, increased (Table 28). Counties with low estimated biomass saw no change in transport price. Santa Cruz, San Benito, and San Luis Obispo counties only required a single tractor-unit to haul the entire year’s biomass regardless of harvest rate. All other counties, however, required increased numbers of trucks as annual biomass harvest increased with firm size. At the largest firm size, Ventura required six tractor-units, Los Angeles and Monterrey required five, San Diego and Orange counties required four, and Santa Barbara required three.

Table 28. Tractor-unit quantities and annual cost at variable firm sizes.

County	Total Biomass	Firm Size 1		Firm Size 2		Firm Size 3	
		Qty	Cost	Qty	Cost	Qty	Cost
Santa Cruz	26	1	$ 1,393	1	$ 1,393	1	$ 1,393
San Benito	694	1	$ 39,383	1	$ 39,383	1	$ 39,383
Monterey	114,204	2	$ 413,695	4	$ 1,654,782	5	$ 3,102,715
San Luis Obisbo	849	1	$ 81,849	1	$ 81,849	1	$ 81,849
Santa Barbara	3,069	3	$ 1,011,038	3	$ 1,020,506	3	$ 1,020,506
Ventura	128,513	2	$ 518,192	4	$ 2,072,769	6	$ 4,663,730
Los Angeles	16,873	2	$ 416,041	4	$ 1,664,163	5	$ 3,120,305
Orange	232,111	2	$ 345,681	3	$ 1,037,044	4	$ 2,074,087
San Diego	126,421	2	$ 267,504	3	$ 802,512	4	$ 1,605,024

Transport system production rates were lowest in the low biomass counties at the largest firm size (Table 29). This is because a three-team system could harvest and process biomass at the lowest cost but only produced enough biomass to require a single tractor-unit. In counties where annual biomass harvest was large, requiring multiple tractor-units to transport to the pulp mill, the lowest production rates were at the smallest firm size. Although the larger firm size lead to reduced harvest operation costs, the greater number of tractor-units required to transport increased quantities of biomass lead to an overall increase in operating costs per ton of *Arundo* harvested.

Table 29. Transport system production rates at variable firm sizes.

County	Firm Size 1	Firm Size 2	Firm Size 3	Optimum
Santa Cruz	$ 150	$ 118	$ 103	3
San Benito	$ 152	$ 121	$ 105	3
Monterey	$ 232	$ 336	$ 389	1
San Luis Obisbo	$ 192	$ 161	$ 145	3
Santa Barbara	$ 428	$ 397	$ 381	3
Ventura	$ 266	$ 405	$ 560	1
Los Angeles	$ 233	$ 338	$ 391	1
Orange	$ 209	$ 235	$ 276	1
San Diego	$ 184	$ 196	$ 225	1

Cost Effectiveness of *Arundo* Biomass Sale by County

Restoration costs for *Arundo* removal were assumed to be $25,000 per acre with an average distribution of 86 green tons of biomass per acre (Giessow et al., 2011). Business-as-usual restoration costs included harvest and chipping costs (Table 30). The maximum annual biomass removal per county was either the total biomass, for low density counties, or the production rate of the optimally sized firm. The maximum area restored in the large density counties was 35 acres per year for a total cost of $825,000. At that rate, the number of years required to completely eradicate *Arundo* from the large density counties ranged from one to seventy-six years with a mean of 34 years. Total eradication costs in the study area were estimated as $170,000,000.

Table 30. Business as usual restoration estimates by county.

County	Annual Harvest	Acres	Management	Implementation	Total	Years
Santa Cruz	26	0.3	$ 1,395	$ 5,581	$ 6,976	0.01
San Benito	694	8	$ 37,669	$ 150,674	$188,343	0.2
Monterey	3041	35	$ 164,941	$ 659,764	$824,705	38
San Luis Obisbo	849	10	$ 46,039	$ 184,157	$230,196	0.3
Santa Barbara	3041	35	$ 164,941	$ 659,764	$824,705	1
Ventura	3041	35	$ 164,941	$ 659,764	$824,705	42
Los Angeles	3041	35	$ 164,941	$ 659,764	$824,705	6
Orange	3041	35	$ 164,941	$ 659,764	$824,705	76
San Diego	3041	35	$ 164,941	$ 659,764	$824,705	42

Biomass transport costs were added to restoration costs and subtracted from gross profit to determine the net profit of the *Arundo* restoration operation (Table 31). There was no instance, utilizing the Giessow et al (2011) restoration cost estimate, where net benefit was positive. In other words, total restoration costs were greater than the profit gained by the sale of *Arundo* chips.

The direct benefits of selling *Arundo* biomass accounted for up to 35% of restoration costs after subtracting the additional transport costs (Table 31). All counties except Santa Barbara and Ventura showed a positive rate of return. The mean subsidy for the low-density counties with large crew sizes was 30% excluding, Santa Barbara County. High biomass counties demonstrated a mean subsidy of 12%, excluding Ventura County.

Table 31. Net benefit of *Arundo* restoration with direct sale of biomass.

County	Direct Benefits	Direct Costs	Net Benefit	Subsidy
Santa Cruz	$ 3,905	$ 8,368	$ (4,463)	36%
San Benito	$ 105,447	$ 227,726	$ (122,279)	35%
Monterey	$ 461,726	$ 1,238,400	$ (776,674)	6%
San Luis Obisbo	$ 128,880	$ 312,045	$ (183,166)	20%
Santa Barbara	$ 461,726	$ 1,835,743	$(1,374,017)	-67%
Ventura	$ 461,726	$ 1,342,897	$ (881,171)	-7%
Los Angeles	$ 461,726	$ 1,240,745	$ (779,020)	6%
Orange	$ 461,726	$ 1,170,386	$ (708,660)	14%
San Diego	$ 461,726	$ 1,092,209	$ (630,483)	24%

The profitability of hypothetical enterprises revealed that certain counties display true profit potential, while others do not (Table 32). Three configurations were used to determine profitability: fully integrated, chipping and transport, and transport-only operations. In the high biomass counties, no fully integrated operation was profitable. For a hypothetical chipping and transport operation, Orange and San Diego were the only high biomass counties to earn a slight profit at $0.06 and $0.72 respectively per ton. For transport-only operations, Los Angeles County was the most profitable followed by San

Diego County with $2.71 and $1.54 respectively per ton. A profit of $2.71 per ton would equate to an annual profit of only $8,241 per year or $46,000 profit for total biomass transport out of the county over six years. Gross profit from direct sales was enough to generate more money than the cost of transport in all counties except for Ventura and Santa Barbara, the two counties with the farthest transport distance.

Table 32. Profitability ($/US t) in high density counties for fully integrated (HCT), chipping and transport (CT), and transport only (T) firms.

County	HCT	CT	T
Monterey	$ (2.13)	$ (0.48)	$ 0.42
Santa Barbara	$ (229.20)	$ (212.52)	$ (178.96)
Ventura	$ (2.70)	$ (1.24)	$ (0.44)
Los Angeles	$ (14.54)	$ (3.40)	$ 2.71
Orange	$ (0.75)	$ 0.06	$ 0.50
San Diego	$ (0.77)	$ 0.72	$ 1.54

The Effect of Commodity Price and Distance on Transport Profitability

The profitable haul (PH) distance, the distance under which transporting biomass generates a profit, was found to be directly influenced by the chip price at the pulp mill (Figure 14). At the estimated chip price of $150/US t, the PH distance is 545 miles. If the *Arundo* stand was directly outside of the pulp mill, requiring a transport distance of less than 5 miles, the chip price would need to be at least $10 per ton in order to cover the costs of transport.

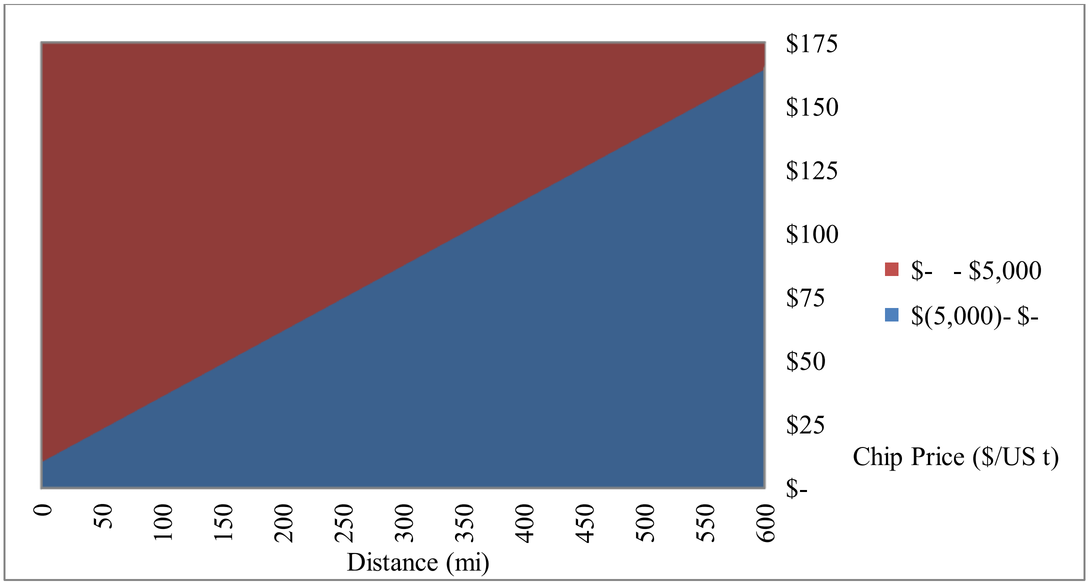


Figure 14. Profitable haul distances at variable *Arundo* chip prices.

Chapter IV

Discussion

This study proposes optimized logistics and profitability of selling *Arundo donax* biomass in southern California to the pulp and paper industry. The revenue generated from direct sales would significantly offset restoration costs leading to greater removal and an overall improvement in the ecological integrity of coastal riparian habitats. Although it is not expected to be as profitable, best management practices for operational logistics can be taken from woody biomass harvesting operations within the forestry sector. Profit generated from *Arundo* sales was usually enough to cover the cost of transport and offset restoration costs to varying degrees. Utilizing machine rate and cost effectiveness analysis methodologies, similar studies could be conducted for additional invasive species or markets.

Several assumptions in this study might lead to different results in real world situations. Business as usual restoration costs of $25,000 per acre were estimated utilizing rates from Giessow et al. (2011). This figure was calculated as the mean value from many previous *Arundo* removal projects within the study area (Table 33). Due to the high variability in project sizes and costs, a more accurate estimate could have been the median value of $16,700 per acre.

Table 33. Known restoration costs from previous Arundo removal projects within the study area according to Giessow et al. (2011).

Watershed	Treated Net Acres	Expenditure	Cost per acre
Salinas	106	$ 500,000	$ 4,699
San Luis Rey	612	$ 7,500,000	$ 12,247
Santa Margarita	685	$10,000,000	$ 14,605
Carlsbad	99	$ 1,500,000	$ 15,198
Los Angeles River	16	$ 250,000	$ 15,337
San Dieguito	90	$ 1,500,000	$ 16,704
San Diego	56	$ 1,000,000	$ 17,794
San Juan	13	$ 250,000	$ 19,084
Tijuana	41	$ 1,500,000	$ 36,496
Santa Ana	1007	$40,000,000	$ 39,726
Ventura River	117	$ 7,500,000	$ 63,884

A second set of critical assumptions has to do with the sale of *Arundo* biomass. First, although it is technically feasible to process *Arundo* chips at a pulp mill without the need for additional processing or retooling, there may likely be other barriers to receiving *Arundo* biomass, such as the pulp mill contracts and the need for regular high-volume chip delivery. Second, the international index price for bone dry hardwood was used as the direct sale price for *Arundo* chips at the pulp mill. This value is valid because *Arundo* exhibits similar characteristics to hardwood pulp and does not require kiln drying (Lewis & Jackson, 2002). Existing pulp and paper mills, however, could be unwilling to pay this price upon delivery. Competition with forestry operations, which often harvest woody biomass residues as a secondary income to high-value logging, may reduce the dollar value per ton of biomass delivered to the mill (Keefe et al., 2014). Finally, there could be unaccounted expenses or complications for the southern counties when attempting to transport *Arundo* biomass across the international border to the pulp and paper mills in Mexicali, Baja California. As a registered invasive species, any part of the *Arundo donax* is typically restricted from being transported across borders. Many of the riparian habitats within the study area are state and federally owned lands, and therefore special agreements may need to be made before the *Arundo* biomass could be taken into Mexico. Should the pulp mills in Mexicali be unable to receive *Arundo* chips, transporting the chips to northern California pulp mills from the southern counties would significantly increase costs such that revenue generated would not even offset the cost of transport.

Further study would benefit from auditing real-world restoration projects to compare time standards of various *Arundo* removal scenarios. For instance there are several variations of mechanized and ground labor work crews, each typically being specific to the site, the available funding, and contractor preference. Trials could compare the costs and productivity of several types of harvest operations to determine the optimal arrangement for a given set of parameters as well as providing more accurate machine rate estimates for future cost estimating.

There may exist an opportunity for an additional industry layer of *Arundo* yarding. Transport costs are high at large biomass outputs due to the additional trucks required to haul the material to the pulp mill. If a staging yard was introduced to the operation, a single truck could transport all material to the yard and then haul the material to the pulp mill over the entire calendar year, not just during the work season. This type of set up could significantly reduce transport cost and allow for easier integration into existing *Arundo* removal operations.

The very concept of harvesting *Arundo* biomass from the wild for profit may draw criticism from both the paper manufacturers and the restoration ecologist. Pulp and paper manufacturers rely on large contracts with reliable deliveries of pulp wood so production may remain constant. Moreover, most transport distances of pulp trees to the mill are less than 50 miles due to high transport costs on logging roads (Ford Torrey & Murray, 2014). A remote, dispersed, and nonrenewable source of biomass is less desirable from an economic perspective than a biomass plantation. Wild harvest of *Arundo* biomass would only ever supplement existing pulp and paper operations, never sustain them entirely. The physical compatibility of *Arundo* biomass with traditional paper making from wood pulp is conducive to variable sized loads delivered to the mill at irregular intervals. Mill operators would simply blend *Arundo* chips in with other incoming woody biomass.

Wildland biologists may also be skeptical of commoditizing an invasive species. If it proved to be an economically sustainable enterprise, private land owners and "guerilla gardeners" may be incentivized to illegally propagate and plant *Arundo* in places where it currently does not exist. This concern, while valid, is less of a threat than it may seem upon first consideration. Currently, private contractors are hired to remove *Arundo* biomass as part of restoration projects. In some instances, contractors have attempted to leave some of the biomass in place knowing that they will be hired sooner to remove the plant once again. Biological monitors, therefore, observe contractors and ensure eradication takes place according to the restoration project goals. As a highly widely known problematic plant species, *Arundo donax*, is not sold in nurseries, cannot be legally imported, and is not accepted for disposal in most landfills (Bell 1997). *Arundo* is already a commodity to restoration contractors, and the fact that it is highly regulated makes it an ideal candidate for allowing direct sale of biomass. Policy enforcement would be less of a challenge with *Arundo* than a comparable species that was less well known or regulated.

Conclusion

Arundo donax is an aggressive invader of riparian habitats in southern California. It negatively impacts biodiversity and threatens human infrastructure with increased fire risk and flood damage. Although a positive cost benefit ratio has been identified with *Arundo* removal, high removal costs prohibit riparian restoration on a larger scale. Additionally, disposal of *Arundo* biomass can pose logistic challenges to restoration projects. In watersheds with large monotypic stands of *Arundo* within 500 miles of active pulp and paper mills, direct sale to the mill may subsidize the restoration effort and allow for a greater positive impact on these sensitive habitats. A typical *Arundo* removal operation would restore roughly 35 acres of *Arundo* per year and generate estimated revenue of $460,000 annually at the mill. This value equates to roughly 10 – 20% of overall restoration costs. Although not independently profitable, incorporating direct sale of biomass into current restoration efforts could provide a nearly $5,000 per acre subsidy and solve the logistical challenge of responsibly disposing of *Arundo* biomass.

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