# 1.0 INTRODUCTION

*Arundo donax* (giant reed, giant cane) is one of the largest grass species. A clonal plant that grows in dense stands, it is found in many subtropical and warm-temperate areas of the world. It is thought to be native to eastern Asia (Polunin & Huxley 1987), but the precise extent of its native distribution is unknown. *Arundo* has been introduced around the world as an ornamental/crop species, for erosion control, and for the production of reeds (musical instruments, construction, paper and pulp). It has become invasive in many places throughout the world, primarily in riparian habitat. Where *Arundo* invades, it often forms dense stands, resulting in a wide range of impacts to natural ecological systems (biotic and abiotic) as well as human created infrastructure. The Invasive Species Group of the World Conservation Union includes giant reed in its top 100 Worst Invaders of the World (Lowe et al. 2000).

*Arundo* was first introduced to California by Spanish colonists in the 1700s (Newhouser et al. 1999), and in the early 1800s for erosion control in drainage canals (Bell 1998). It is now a major threat to riparian areas in California, as well as other southwestern states. Two portions of the United States have particularly significant *Arundo* infestations (characterized as >40% of riverine habitat over areas longer than a river mile): coastal California (Monterey to San Diego) and the Rio Grande (Texas).

This study is the first research to take a broad range of impacts caused by the invasive non-native plant *Arundo*, and apply them to a significant portion of the plant's distribution in California. This was not previously possible because detailed *Arundo* spatial distribution data did not exist prior to this study. Mapping *Arundo* in high resolution from Salinas, California to the Mexican border in all coastal watersheds was the initial task. This captures *Arundo*'s primary distribution in coastal California.

There has been a significant increase over the past ten years in studies examining *Arundo*'s impacts and quantifying aspects of its productivity, structure, physiology, genetics and reproduction. We compiled information, and completed additional research and data collection to fill gaps in understanding or documentation. New research was primarily related to fluvial/geomorphic impacts, leaf area, biomass water use and fire impacts. Data collected also allowed verification that relationships described in the literature, such as biomass and structure data, applied to the study region. Many studies and reports have alluded to impacts related to fire, but this study explicitly quantifies fires that started in *Arundo*, as well as wildfires that burned *Arundo*, over the entire study area. Impacts to 22 federally-listed sensitive species were examined using spatial data for the species, spatial data for *Arundo*, and current understanding of the biology of the species. From this the magnitude of impact on listed species from *Arundo* is described and scored. Scores of cumulative impact are examined by species, taxa group, and watershed. To date, this is the largest suite of species over the broadest area to examine *Arundo* impacts.

This report presents the entire range of impacts over the entire study area, as well as each watershed. A coarse Cost Benefit Analysis is presented and made possible due to the explicit quantification based on acreage for each watershed, and the range of impacts that were quantified (with a cost assigned to them based on previous studies).

Finally this report provides a review of each watershed's *Arundo* control program, including: completed work to date, status of permits allowing work, and the identification of the lead entities carrying out the work. The spatial data set and impact quantification is used to highlight priority watersheds and actions. This is also examined in the context of current capacity to implement *Arundo* control projects. The need to implement sustainable watershed control programs with eradication as an obtainable goal is explored, as well as an evaluation of the challenges in completing programs, which is a process that can take over 20 years.

# 2.0 *ARUNDO* BIOLOGY

## 2.1 Physiology

*Arundo* is generally a hydrophyte, achieving its greatest growth near water. However, it adapts to many different habitat conditions and soil types, and once established is drought tolerant and able to grow in fairly dry conditions (Lewandowski et al. 2003). It can also tolerate saline conditions (Perdue 1958, Peck 1998), and in California it is found growing along the edges of beaches and estuaries (Else 1996). *Arundo* is a $C_3$ plant, but it shows the unsaturated photosynthetic potential of C4 plants, and is capable of very high photosynthetic rates (Papazoglou et al. 2005, Rossa et al. 1998).

*Arundo*'s stems and leaves contain a variety of noxious chemicals, including triterpenes and sterols (Chandhuri & Ghosal 1970), cardiac glycosides, curare-mimicking indoles (Ghosal et al. 1972), and hydrozamic acid (Zuñiga et al. 1983), as well as silica (Jackson and Nunez 1964). These likely reduce herbivory by most native insects and grazers where *Arundo* has been introduced (Miles et al. 1993, Zuñiga et al. 1983).

*Arundo* responds strongly to excess nitrogen from anthropogenic and fire sources (Ambrose & Rundel 2007). Most studies on growth and transpiration indicate that water availability is the primary factor affecting metabolic rates and productivity (Abichandani 2007, Perdue 1958, Watts 2009). *Arundo* generally has a shorter stature and is less productive when there is limited water availability, such as on higher elevation riparian terraces or drier portions of the watershed. This observation is based on the distribution of these less productive stands on many watersheds within the study area.

## 2.2 Genetic variation

Isozyme and RAPD analyses of *Arundo* on the Santa Ana River in California indicated genetic diversity comparable with those in the literature for clonal species, supporting asexual reproduction as the primary means of *Arundo* spread (Khudamrongsawat et al. 2004). Samples were also taken from one out-group on a separate watershed (Aliso Creek, Orange County). Several phenotypes were dominant and were found spread along the Santa Ana River. These dominant phenotypes were also found in the out-group population, possibly due to spread by humans. The moderate levels of genetic diversity in *Arundo* are likely explained by multiple introductions over time, with early introductions as a building material, and more recent use for erosion control and as a landscape ornamental (Bell 1997; Frandsen 1997). The moderate level of genetic diversity and the asexual mode of reproduction increases the potential for application of biological agents for control of *Arundo* (Tracy and DeLoach 1999).

## 2.3 Physical Structure

For this study, data were collected from fourteen *Arundo* plots on five watersheds (Figure 2-1). A variety of measurements were taken, and canes were collected from these plots. These data are presented in this section, section 2.4, and Chapter 4.

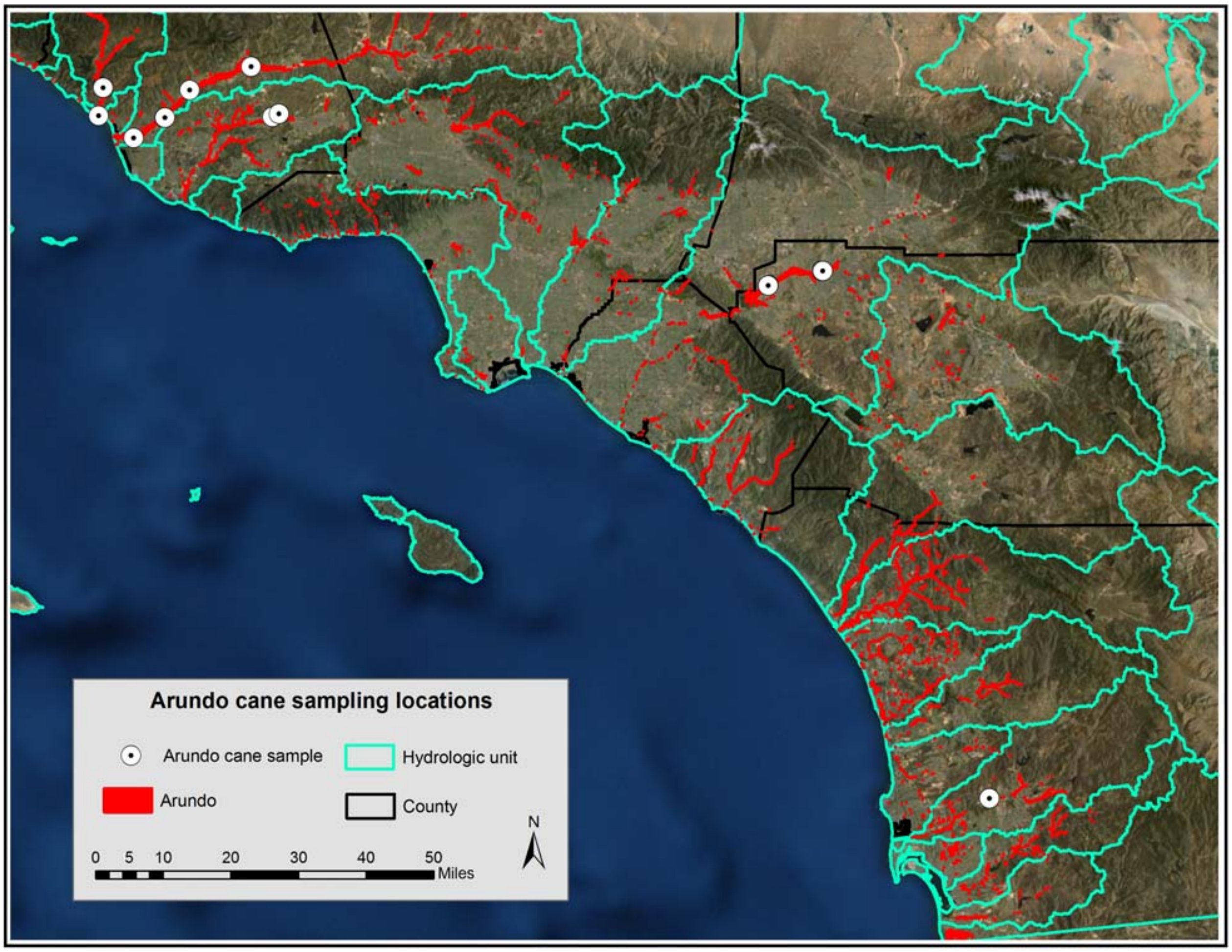
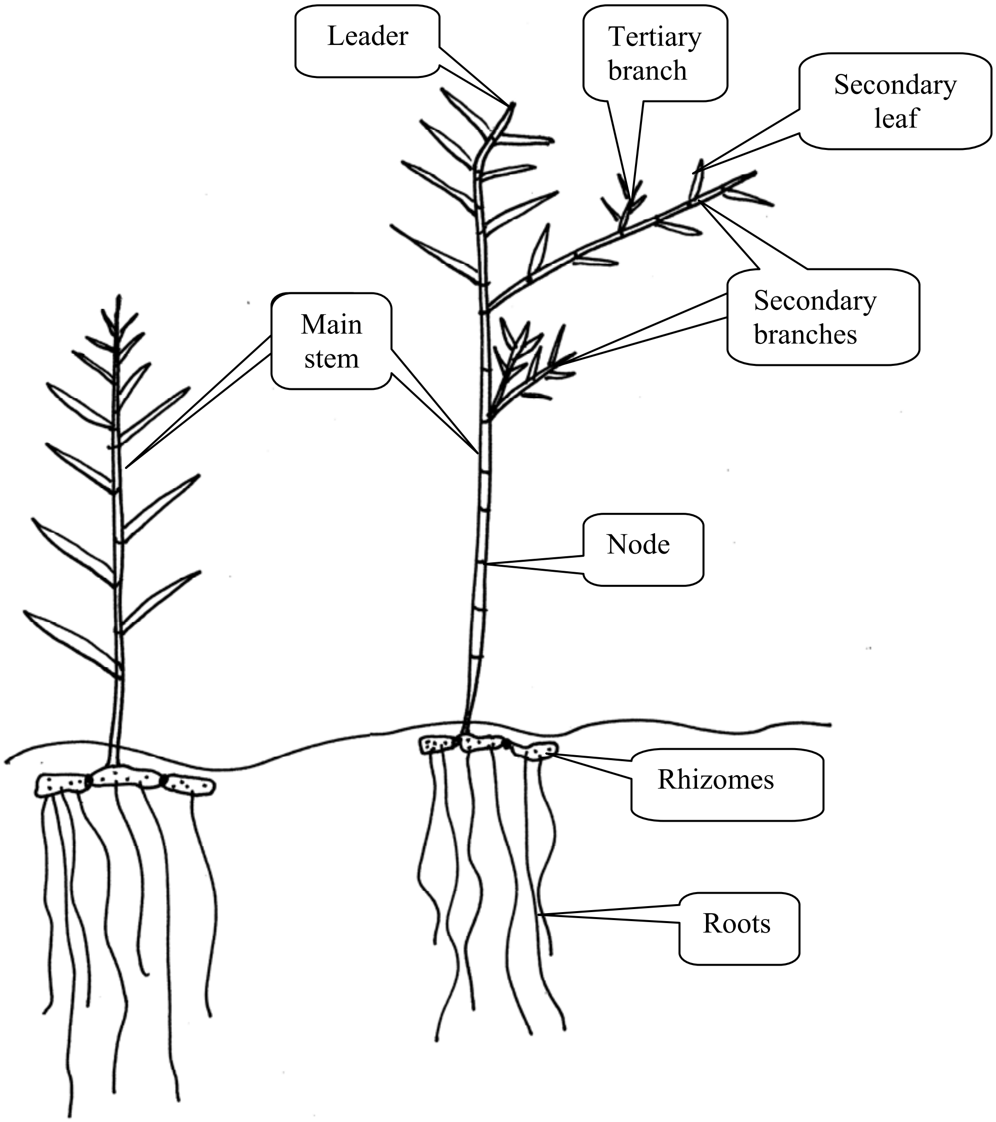


**Figure 2-1.** *Arundo* sampling locations in southern California.

*Arundo* is a clonal organism, so the plant will be examined at both the individual level (ramet) and at the stand scale (colony).

<u>The individual plant or ramet:</u>

*Arundo* is one of the largest herbaceous grasses, and is often mistaken for a bamboo (Figures 2-2 to 2-6). It is a tall, erect, perennial grass, 2 to 8 m high (Perdue 1958). Canes frequently attain lengths of 8 to 9 m in coastal California, as this study shows (Table 2-1). The main stems, or culms, are hollow with walls 2 to 7 mm thick and are divided by partitions at the nodes. In this study the culms were on average 23.8 mm wide (measured between nodes one and two). First year canes are un-branched, and in the second year single or multiple lateral secondary branches may form from the nodes (Figures 2-2 to 2-3) (Decruyenaere & Holt 2005). The secondary branches are a much smaller diameter than the main canes (typically <10mm versus >20 mm). In canes that are two years and older, the secondary branches bear a significant proportion of the leaves (this study). These secondary branches can themselves give rise to third degree and even fourth degree branches, but this is uncommon (Decruyenaere & Holt 2005, this study). Once a cane generates secondary branches these become the primary area of new growth, and continued growth of the main cane (leader) is slow to non-existent (Decruyenaere & Holt 2005).



**$1^{st}$ YEAR CANE** **2+ YEAR CANE**

**Figure 2-2.** Illustration of *Arundo* structure for first year and 2+ year old stems. Older canes would have many secondary braches. Drawing by J. Giessow.

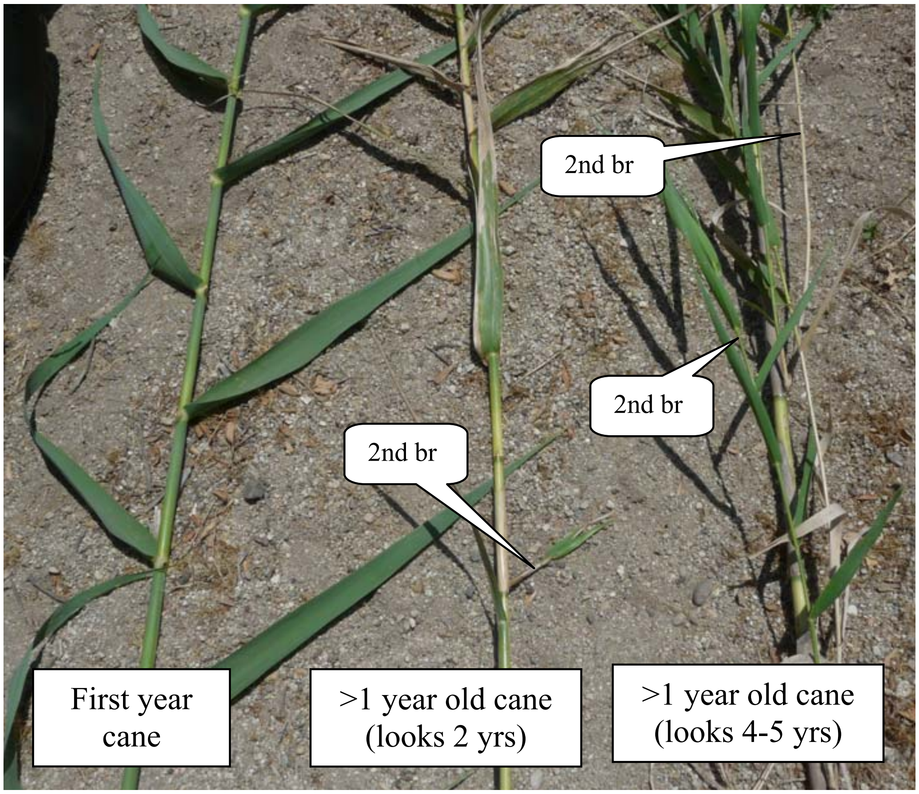


**Figure 2-3.** First year and >1yr year old *Arundo* canes, showing leaf and branching structure. First year canes have only cauline leaves. Older canes have an increasing number of secondary branches with leaves on them, and leaves on the old leader are often damaged and dying.

**Figure 2-4.** A single older cane with all secondary branches (25), leader, and main stem. This was cane SD#1b from the San Diego River with a height of 8.1m.

**Figure 2-5.** New first year canes often protrude from the *Arundo* canopy.
Older canes with extensive secondary branching cannot support the weight of the branches and leaves, and usually flop over and do not stand upright, especially in the upper portions of the stand's canopy.

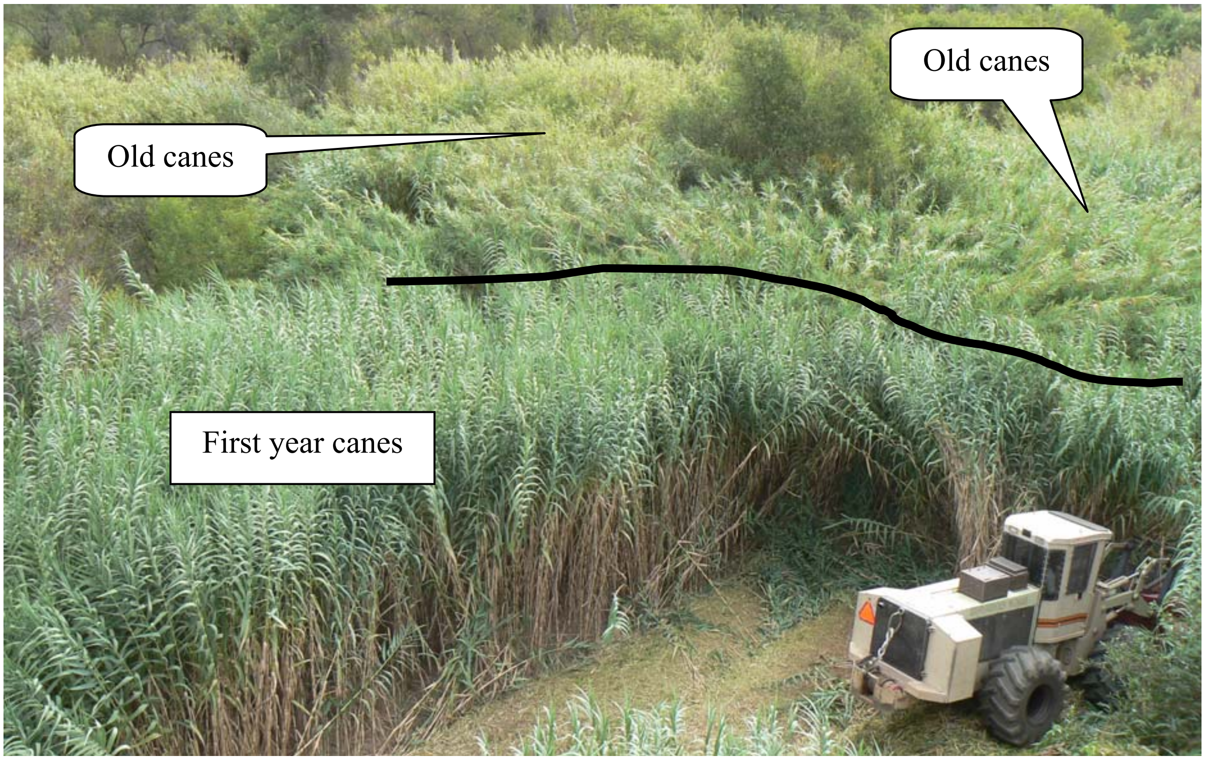


**Figure 2-6.** First year *Arundo* canes at full height (6+ m).
The tractor is 10' high. This area had been cut as a fuel break the year before and is being cut again. Energy stored in rhizomes underground allow this rapid regrowth after cutting or fire events. Note simple unbranched vertical structure, very high cane density, and deep green color of the new, resprouted canes. Older canes in the background are less vertical and are a more yellowish color.

**Table 2-1.** Summary of *Arundo* cane data from the fourteen locations sampled for this study. Locations of sampling plots are shown in Figure 2-1.

| Plot | Cane height (m) | Cane diameter (mm) | Leader length (cm) | Leader # leaves | Mean leader single leaf area (cm$^2$) | # secondary branches | Mean branch length (cm) | Mean branch # leaves | Mean branch single leaf area (cm$^2$) | New cane # leaves | Mean new cane single leaf area (cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CC1 | 5.1 | 20 | 19 | 10 | - | 15 | 47.7 | - | - | 21 | 168.7 |
| CC2 #1 | 9.7 | 28 | 90 | 23 | 83.7 | 57 | 11.7 | 4.5 | 10.5 | - | - |
| CC2 #2 | 8.5 | 27 | 82 | 23 | 117.3 | 9 | 70.9 | 13.0 | 63.2 | - | - |
| SA1 | 6.1 | 25 | 45 | 17 | - | 34 | 21.4 | - | - | - | - |
| SA2 | 6.1 | 25 | 32 | 15 | 58.5 | 31 | 36.2 | 23.0 | 44.4 | - | - |
| SA3 | 7.7 | 27 | 74 | 28 | - | 33 | 10.7 | - | - | - | - |
| SA4 | 7.4 | 26 | 33 | 12 | - | 48 | 20.0 | 13.5 | 29.5 | - | - |
| SC1 | 9.9 | 25 | 23 | 12 | - | 31 | 46.0 | 11.0 | 34.8 | - | - |
| SC4 | 4.2 | 22 | 0 | 0 | - | 34 | 41.3 | 14.0 | 19.2 | - | - |
| V1 | 8.4 | 26 | 0 | 0 | - | 28 | 43.4 | - | - | 21 | 216.2 |
| V2 | 6.2 | 24 | 76 | 20 | - | 14 | 41.8 | - | - | - | - |
| SD#1a | 8.1 | 26 | 65 | 16 | - | 29 | 56.1 | 10.9 | 34.9 | - | - |
| SD#1b | 8.1 | 24 | 66 | 13 | - | 25 | 60.0 | - | - | - | - |
| SC2 | 4.3 | 22 | 11 | 7 | - | 11 | 37.0 | - | - | - | - |
| SC3 | 4.2 | 18 | 19 | 7 | - | 7 | 37.1 | - | - | 27 | 227.9 |
| SC5 Lg | 3.8 | 25 | 13 | 8 | - | 10 | 26.2 | - | - | - | - |
| SC5 Sm | 2.6 | 15 | 12 | 7 | - | 5 | 22.8 | - | - | - | - |
| **Mean** | **6.5** | **23.8** | **38.8** | **12.8** | **86.5** | **24.8** | **37.1** | **12.8** | **33.8** | **23.0** | **204.3** |
| **StdDev** | **2.2** | **3.5** | **30.5** | **7.8** | **29.5** | **14.8** | **16.8** | **5.5** | **17.1** | **3.5** | **31.4** |

CC = Calleguas Creek, SA = Santa Ana River, SC = Santa Clara River, V = Ventura River, SD = San Diego River.

Leaves are borne at nodes along the main stem and on the secondary branches. In this study, leaves found on the main stem were 5-6 cm (up to 8cm) broad toward the base, up to 61 cm long, and tapered to a fine point. Leaves on first year canes had an average width of 5.0 cm and length of 54.4 cm (n = 69) (Table 2-2). The main stem of older canes (>1 year) had much smaller leaves, average of 2.8 cm wide and 41.5 cm long (n = 60). As expected, secondary branch leaves were the smallest, average length of 27.9 cm and width of 1.7 cm (n = 200).

**Table 2-2.** Length and width of leaves of *Arundo* sampled in this study, by age and location.

| Cane age and leaf location | # leaves sampled | Max (cm) | Min (cm) | Ave (cm) | SD |
|---|---|---|---|---|---|
| ***1st year cane: Leaves on stem*** | | | | | |
| Leaf length | 69 | 74 | 15 | 54.4 | 14.5 |
| Leaf width | 69 | 6.8 | 2 | 5.0 | 1.2 |
| ***>1yr cane: Leaves on main stem*** | | | | | |
| Leaf length | 60 | 57 | 24 | 41.5 | 10.3 |
| Leaf width | 60 | 3.8 | 1.3 | 2.8 | 0.6 |
| ***>1yr cane: Leaves on secondary branches*** | | | | | |
| Leaf length | 200 | 52 | 4 | 27.9 | 10.8 |
| Leaf width | 200 | 2.8 | 0.1 | 1.7 | 0.5 |

This reduction in leaf size as canes mature is more than made up for by the much higher number of leaves found on secondary branches. Leaf density on the main cane decreased from an average of 23 for first year canes to 12.6 for older canes (Table 2-3), and leaf size also decreased. However, an entire new secondary branch class of leaves is present on canes >1 year. Leaf density on secondary branches was >270 on canes >1 year (Figure 2-4, Table 2-3). Canes older than one year had a leaf area that is greater than that of first year canes, and was predominantly made up of the secondary leaf area.

As canes mature, the leaves on the main cane become less important to photosynthetic production. The contribution of secondary branches to cane leaf area is an important observation that is not well documented in the literature. Decruyenaere and Holt (2005) note that the main canes have little growth once they generate secondary branches, and that the secondary branches become the primary areas of new growth. Leaf area is used to estimate water use and photosynthetic activity. This study will examine transpiration levels using leaf area data (Section 4.1). The field samples for this study were composed primarily of old canes. The large contribution of old canes with their secondary branches to stand leaf area can be seen in Figure 2-5, where the bulk of the leaves are secondary, and only a few new canes emerge out the top of the stand. First year and >1 year old canes can also be seen in Figure 2-6. The first year canes have a simpler structure with no branching, while the older canes in the background are more complex.

The underground structure of *Arundo* is composed of fleshy rhizomes from which arise roots that penetrate deeper into the soil (Figures 2-2 & 2-7 to 11). Rhizomes are generally shallowly buried, spreading out horizontally from the plant and forming a dense underground mat. Rhizomes are generally found 5-15 cm below the soil surface, with a maximum depth of 50 cm, while roots can be more than 100 cm deep (Sharma et al. 1998, this study).

**Table 2-3.** Density of leaves on *Arundo* stems sampled for this study, by class.

| Cane Age and Leaf Location | # Sampled | Max | Min | Mean | StdDev |
|---|---|---|---|---|---|
| ***1st year cane: Leaves on*** | | | | | |
| Leaf density per cane (count) | 3 | 27 | 21 | 23 | 3.5 |
| Leaf area per leaf (cm$^2$) | 69 | 352 | 29.6 | 206.3 | |
| Leaf area per cane (cm$^2$) | 3 | 6,153 | 3,542 | 4,740 | |
| ***>1 year old cane: Leaves on culm*** | | | | | |
| Leaf density per cane (count) | 3 | 23 | 15 | 12.6 | 8.3 |
| Leaf area per leaf (cm$^2$) | 60 | 141 | 30 | 86.5 | |
| Leaf area per cane (cm$^2$) | 3 | 2,580 | 877 | 1,000 | |
| ***>1 year old cane: Leaves on secondary branches*** | | | | | |
| Leaf density per branch (count) | 19 | 15 | 3 | 11.1 | 3.3 |
| Leaf area per leaf (cm$^2$) | 200 | 102 | 1.8 | 33.9 | |
| Leaf area per branch (cm$^2$) | 18 | 837 | 12 | 406 | 240 |
| Leaf area per cane (cm$^2$) calculated | 14 | 8,904 | 906 | 4,699 | 2,628 |

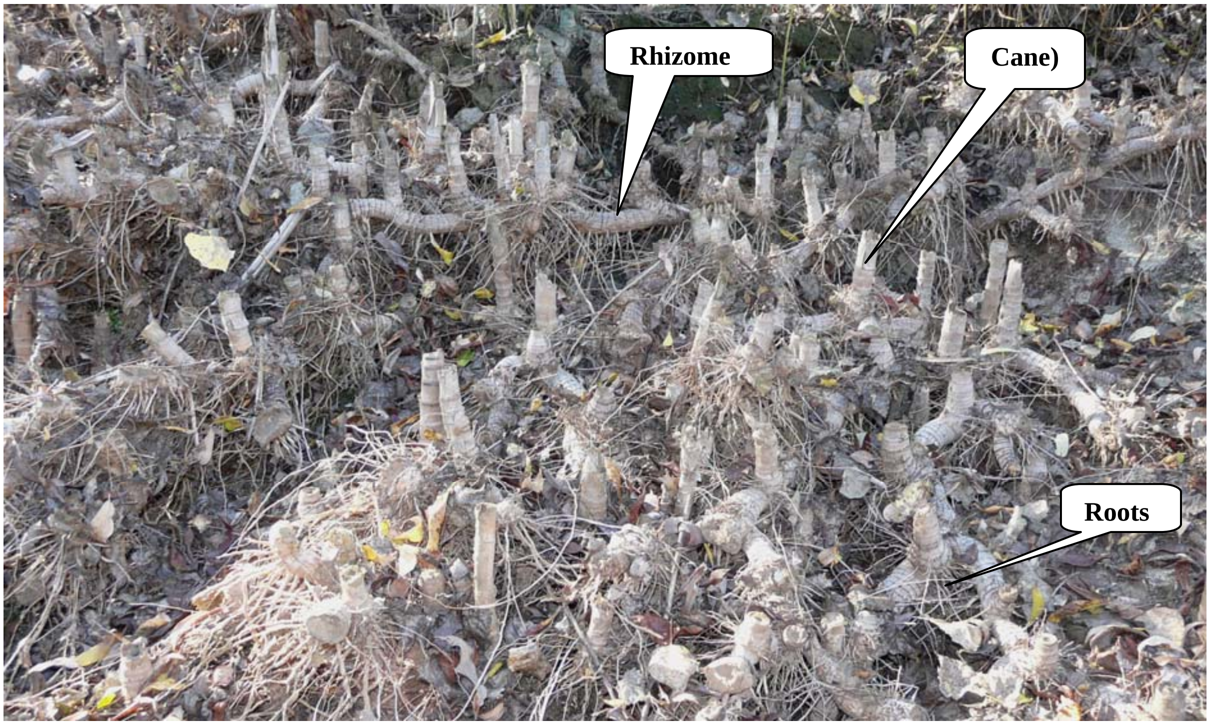


**Figure 2-7.** Dense rhizome and root network of an *Arundo* clump that was scoured during a flow event, removing the upper soil matrix and canes.

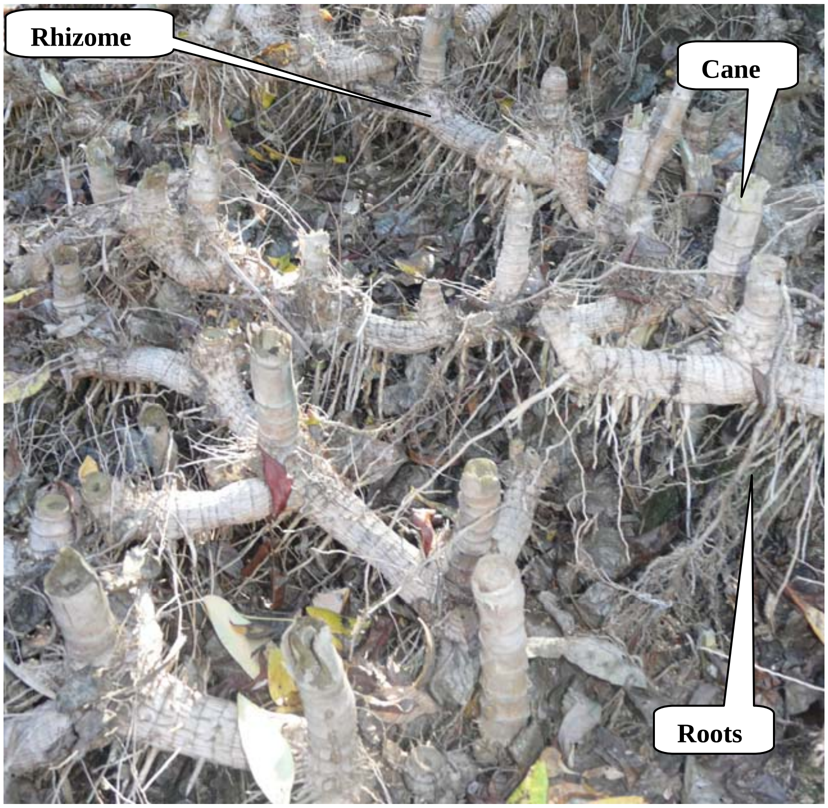


**Figure 2-8.** Close up of rhizomes showing emerging canes and roots.

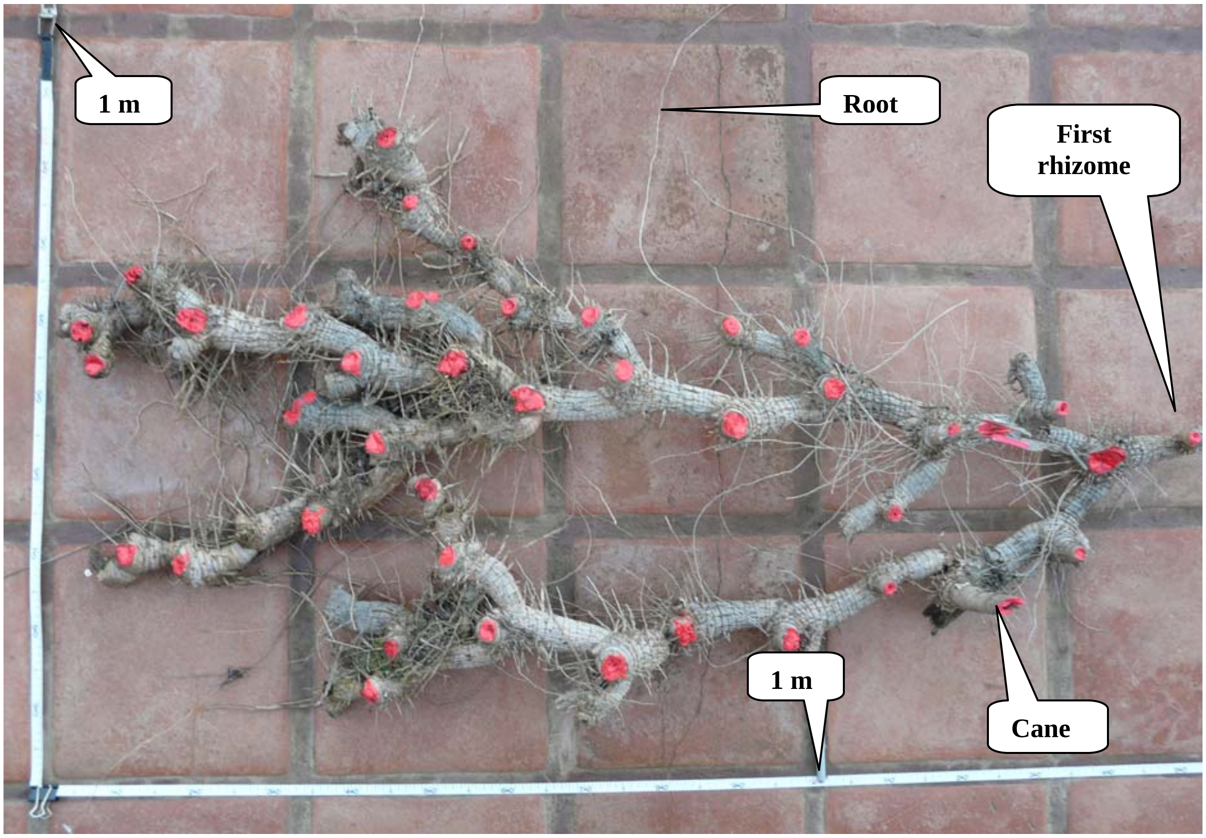


**Figure 2-9.** Rhizome network arising from a single growth point.
33 canes emerged from the marked 1 x 1m area (painted red).

**Figure 2-10.** Close-up of slightly desiccated *Arundo* rhizome.
The cane emergence points at the nodes are painted red, and long thin roots are visible.

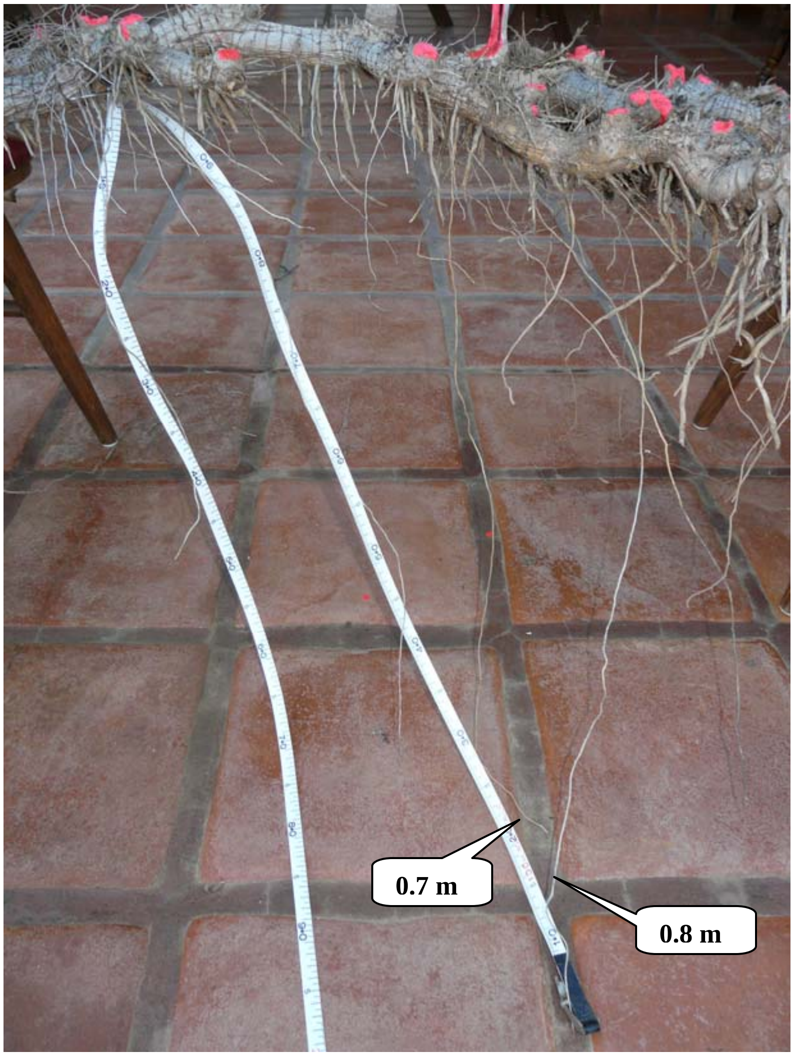


**Figure 2-11.** Rhizome network showing root length of up to 80 cm.
This was a dislodged rhizome network scoured out by flood action, so many of the roots have already been broken off, but it gives an idea of root density (near the rhizome) and length.

*Arundo* flowers are borne in large (3 to 6 dm long) plume-like terminal panicles, generally between March and September. However, many plants do not seem to ever flower, or at least not every year (Else 1996). The spikelets are several-flowered, approximately 12 mm long with florets becoming successively smaller.

Plants generally become dormant during the colder months, signified by the leaves turning brown/yellow, and the stems fading from their green color. These leaves and stems then turn green again in spring as temperatures rise and daylight lengthens. In areas with hard freezes during winter months, *Arundo* generally dies back to the ground and then re-sprouts in the spring. Deep freezes can kill the plant, probably by destroying the rhizome network.

### The stand or clonal mass:

Few studies have specifically examined stand structure. Quantification of stand structure is critical in the scaling up of information derived from specific canes, leaves, or rhizomes to the stand scale. Specific information on biomass, leaf area, transpiration, and other data derived on a per cane basis cannot be converted into per unit land area without an understanding of stand structure. Some recent studies have specifically accounted for stand structure in scaling up cane-specific data (Abichandani 2007, Watts 2009, Spencer et al. 2006) although it was not always clear how they defined the stand area.

Scaling up from cane to stand (land area) based data is very sensitive to the measured cane density per land area. Determining cane density for a stand is not as straightforward as one might expect. Overestimations of cane density may be generated if one only samples in areas where canes emerge. Extrapolating specific data on a given parameter to spatial data, such as the GIS data set produced in this study, requires that the same definition of "stand area" be used when measuring cane density, or that adjustments be made to account for the sampling of canes from only the portion of the stand that has cane emerging.

In this study the *Arundo* stand is defined as its aerial extent as viewed from above, and all areas that have *Arundo* cover are classified as part of the stand footprint (Figure 2-12). This is the spatial extent of the stand as recorded in the GIS spatial data that was mapped for this project (more details can be found in Chaper 4). However, data on *Arundo* is typically collected on a per cane basis. To use cane data to represent an entire stand, we must understand cane distribution within the spatial area of the stand and if there is variation by stand size and/or age.

*Arundo* canes are not uniformly distributed within the aerial extent of the stand. There are two portions of the stand footprint that have no or very few canes. The first area we will examine is the edge of the stand. This area, when viewed from above, has *Arundo* canopy cover, but the canes are not rooted within the edge area, rather they are draping over into this space (Figures 2-12 & 13).

When individual ramet (cane) based data is scaled up to represent stand or clonal mass, adjustments need to be made to account for the areas that have no canes within the stand (if these areas were not sampled). This adjustment can occur as a reduction in cane density for the stand, or as an adjustment applied to account for the percentage of the stand that has no cane emergence. Most studies do not specify what was done with edge areas and gaps within the *Arundo* canopy. If these areas were sampled they would have cane density accounts of zero. Most studies seem to sample within the cane emergence zone only. The importance of the edge areas depends on stand size, which is usually a function of age. A small stand has significant edge (areas with aerial vegetation cover but no canes emerging from the zone, Figure 2-14). Over 70% of the stand area may have no canes emerging from it. Large stands, as long as they are not linear, have much less edge area as a proportion of the total stand area. Only 5% of the stand area might not have canes emerging from it.

The second area that has no canes in the aerial canopy of a stand occurs as alleys or gaps and is less predictable to specific locations of the stand (Figures 2-12 & 14). These areas are important in mid to large-sized stands that often form as multiple clumps grow into each other. As the stands grow older, these 'alleys' or gaps fill in. *Arundo* stands older than 10 to 15 years have fewer and fewer areas within the stand that have no canes. *Arundo* stands older than 20 years are difficult to sample internally, as these areas are not accessible from the ground. Old *Arundo* stands are more easily traversed across the top of the canopy than on the ground, where cane density precludes movement (Figures 2-15 & 16). Vegetation sampling crews on the Santa Margarita River could walk across the *Arundo* canopy for hundreds of meters in 1996 (Cummins pers. comm. 1998).

Gaps within *Arundo* stands also occur where there are low-flow channels (primary and sometimes secondary. These would technically be defined as separate stands as they have different rhizome systems, but they may appear as one stand when mapping. The 10 meter wide low flow channel of the San Diego River was crossed within *Arundo* canopy, attesting to the strength and density of the aerial cane network (Giessow pers. comm. 2009).

Cane density also varies within the portion of the stand where canes emerge. This makes sense since a stand starts as an individual (single fragment) or group of individuals (larger rhizome fragment with many nodes), and continually expands outward. Lateral growth creates a pattern of greater density within the older portions of the stand and lower density toward the edges (Figure 2-17). However, this variation is fairly minimal compared to the variation in cane density between different stands (field observation J. Giessow, this study). Data from this study recorded an average cane density of 6.5 m (maximum 9.9 m, minimum 2.6 m, Table 2-1). *Arundo* cane density is significantly higher than that of native vegetation (Ambrose 2006, NHC 1997a,b & 2001), and this has multiple effects such as restricting wildlife movement and blocking water flow. Sampling bias may also be occurring in many studies where cane density is not sampled from the interior of older stands which are hard to access. This study was able to sample deep interior portions of stands that were accessible during biomass reduction with heavy equipment. However, cane density does not increase indefinitely; eventually new canes that emerge do not reach light and they senesce each year (Decruyenaere1 & Holt 2005). Cane data collected in this study indicates that each square meter within the rhizome/cane emergence zone generates 3.4 (n=14, ± 2.7) canes per year. Dead canes were not common, with a density $<1/m^2$ on the study plots (Table 2-4). This study will adjust stand based calculations by multiplying the cane per $me^2$ by 70% to account for areas with no canes emerging from them (adjusting for edge drape and areas with no cane emergence within the aerial footprint of the stand).

Some areas are near a typical mature density (center), while edges and runners are expanding outward, creating lower density. Also see Figure 2-9 to look at rhizome growth pattern. This is a small 3 x 3 m clump, but similar patterns occur in larger stands. The canes drape and extend well outside of the central cane emergence footprint indicated in red.

This study will make scaling up adjustments of 70% to account for cane density measurements from sampling only carried out within the cane emergence zone. This will occur for stand-based biomass and water use calculations.

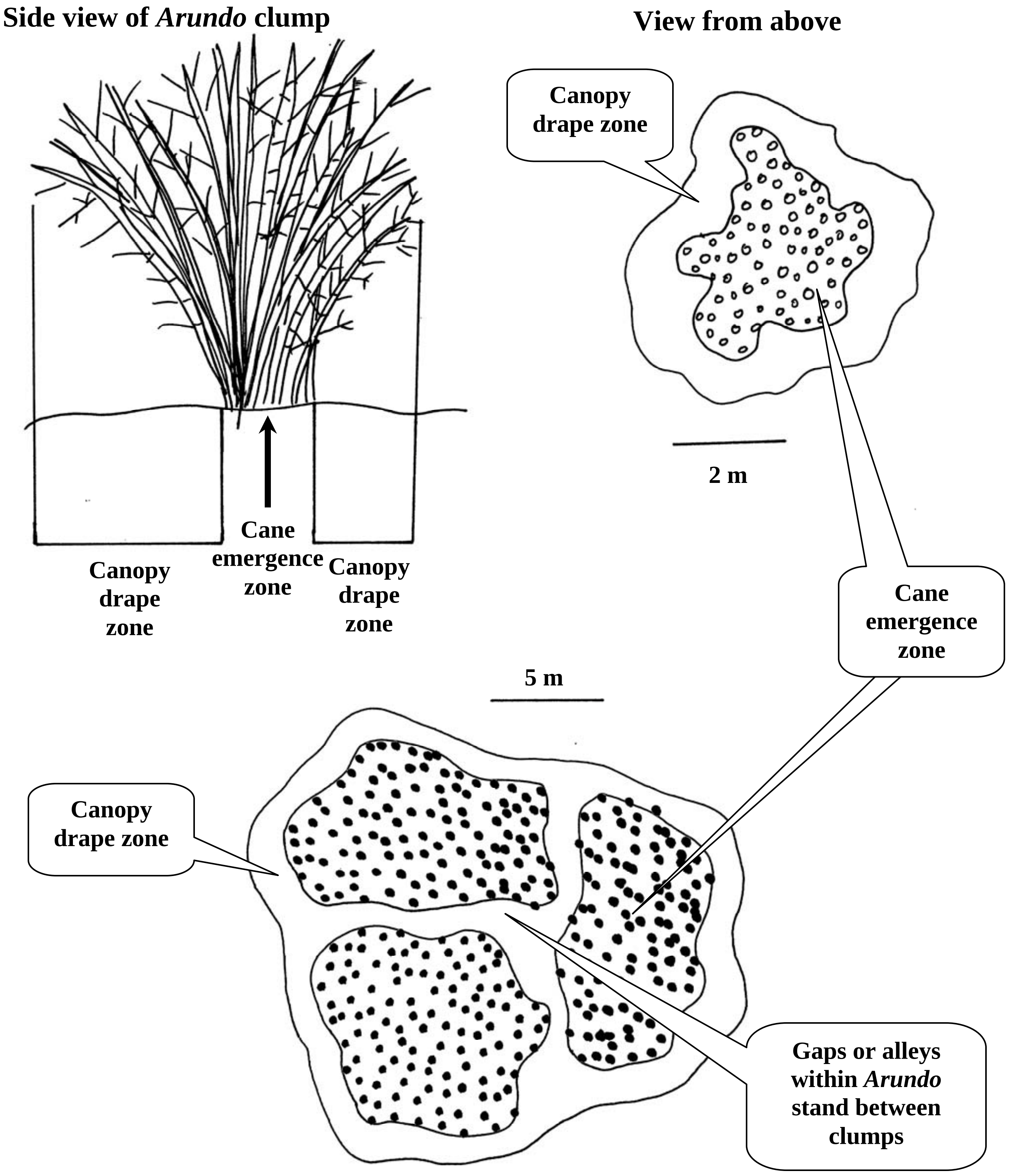


**Figure 2-12.** Draping effect of *Arundo* on the edge of the stand and gaps between clumps within a stand.
Drawing by J. Giessow.

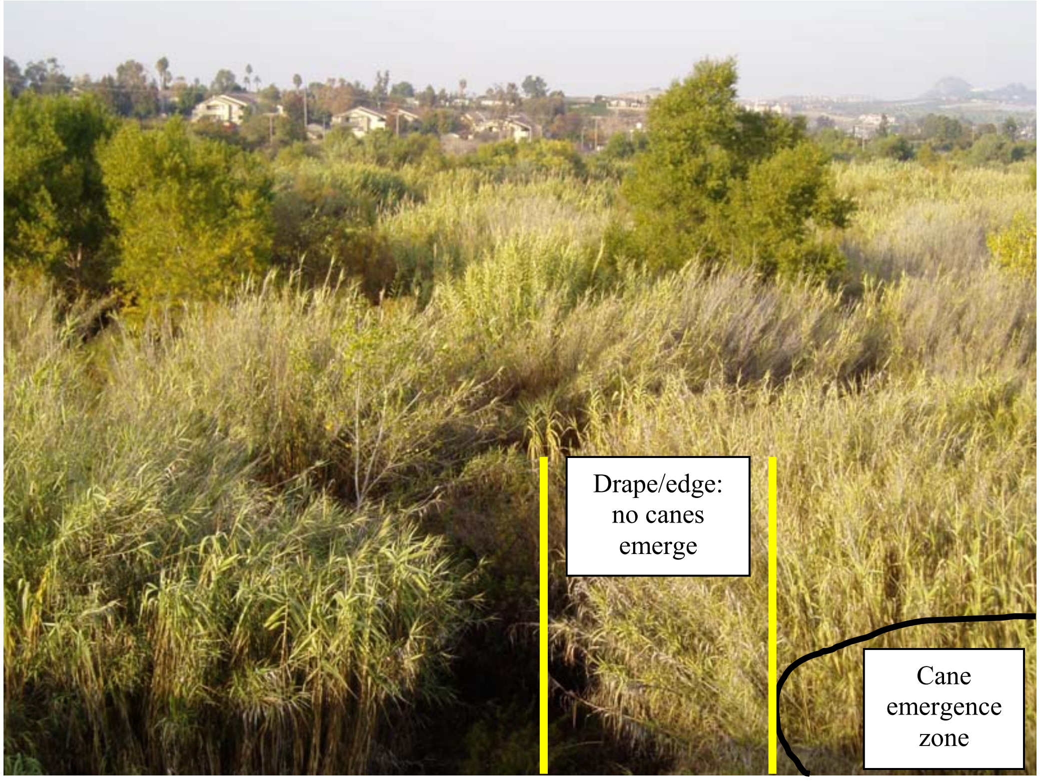


**Figure 2-13.** A mature *Arundo* stand showing draping of *Arundo* canes along an edge.

**Figure 2-14.** Oblique aerial photo showing patchiness of *Arundo* stands, particularly farther from the low-flow channel.
Greater patchiness means greater edge area composed of *Arundo* cover without actual canes emerging. The left side of image is unmowed/reduced *Arundo* and the right is immediately after reduction/mowing (San Luis Rey River 2007, J. Giessow).

**Figure 2-15.** View from bridge over San Luis Rey River showing the top of a mature *Arundo* stand. This stand is >10 years old, > 9 m height, and 100% cover. Note the high amount of leaf surface area and non-vertical (nearly horizontal) position of the upper portion of the canes with secondary branches.

**Figure 2-16.** *Arundo* stand being prepared for foliar herbicide treatment.
The crew is pushing the stand away from the native trees. *Arundo* canes are supporting the worker on the left. Canes are 8-9 m long and density is typical of a mature stand (about 40 canes/$m^2$). San Diego River, Giessow 2010.

**Figure 2-17.** A cut *Arundo* clump showing uneven cane density.

**Table 2-4.** Summary of *Arundo* cane density measurements from this study and others. This study and others typically sample cane density from the cane emergence zone.

| Source | Location | New | Old | Dead | Total |
|---|---|---|---|---|---|
| Giessow et al.(2010) | S. California, coastal | 3.4 | 38.1 | <1 | 41.5 |
| Spencer eta al. (2006) | Across U.S. | | | | 74.5 |
| Ambrose & Rundel (2007) | S. California: Santa Clara River (post fire) | | | | 31.6 |
| Abichandani (2007) | S. California: Santa Clara River | | | | 34.9 |

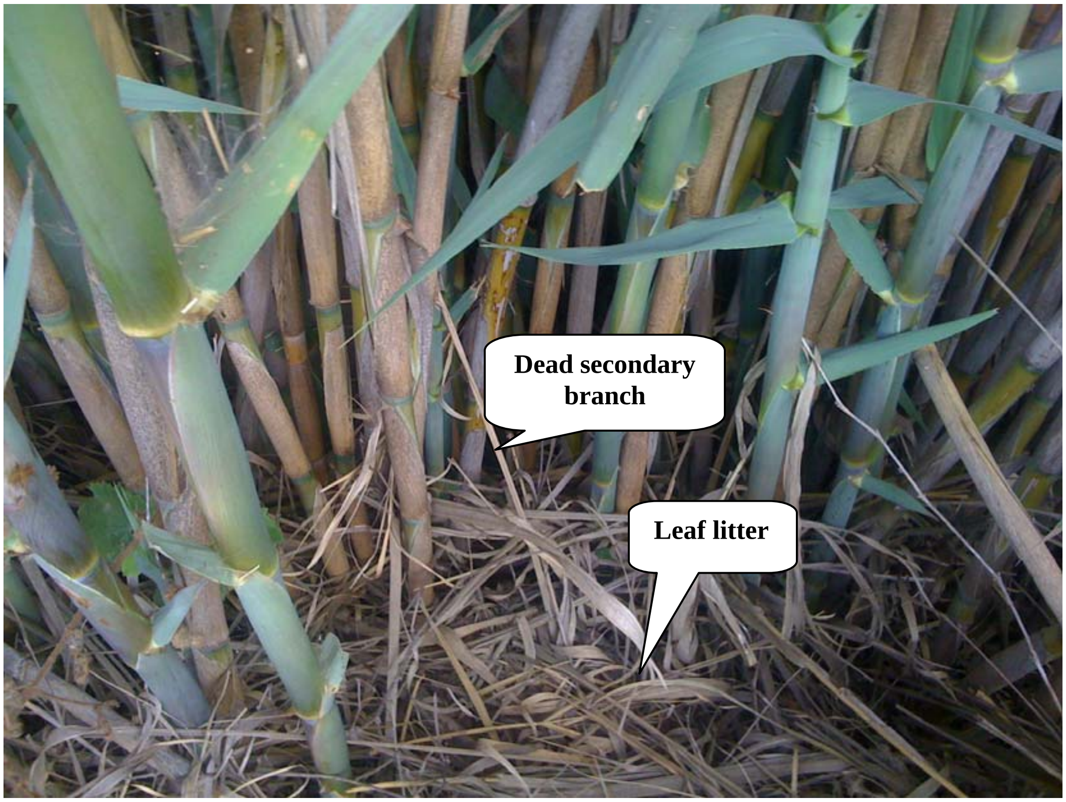


**Figure 2-18.** Cane density and dead leaf litter within a dense *Arundo* stand.

## 2.4 Biomass and Cane Density

Biomass (above and below ground) generated from *Arundo* is important as it sheds light on several factors related to impacts caused by the plant. It provides information on productivity, resource consumption (nutrients, light, and water), physical presence in the system (with impacts to flows, sediment, wildlife, light, wind, and other physical parameters), as well as indicating issues with the fate of the biomass material itself (both in aquatic and terrestrial portions of the watershed system).

*Arundo* has very high amounts of biomass per unit of land area as documented in many studies looking at standing biomass of wild infestations and annual productivity of cultivated stands (Table 2-5). This study found an adjusted *Arundo* stand biomass of 15.5 kg/m2, which is corroborated by the most comprehensive study evaluating *Arundo* biomass (Spencer 2006). The large amount of biomass is related to high productivity of the plant, high density of individuals (high cane density), and tall growth form of the plant (average 6.5 m in southern California). In addition to the high amount of biomass per unit of land area, *Arundo* has a large amount of energy per unit of dry weight (17 MJ/kg to 19.8 MJ/kg, see chapter 6). These values compare favorably with other fuel crops (*Arundo* is one of the highest) and are higher than most native tree, scrub, and herbaceous assemblages in the riparian zone. This is why fuel crop producers consider *Arundo* one of the top potential biofuel crops.

Belowground biomass estimates have been less studied, but appear to be in the range of 22.5% of the total plant/stand biomass (Sharma et al. 1998). Applying this proportion of above and below ground biomass generates overall estimates of 20.0 kg/$m^2$ or 89 t/acre (Table 2-6). These biomass levels are at the upper end of any vegetation class (Table 2-7), and are well above typical riparian vegetation values.

**Table 2-5.** *Arundo* aboveground biomass from various studies (wild and cultivated).

| **Location** | **Description** | **Above ground dry mass** | **Source** |
|---|---|---|---|
| U.S. -<br>13 sites across US | Biomass of stands in field: wild | 17.1 kg/m$^2$<br>171 t/ha<br>76 US t/ac | Spencer 2006 |
| U.S. - 14 sites,<br>6 coastal watersheds in southern California | Biomass of stands in field: wild | 15.5 kg/m$^2$<br>155 t/ha<br>69 US t/ac | This study |
| India | Biomass of stands in field: wild | 3.6 to 16.7 kg/m$^2$<br>36 to 167 t/ha<br>16 to 74.3 US t/ac | Sharma et al. 1998 |
| Southern CA<br>(Santa Clara) | Annual yield<br>(post fire): wild | 49 t/ha<br>21.8 US t/ac | Ambrose & Rundel 2007 |
| India – wild stands | Annual yield: wild | 72 t/ha<br>32 US t/ac | Raitt 1913 |
| Australia | Annual yield: crop | 101 t/ha<br>45 US t/ac | Williams et al. 2008 |
| Europe | Annual speculated max yield: crop | 100 t/ha<br>45 US t/ac | Shatalov & Pereira 2000 |
| Italy | Annual yield: crop | 30 t/ha<br>13.4 US t/ac | Angelini et al. 2005 |
| Italy – cultivated stands | Annual yield: crop | 39.3 t/ha<br>17.5 US t/ac | Marinotti 1941 |
| Greece | Annual yield: crop | 120-230 t/ha<br>53.4-102.4 US t/ac | Mavrogiapolus et al. 2001 |
| Greece | Annual yield (Yr 1, new crop): crop | 15 t/ha<br>6.7 US t/ac | Hidalgo & Fernandez 2000 |
| Greece | Annual yield (Yr 2): crop | 20 t/ha<br>8.9 US t/ac | Hidalgo & Fernandez 2000 |
| Greece | Annual yield (Yr 3): crop | 30 t/ha<br>13.4 US t/ac | Hidalgo & Fernandez 2000 |
| Greece | Annual yield (Yr 4, mature): crop | 39 t/ha<br>17.4 US t/ac | Hidalgo & Fernandez 2000 |
| Spain | Annual yield: crop | 45.9 t/ha (ave)<br>29.6-63.1 t/ha (range)<br>13.2-28.1 US t/ac | Hidalgo & Fernandez 2000 |

**Table 2-6.** Above and below ground biomass values for *Arundo*, using relationship from Sharma 1998 (22.5% of biomass is below ground).

| Study | Above ground biomass | Below ground biomass | Total biomass |
|---|---|---|---|
| This study | 15.5 kg/$m^2$<br>155 t/ha<br>69 US t/ac | 4.5 kg/$m^2$<br>45 t/ha<br>20 US t/ac | 20.0 kg/$m^2$<br>200 t/ha<br>89 US t/ac |
| Spencer 2006 | 17.1 kg/$m^2$<br>171 t/ha<br>76 US t/ac | 5 kg/$m^2$<br>50 t/ha<br>22 US t/ac | 22.1 kg/$m^2$<br>221 t/ha<br>98 US t/ac |

**Table 2-7.** Typical biomass values for different vegetation types.

| Study | Above ground biomass | Study |
|---|---|---|
| Willow forest (as crop) | 4-8 t/ac (annual)<br>15 t/ac (4 year growth) | Turhollow 1999 |
| Switch grass | 5 t/ac | Turhollow 1999 |

## 2.5 Growth Rate

Individual Ramet or Cane Growth:

When conditions are favorable, *Arundo* canes can grow 0.3-0.7 m per week over a period of several months (Perdue 1958). Young stems rapidly achieve the diameter of mature canes, with subsequent growth involving thickening of the walls (Perdue 1958). Annual yield studies demonstrate the productivity of *Arundo* stands (Table 2-5). Old canes typically have little new growth on the main leader (Decruyenaere & Holt 2005), but have extensive growth on secondary branches, as well as growing new secondary branches. In colder regions of the world *Arundo* dies back and then resprouts, although frost can damage the plant if it occurs after initiation of new growth (Sharma et al. 1998, Perdue 1958). In southern California dormancy is limited to total to partial browning of the canes and leaves during the winter.

Rhizome Growth:

In mature stands, most new shoots develop from large apical buds at rhizome termini, resulting in relatively evenly spaced, vertically oriented shoots 2 cm or more in diameter (Decruyenaere & Holt 2005). Rhizome growth extends laterally along an axis, but will branch (Figure 2-8). Rhizomes appear to 'self-discriminate', growing into areas with no rhizomes present (Decruyenaere & Holt 2005). Stands expand 7-26 cm/year (Decruyenaere & Holt 2005), as well as generating higher density. Comparisons of imagery over a 10 year period for sites in San Diego showed minor (none visible) to moderate

(0.5m/yr) expansion of established stands. Generally expansion was surprisingly slow, but highly variable. A few studies have examined expansion and lateral spread of rhizomes and canes, but these data are presented as increasing cane density within quadrats. Future studies should more explicitly describe length (m) or area ($m^2$) of spread.

Stand Growth:

Three general factors seem to affect growth rates of both canes and rhizomes: 1) availability of water, 2) availability of nutrients and 3) temperature regimes (affected by shade). Water availability seems to be the primary factor restricting the growth of *Arundo* stands in coastal California. This is based on field observations across the study area and our review of transpiration and nutrient studies. Generally watersheds in coastal California have favorable temperature ranges and are not nutrient limited. Areas with water available throughout the year develop into dense, tall *Arundo* stands. Areas with low water availability, such as upper terraces that are far from the water table, frequently have *Arundo* stands with lower cane density, shorter stature, and large amounts of dead material in the canopy (an indicator of stress).

Riparian systems are typically not nutrient limited in coastal California (Peterson et al. 2001, Suffet & Sheehan 2000). Artificially high nutrient levels increase growth rates of all riparian vegetation, but *Arundo* with its higher productivity potential (compared to native vegetation) is able to capitalize on this, turning it into a competitive advantage (Ambrose and Rundel 2007).

**Nutrient use/nutrient loaded systems:**

In the last century, nutrient inputs to river systems have increased dramatically due mainly to agriculture and municipal sewage. These same nutrient inputs are present in high quantities in the rivers of Southern California’s watersheds (Pederson 2001, Suffet and Sheehan 2000). Nationwide, the use of fertilizer in agricultural areas has increased from 20 to 40 million tons annually. The average percent of nitrogen, the main constituent in commercial fertilizers, has risen from 6.1 to 20.4 % (Texas Water Resources Institute 1986). This increase in use and composition of fertilizer alone has led to a loading of river systems with nutrients, mainly nitrogen and phosphorus. Nitrogen, found in the form of nitrate in fertilizer, poses unique risks to river systems; it is soluble and moves quickly through soils in the shallow groundwater between agricultural practices and rivers. Phosphorus, on the other hand, is not very soluble and typically adheres to soil particles. Other anthropogenic and natural sources are thought to have also contributed to nutrient loading in river systems, including: nitrogen enriched rainfall and air; manure from animal feedlots and corrals; fertilizer applied to lawns; leaky septic tanks; oxidation of organic materials; and the symbiotic nitrogen fixation by plants.

## 2.6 Reproduction and Spread

This discussion is separated into spread within a site, spread within a watershed, and spread between watersheds.

### *2.6.1 Within Stand Spread*

Once *Arundo* is present at a given location it grows and spreads laterally. Lateral spread occurs mainly through lateral rhizome growth and budding (forming new ramets or individuals in the asexual colonial

*Arundo* stand) (Decruyenaere & Holt 2005). In addition, *Arundo* canes can drape/bend over and touch the soil surface, and if conditions are favorable (wet and/or sediment covering a node) a new bud may form (developing into a new ramet or individual) (Boland 2006).

### *2.6.2 Spread Within A Watershed*

*Arundo* is dependent on asexual reproduction. *Arundo* plants in North America do not appear to produce viable seed. Multiple studies in California have determined that seedlings are not present in the wild (Else 1996, Witje et al. 2005) and that plants that flower do not produce viable seed (Khudamrongsawat et al. 2004). Studies in India indicate that the apparent sterility of *Arundo* seed is caused by the failure of the megaspore mother cell to divide (Bhanwra et al. 1982).

New individuals within a watershed and the colonies they grow into are created through vegetative propagation. This occurs when plant fragments, usually rhizomes, become rooted at new locations and form into separate plants. Dispersal generally occurs during flood events, when floodwaters break off pieces of *Arundo* plants and transport them downstream (Else 1996, Decruyenaere & Holt 2005). Establishment of new *Arundo* stands within a watershed is, therefore, generally limited by the extent of river flow and floodplain inundation. However, *Arundo* fragments can also be moved to new locations within a watershed via human disturbance.

Several studies have shown that almost any segment of stem or rhizome can sprout if it possesses an axillary bud (Boose and Holt 1999, Wijte et al. 2005, Else 1996). Buds occur at the stem nodes and approximately 5-10 cm apart on the rhizomes (Wijte et al. 2005). Both rhizomes and stems can withstand a certain amount of drying out and still sprout. Drying rhizomes to 58.8% moisture loss and stems to 36.5% moisture loss did not affect their ability to sprout (Else 1996). Rhizomes were able to sprout when buried up to one meter deep (Else 1996), but stems have shown reduced sprouting at depths as low as 10 cm due to limited energy reserves in the stem (Boose and Holt 1999).

Else (1996) reported that of *Arundo* vegetative reproduction observed following dispersal by flooding on the Santa Margarita River in San Diego County, 57% was from rhizomes, 33% was from stem fragments, and for the remaining 7% the plant part that gave rise to the new plant could not be identified. Rhizomes are frequently broken off at bank edges when they are undercut (Brinke 2010) or scoured out (Figure 2-7). Any disturbance (natural or human caused) that mobilizes live rhizome material during conditions that are favorable for establishment will likely result in spread of *Arundo*. Flow events will break off rhizome fragments along stand edges and disperse them within flow areas (Brinke 2010). For this reason significant spread of *Arundo* within a watershed is episodic. Flows reach higher geomorphic forms (floodplain and terraces) only during large events. These large hydrologic events mobilize *Arundo* material for potential asexual propagation. Low flow events are confined to channel areas. New *Arundo* establishment in this area is often removed during later flood events. Little propagule material is typically mobilized during these low flow events in comparison to larger events, but undercutting of *Arundo* stand edges does generate a steady amount of propagules downstream.

The combination of within watershed dispersal events and stand growth rates generates a pattern of expansion that increases episodically to the system's maximum carrying capacity for *Arundo*. Larger watersheds with favorably wide floodplains have about 13% *Arundo* cover, but portions of these systems can have cover >44%.

### *2.6.3 Historic Air photo Analysis: Stand Growth Rates and Spread Within Watershed*

Review of historic aerial photography on watersheds in the study area indicated some interesting patterns of spread and growth. The basic pattern that repeated on most watersheds was that there was little *Arundo* present on most systems from the 1930's to the 1960's. It looks as though *Arundo* was present as scattered clumps and small stands. Aerial photography during this time was of low resolution and black and white, limiting our ability to detect and map *Arundo*. Large stands of *Arundo* would have been detectable, but they were not present. The overall historic extent of *Arundo* on most systems was scattered with low total acreage. As will be seen later in this report (Chapter 5), this makes sense, since historically riparian systems were broad and dry.

In the 1960's riverine systems became much narrower (levees and land use change) and water was imported. This resulted in perennial flows on many systems or at minimum, significantly raised water tables. *Arundo* responded to these changes by aggressively spreading and growing into dense stands. This transformation occurred during the 1970's and 1980's on most systems. By the 1990's *Arundo* had achieved an extensive distribution that appears to be at or near the current distribution of the plant.

Lateral expansion of established stands appeared to be fairly slow, on the order of 1 to 2 feet a year. Disturbance events (fire, grading, clearing, flood action) and the subsequent growth seem to be more important to rapid expansion of *Arundo* than the slow lateral growth of established stands. The concurrent use of both growth strategies allows *Arundo* to become abundant on southern California watersheds that are characterized by episodic flow events. Review of historic aerial photos indicated that significant spread of *Arundo* within a watershed appears to be very episodic. Large magnitude flow events (25 to 100 year) are necessary for the plant to actively invade significant new areas in a riparian system, particularly higher floodplains and terraces.

### *2.6.4 Spread Between Watersheds*

The spread of *Arundo* between watersheds is primarily due to humans moving *Arundo* plants (planting or dumping biomass) or soil/fill material contaminated with *Arundo* fragments. *Arundo* fragments can wash up into estuaries, but generally cannot get very far up into the riparian system as river flows push material out of the system.

## 2.7 Ecological Function: Abiotic and Biotic

### *2.7.1 Abiotic*

Invasive species that modify abiotic ecosystem processes have significantly greater impacts than those that affect only biota (flora and fauna) because abiotic processes shape and control the entire ecosystem. *Arundo* strongly affects riparian abiotic processes, including: hydrology/geomorphology (including flooding - Chapter 5, water use/transpiration - Chapter 4) and fire (Chapter 6). *Arundo*'s strong influence on these ecosystem properties has two main consequences: 1) it modifies the habitat in ways that impact native flora and fauna, and 2) it modifies habitat in ways that benefit its own growth and continued spread. The modification of flows, geomorphology and sediment transport strongly affects successional patterns of vegetation. *Arundo*’s proliferation indicates that it benefits from this alteration of river processes. The significant increase in fire events (area and frequency, as documented in Chapter 6) and intensity also favors *Arundo*, as it is more productive than native vegetation after fire events (Ambrose & Rundel 2007).

### *2.7.2 Biotic*

#### 2.7.2.1 Vegetation

*Arundo* tends to form dense, monotypic stands that replace native riparian vegetation and naturally occurring open areas between vegetation groups. The displacement of native vegetation results in changes to vegetation composition, vegetation structure, and food resources. These changes have impacts on the native flora and fauna.

When *Arundo* forms dense stands, there is generally less plant diversity in comparison to un-invaded areas. A study in the Russian River in northern California showed that *Arundo* invasion was associated with significantly lower richness of native perennial plant species on stream banks, but not on gravel bars (Cushman and Gaffney 2010). Plots invaded by *Arundo* exhibited significantly lower native and exotic species richness and abundance of both established plants and seedlings than un-invaded plots. In coastal southern California watersheds, *Arundo* often displaces nearly all vegetation, leaving only mature gallery trees, which have a canopy layer higher than the *Arundo* stand (Figures 2-15 & 16). Native vegetation displacement is particularly pronounced in the shrub, perennial herb and annual herb growth form classes. Within dense *Arundo* stands there is generally little or no understory vegetation (Figure 2-19). In addition to displacing native vegetation, *Arundo* also alters the habitat by filling in areas that would naturally be open and unvegetated. Open portions of riparian habitat can be critical for fauna that use these areas for movement (both within and through the habitat). Unvegetated soil substrate can also be a place of refuge (both sand and litter covered).

A system that has dense stands of *Arundo* affects abiotic processes, tending to have a higher fire frequency and intensity, as well as altered flooding patterns. Removal of riparian vegetation by *Arundo* exacerbated flood and fire events alters the natural riparian successional patterns, and generally leads to more dominance of *Arundo*. This is an important positive feedback loop that leads to type conversion (Ambrose & Rundel 2007).

*Arundo*'s impacts on vegetation and federally listed plants will be discussed further in Chapter 7.

#### 2.7.2.2 Arthropods

Several studies have examined the impacts of *Arundo* on arthropods. All have indicated reduced diversity, density and/or productivity of arthropods within *Arundo* stands compared to native riparian vegetation. Native riparian vegetation in Sonoma County in spring contained twice the abundance, biomass, and species richness of aerial insects compared to *Arundo* (Herrera & Dudley 2003). Furthermore, insects recorded in *Arundo* were rarely observed feeding there, indicating that *Arundo* is used for its structure more than as a food source. Ground dwelling insects showed the same responses to *Arundo*, but to a lesser degree than aerial insects. Habitat that contained a mixture of *Arundo* and native riparian habitat showed an intermediate response. The *Arundo* infestation within the study area was at a much lower level than some southern California systems. High cover stands would likely show even less use.

Studies on arthropod use of *Arundo* leaf material indicate it is of low quality for native arthropods. Aquatic caddisfly larva survival was much lower for individuals fed *Arundo* (20%) compared to Alnus, Salicaceae, or Tamarix litter (85%) (Going & Dudley 2008). The high concentration of secondary compounds (tannins, alkaloids) and silica in *Arundo*, and the low nitrogen levels are likely to be poor food resources (Khuzhaev & Aripova 1994, Wynd et al. 1948).

Invertebrate species assemblages within soil and leaf litter in *Arundo* stands tend to be opportunistic forms that generally do not utilize the plant tissue directly and tend to be non-native. Invertebrates associated with *Arundo* rhizomes in southern California followed this pattern (43% non-native), and non-native detritivorous isopods were the most abundant in the Sonoma County study (Lovich et al. 2009, Herrera & Dudley 2003).

The preference of arthropods for native riparian vegetation over *Arundo* stands is likely due to the greater habitat structure, the more complex and massive litter layer, and the higher quality food resources. Despite its large biomass per square meter, *Arundo* appears not to provide much to the food web. This has significant impacts on wildlife. A large reduction in aerial insects, in particular, could have serious negative impacts for insectivorous birds such as the endangered least Bell's vireo (*Vireo bellii pusillus*) and southwestern willow flycatcher (*Empidonax traillii extimus*).

### 2.7.2.3 Wildlife

Dense *Arundo* stands can negatively impact fauna through a reduction in food resources, alteration in structure for nesting/denning, and creation of a physical barrier to movement within and through riparian habitat to upland areas (wildlife corridor). While there have not been many studies that document all of these impacts, they do seem probable based on the limited research that does exist, coupled with personal field observations and wildlife specialists' assessments as reported in management plans and regulatory documents. *Arundo* biomass has the potential to contaminate pools and areas used by native fish and amphibians for breeding and feeding, and can impact wildlife on beaches and estuaries where it collects after flood events. *Arundo* biomass piles and live plants may also create structure in areas where none naturally occurs, which may impact predation.

Studies on the use of *Arundo*-invaded habitat by wildlife are often compromised by native riparian habitat adjacent to and/or dispersed within the *Arundo* stands. Large continuous stands of *Arundo* do exist, but they are difficult to monitor as the density of canes restricts access to interior portions of the stand. Species frequently have territories/ranges that include *Arundo*-invaded and un-invaded habitat. Even with this caveat, patterns are still apparent.

Many reports and surveys have identified *Arundo* as a factor in reduced habitat fitness for reptiles and amphibians, although there are no specific research studies. Since reptiles and amphibians are highly dependent on specific hydrological/geomorphological processes occurring, they may be severely impacted due to *Arundo*'s complicated, long-term impacts on hydrology, geomorphology, and water use. This report explores these impacts in depth, and the impacts appear to be significant. *Arundo* stands can impact reptiles and amphibians by creating physical barriers to their movement within the riparian habitat, and to adjacent upland areas. Arroyo toads appear to avoid *Arundo* stands on MCB Camp Pendleton (Camp Pendleton Land Management Branch Reports and pers. comm. with land managers), but are dependent on migrating from breeding pools to upland habitat. Specific impacts will be explored for four endangered reptiles and amphibians in Chapter 7.

*Arundo* impacts on geomorphology/hydrology, especially channel and pool formation, are likely to be significant factors affecting fish species. There may also be impacts associated with contamination by large amounts of *Arundo* biomass within pools and other areas used for breeding and juveniles. It is generally thought that *Arundo* does not shade the waterway in the same way as native vegetation, resulting in increased water temperatures that would negatively affect fish and amphibian species. However, there is no published data on temperature in *Arundo* dominated streams as compared to native vegetation. Of greater consequence would be *Arundo*'s impact on channel depth, width, and number of channels/braiding (Chapter 5). Deeper, narrower channels may be cooler, but they also have reduced feeding opportunities and appropriate substrate may be lacking. Wrong depth and aspect, and higher water velocity may also impede movement and/or cause reproduction to fail. Four endangered fish are examined in Chapter 7, with a more detailed discussion of *Arundo* impacts on habitat, movement/migration and reproduction.

*Arundo* impacts bird species due to its physical structure and its apparent reduction in abundance and diversity of insects (available data primarily relate to insectivorous species). In three drainages in southern California, *Arundo* stands contained reduced abundance and species richness of birds compared to native stands (Kisner 2004). The number of non-listed avian species declined by 32-41% as *Arundo* cover increased from 0 to 50%. Species richness of both ground and foliage gleaning birds declined in areas with increased *Arundo* cover. Preliminary results of a study on the lower Santa Clara River in southern California show diminished avian species diversity and fewer total individuals in *Arundo* stands relative to native stands, with intermediate diversity in mixed patches (Orr 2010). *Arundo* may also affect bird abundance as avian species rarely use it for nesting. The branching structure of *Arundo* is very different from native shrubs and trees, and it is presumed that it does not provide the architecture or support required for nesting. In the Prado Basin on the Santa River in southern California, from 1987 to 2006, only 0.8% percent of least Bell's vireo nests were in *Arundo*, compared to 76% in willow and mulefat (Pike et al. 2007). *Arundo* biomass washes downstream during flood events and can collect within estuaries and beaches. On the Santa Margarita River watershed, large piles of dead and sprouting *Arundo* eliminate nesting sites for Western snowy plovers and increase the presence of predators, which use it as perches and prey on rodents in the piles of vegetation (USFWS 2001). Eight endangered bird species will be reviewed in Chapter 7.

*Arundo* has complicated effects on mammal species. *Arundo* stands may provide areas for dens, but food resources are lower in comparison to native plants due to lack of seed and low quality forage. The dense cover and growth reduces mobility of mammals, which could reduce the use of riparian habitat as corridors for movements. This would be a significant impact and it remains undocumented. One endangered mammal, the San Joaquin kit fox, will be examined in Chapter 7.

## 2.8 *Arundo* Biology: Conclusions

Several observations were made in field studies, including:

- Mature stands are taller than has been typically reported in the literature: 6.5 m mean and a range of 2.6 – 9.9 m. (Section 2.3)
- Adjustments need to be made when scaling up from cane specific data to stand data due to canes not actually emerging within all areas of the *Arundo* canopy. Areas along edges and gaps within stands few to no canes. (Section 2.3)
- Biomass per unit area measured in this study is very high for mature *Arundo* stands: 15.5 kg/m$^2$. This is in general agreement with the literature. (Section 2.4)
- Reviewed literature demonstrates that *Arundo* spreads through asexual propagation (fragments of rhizomes and, infrequently, canes). Seeds are not viable. This makes *Arundo* spread dependent on flood action or anthropogenic disturbance. (Section 2.5)
- Review of historic aerial photography indicates that spread of *Arundo* within a watershed is very episodic. Large magnitude (50 to 100 year) events are necessary for the plant to actively invade significant new areas in a riparian system, particularly floodplains and terraces. (Section 2.6.4)