ARI
Final Report

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B. Reporting Period: **July 1, 2003-March 30, 2006**

C. Project Number: **49508**

D. Project Title: **Development of a Predictive Model for *Arundo donax* Based on Climate in California**

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H. Executive Summary:

The main objective of this project was to develop a predictive model that would aid land managers in their fight to control the invasive grass, *Arundo donax* (giant reed), hereafter referred to as Arundo. We developed a climatic database representative of the diverse ecoclimatic regions of California for the purposes of predicting species success or failure based on factors such as temperature, moisture, light, and relative humidity. Specifically, we formatted the database for use in the simulation building software, CLIMEX and DYMEX. The response of Arundo to moisture and temperature gradients were characterized and quantified. The parameters from these characterizations were used to develop growth simulation models in CLIMEX and DYMEX. The CLIMEX simulation predicted that all sub-alpine locations of riparian habitat would be susceptible to Arundo growth with the greatest threat to warmer regions of California. It also illustrated the significant water requirement of Arundo in order for it to become a serious threat under most California climates. The simulation developed in DYMEX illustrated the stochastic nature of success and failure of a species associated with the fluctuations of actual weather patterns. DYMEX predicted the characteristic sigmoidal development expected of an invasive species such as Arundo in riparian habitat on the central coast of California. Control simulations demonstrated the limited utility of fire or other foliage removing measures in controlling Arundo. Cutting the plants at the 10 tiller or greater stage and treating with concentrated glyphosate (termed the "hack and squirt" method) in August-September provided the best chance of completely removing Arundo. However, the method was predicted to require three years of successive application and must be initiated when the population just begins to infest a site.

I. Major Accomplishments:

The primary objective with this research was to develop climatically based simulation models to assess the threat of the invasive grass, *Arundo donax* (giant reed), hereafter referred to as Arundo, and then develop predictions for how to best control this species on the California Central coast. Four lifestages were identified previously as key to the survival and success of Arundo by Holt and Boose (2000): rhizome, sprout, juvenile (4 tiller), and mature adult (10 tiller or greater) (FIGURE 1). Arundo does not produce viable seed in California, and therefore, was not followed in this project. Arundo is currently most prolific in southern California riparian habitat, but has been found in large populations in northern California along waterways in the Sacramento valley.

FIGURE **1.** *Arundo donax* lifestages utilized for model. The sprouts (a) appear from rhizomes (b) during the spring of each year. Mature adult plants (c) can attain heights exceeding 40 feet.

Objective 1. AUGMENTATION OF CLIMEX AND DYMEX CLIMATIC DATABASES
Acquiring additional database:

- The CLIMEX and DYMEX software come with a limited climatic database for California. To increase the spatial resolution of CLIMEX and DYMEX, data were added from 319 weather stations throughout California to the meteorological database. This included average monthly values of maximum and minimum temperatures for each station. Average precipitation was also added. Weather data were downloaded from U.S. Department of Commerce National Oceanic Atmospheric Administration's (NOAA) website (http://www.noaa.gov/wx.html) and subsequently reformatted for use in CLIMEX and DYMEX using the macro-generating tools available in Microsoft Office Excel (version 2003). Few of these NOAA climate stations collect data for relative humidity. In order to make reliable predictions for California a novel method had to be developed to provide values for relative humidity for these locations using the relationship of air temperature with water vapor pressure and the mol fraction of water to predict the relative humidity (see below). Vapor pressure values were obtain from DAYMET, a large modeled climatic database that uses a raster grid (Kimball et al. 1997; Thornton et al. 1997; Thornton and Running 1999; Thornton et al. 2000). Therefore, we can extrapolate information from this database to any precise longitude:latitude in the United States. FIGURE 2 is an excerpt from the website (http://www.daymet.org/default.jsp). It was developed to provide fine

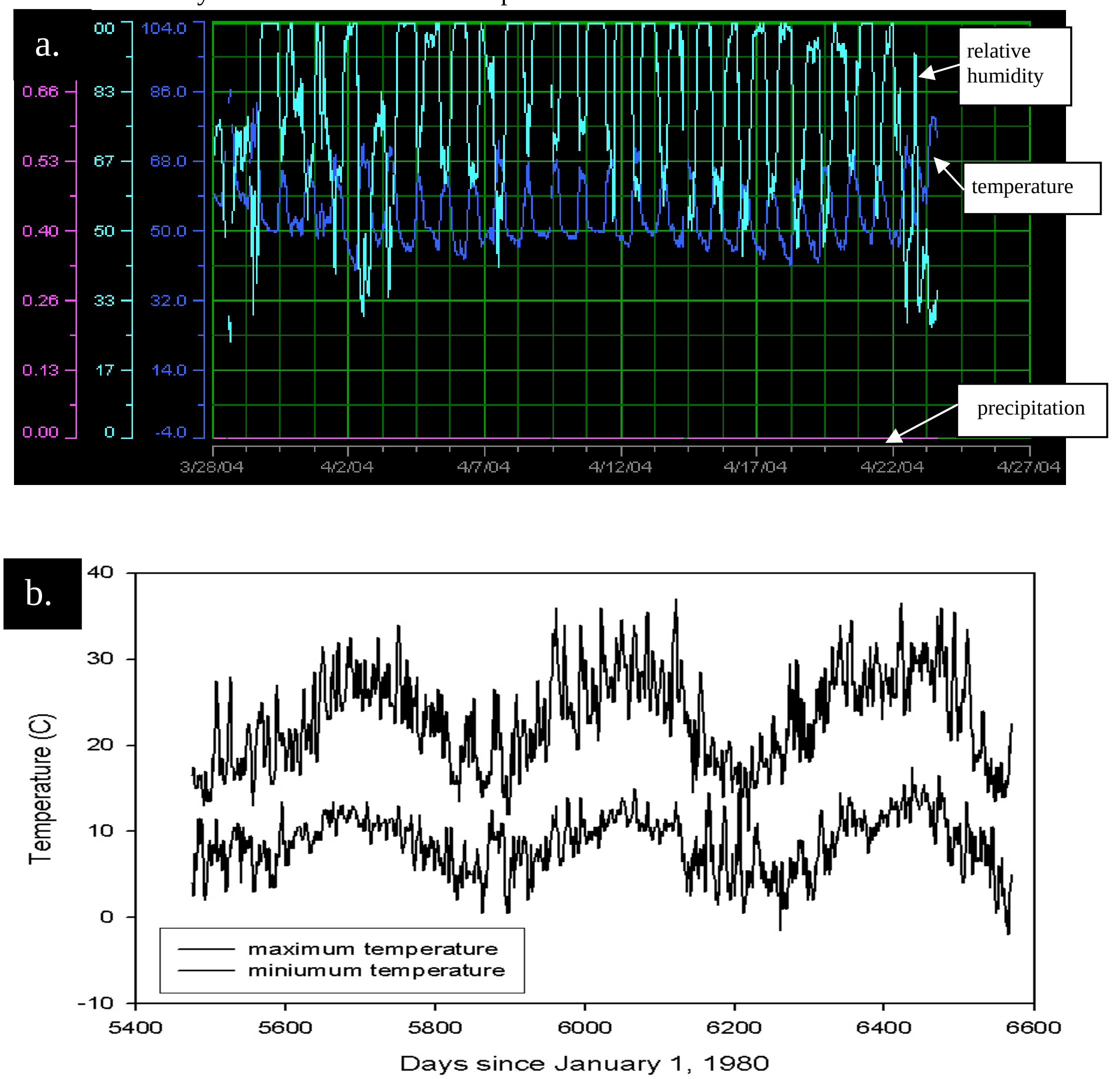


FIGURE 2. Sample of climatic data from the Western Farm Service used for validation purposes (a) and the DAYMET climatic database used to augment the CLIMEX/DYMEX meteorological database (b) showing temperatures from March 2004 through April 2004 and January 1, 1995 through December 31, 1997, respectively.

resolution, daily climatological and meteorological data for plant growth model inputs. Data is provided as a continuous surface of the conterminous United States at a 1 km resolution. This data is distributed from the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana. The DAYMET model generates daily surfaces of temperature, precipitation, vapor pressure, and radiation over large regions of complex terrain. Using a digital elevation model and daily observations of minimum and maximum temperatures and precipitation from ground-based meteorological stations, an 18 year daily data set (1980 - 1997) of temperature, precipitation, humidity and radiation has been produced as a continuous surface at a 1 km resolution. A wide range of summary and point daily data over the conterminous United States is now available on-line. No other data at this temporal and spatial resolution exists. We validated the DAYMET data and our calculations for relative humidity for several locations in California using a Western Farm Service database of remote weather stations with access provided by Luis Aguilar, an Adcon Telemetry Technician for Western Farm Service (FIGURE 2). Western Farm Service collects weather data from their growers' fields using weather stations, which provide temperature, precipitation, and relative humidity.

- ***Relative humidity calculations:*** To estimate the relative humidity values required as input for CLIMEX and DYMEX we utilized vapor pressure values extracted from DAYMET. Relative humidity refers to the value of vapor pressure (VP) relative to saturated vapor pressure (sVP) or water vapor relative to the temperature of the air. Relative Humidity is provided by the equation:

$$RH = 100 \times \frac{VP}{sVP} \qquad \text{Eq. 1}$$

Data were presented as the 18-year (1980-1997) mean of the monthly vapor pressure values. Data is available as binary (floating point) grids. They were imported into Arcview 9 as raster grids using the spatial analyst extension. Point data for climate station locations were then overlaid and corresponding raster grid values were extracted. These vapor pressure values were incorporated into equation 1 (Eq.1). Next, saturated vapor pressure, sVP(T)(Pa), at temperature, T (^{o}C), for equation 1, was estimated using the Murray formulation (Murray 1967):

$$sVP(T) = 610.78 \exp\left[\frac{17.269T}{237.3+T}\right] \qquad \text{Eq. 2}$$

CLIMEX and DYMEX requires 'Relative Humidity' values at two specific times of the day (9:00 and 15:00 hours). The corresponding temperature values (T) for equation 2 (Eq.2) at these two times were derived from the equation:

$$T(t) = -0.32815 + 0.96592\ T - 0.43503\ R \cos\left(\frac{\pi(t)}{12}\right) - 0.14453\ R \sin\left(\frac{\pi(t)}{12}\right) + 0.09995\ R \cos\left(\frac{\pi(t)}{6}\right) + 0.0245\ T \sin\left(\frac{\pi(t)}{6}\right) \qquad \text{Eq. 3}$$

where T(t) is the predicted surface temperature at any time t (in local military time), T is the daily mean temperature and R is the daily range of temperature (all in ^{o}C) (McCutchan 1979). This equation requires values for maximum and minimum temperatures as input. These values were provided by actual mean monthly maximum and minimum temperatures provided by the 319 weather stations used. These humidity values were then added to the new CLIMEX and DYMEX meteorological database. Two files were created: a ***.met*** file with the meteorological data for each site and a ***.loc*** file that contains the GPS coordinates for each of the weather stations. These files were subsequently imported into the meteorological database using the program's **met manager** function. CLIMEX's mapmanager feature was then used to create a corresponding map for the new dataset.

- The augmented database represents a significant improvement in resolution for any investigator wishing to look at climatic suitability for a species: plant or animal, native or non-native, pest or desirable. California has many diverse ecoclimatic regions ranging from Mediterranean to desert to alpine to temperate. The limited meteorological database typically available on simulation models will essentially average over significant biological and ecological nuances associated with species success or failure. This averaging effect will tend to underestimate the positive or detrimental effects of climatic amplitudes that occur in diverse ecoregions. Our database and the methods utilized to generate it are novel and will aid policy makers and land managers in assessing invasive species threat.

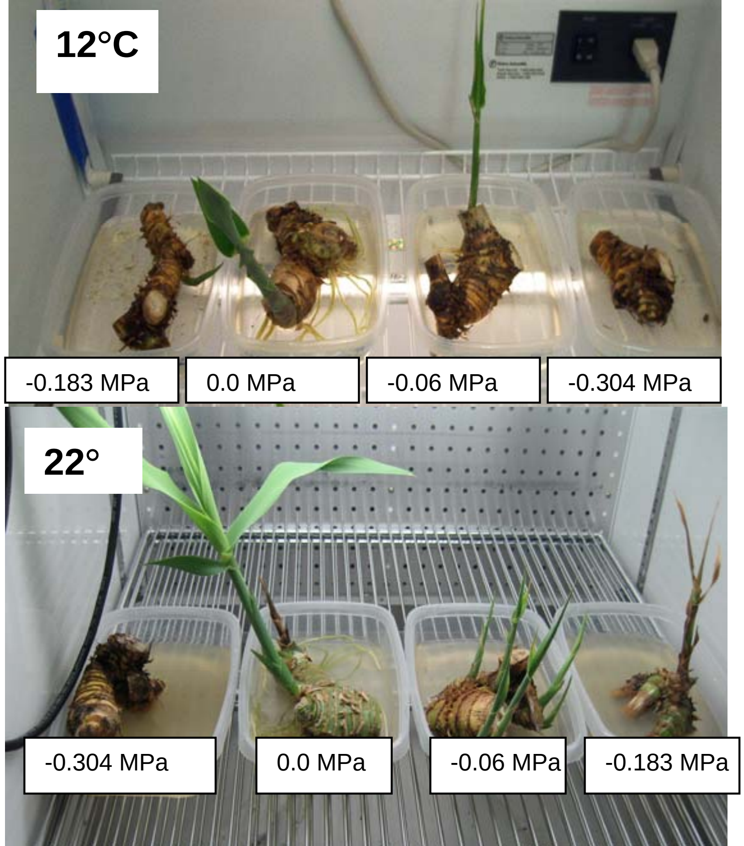


FIGURE 3. Experimental design using polyethylene glycol (PEG) solutions to simulate a water status of -0.304, -0.182, -0.060 MPa and distilled water (0.00 MPa) for the *Arundo* rhizomes. Shown is one block (shelf) with a "grow" light and the four clear plastic containers with rhizomes at various stages of sprouting.

Objective 2. DETERMINE TEMPERATURE AND MOISTURE PARAMETERS

- ***Controlled environment studies:*** Polyethylene glycol (PEG) has been used to test seed germination under a simulated moisture gradient (Cheng and Bradford (1999). In a unique approach, we utilized PEG to create a moisture gradient to measure moisture response for Arundo rhizomes. Using the Michel equation, PEG solutions were mixed to simulate -0.304, 0.182, 0.060 MPa (Michel 1983). Distilled water was used to for the 0.00 MPa condition. Solutions were validated to within 0.01MPa of their target osmotic level with a vapor pressure osmometer (Wescor VAPRO 5520). This experimental design provided the most consistent sprouting results of other designs that relied on maintaining specified moisture levels in a volume of soil (FIGURE 3). There has not been any reported research where PEG solutions have been used to assess rhizome sprouting in response to water status.
- Rhizome sprouting progressed in all trials according to a typical pattern where more negative water potentials (drier) demonstrated longer durations to sprouting, bud break (FIGURE 3-5).
- Survival analyses using proportional hazards modelling (Cox regression) revealed no significant moisture effect when temperatures were below about 20°C (FIGURE 4 AND 6). This is indicative of a significant interaction between the effect of moisture and temperature.

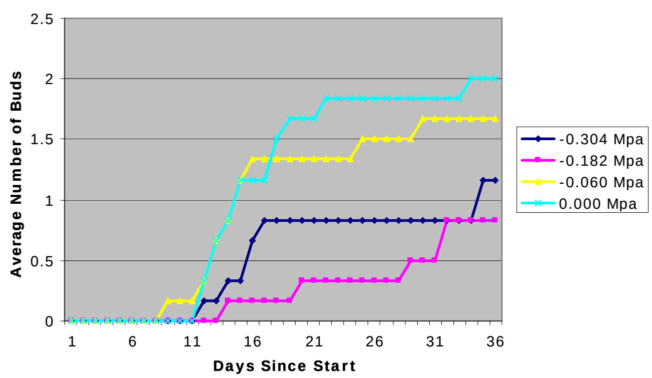


FIGURE 5. Sprouting progression (average number of buds emerging per rhizome) for the various moisture treatments from a growth chamber trial in April 2004

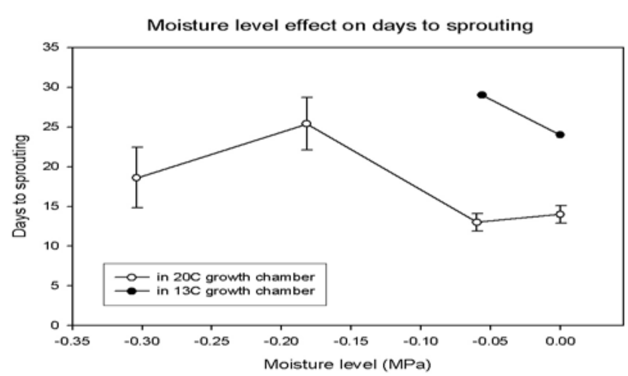


FIGURE 4. Moisture effect on days to Arundo rhizome sprouting for rhizomes grown at 20C and 13C.

- An interesting relationship that was observed in the growth chamber trials was that a large initial rhizome biomass effectively insulates the rhizome from drier conditions, allowing sprouting times to approach those where moisture conditions were not stressful (FIGURE 7). Therefore, moisture may not play a crucial role in time to sprouting for larger rhizomes.

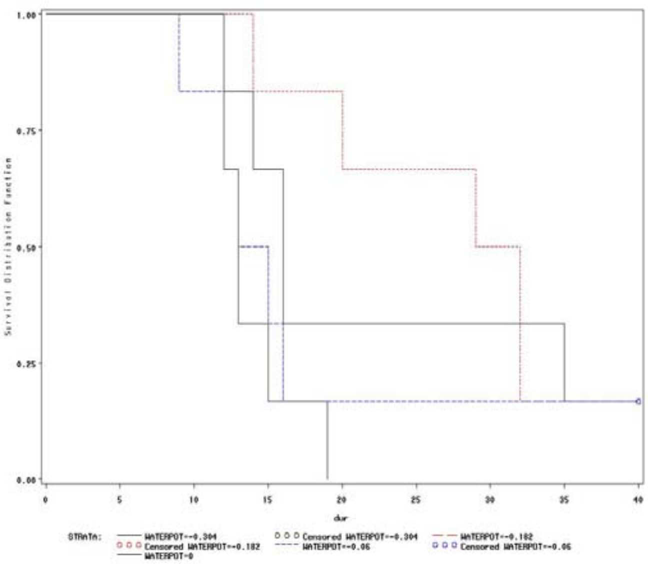


FIGURE 6. Survival functions over time (dur) of *Arundo donax* (proportion of rhizomes sprouting) from four simulated moisture conditions established with PEG solutions 2005 growth chamber trial.

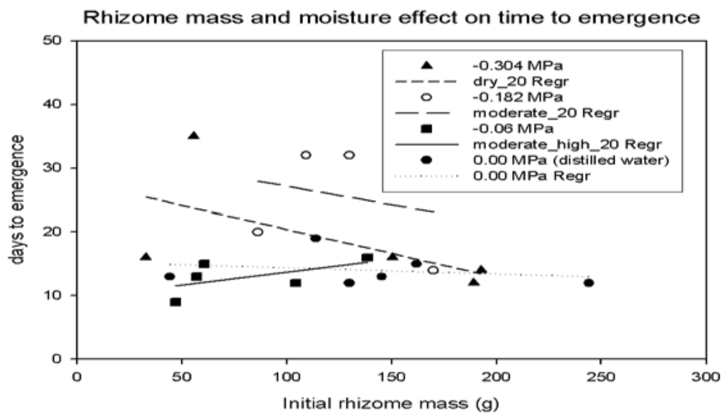


FIGURE 7. Relationship between initial rhizome biomass and days to emergence. The regression lines correspond to the moisture conditions: short dash line dry=-0.304 MPa, long dash moderate=-0.182 MPa, solid moderate_high=-0.06 MPa, and dotted 0.00MPa

- ***Field Trials:*** Field trials were conducted in plastic circular basins (1.5m diameter) with clear polycarbonate sheets perched above to protect the basins from rain and external sprinkler irrigation (FIGURE 8). The experimental unit was one of these plastic basin submerged into the surrounding soil and filled with a river-ocean silt sand mix that we collected around large Arundo patches found in San Luis Obispo County (Pennington Creek and the Morro Bay Estuary water shed). We used a timed micro-sprinkler system to deliver the required amount of water. Aside from the CLIMEX/DYMEX modeling; another goal of ours was to develop a stand-alone model that land managers can use to predict Arundo emergence and growth. In order to use the California Irrigation Management and Information Service (CIMIS), NOAA, and DAYMET database, a correspondence between the data from the nearest CIMIS weather station and the data actually recorded at the specific site of emergence was established. The CIMIS, NOAA, and DAYMET databases were collected or established under similar conditions. For many locations, the NOAA and CIMIS database are exactly the same data. As mentioned previously, the CIMIS database is collected from weather stations that are perched over irrigated

FIGURE 8. The plastic basin design used for the field trials. The inverted cups are thermocouples measuring air and soil temperature and are attached to a Campbell Scientific 23X datalogger.

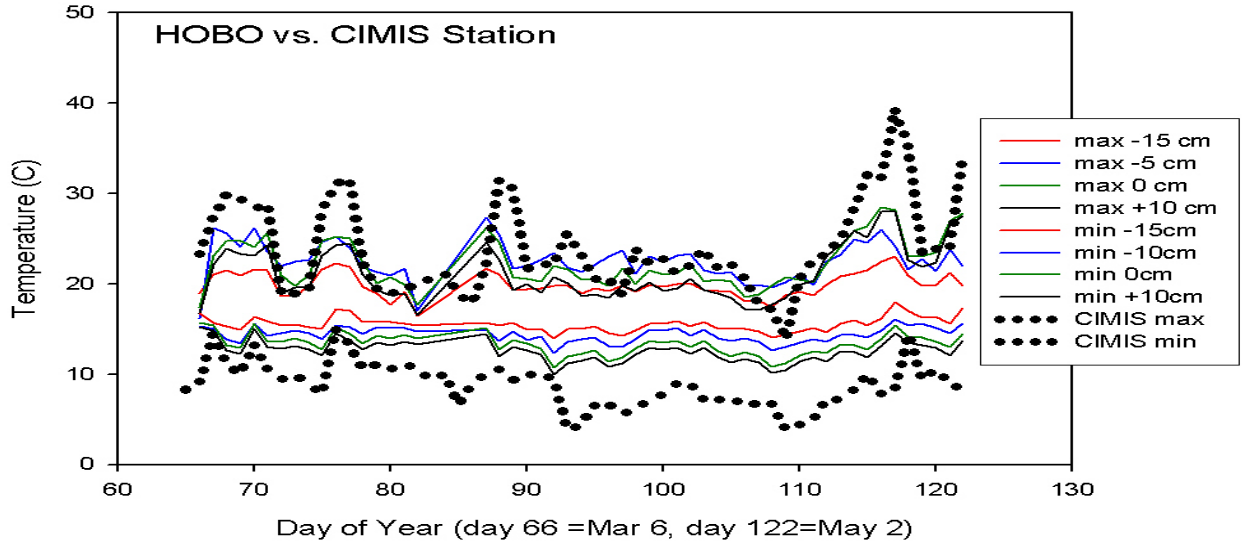


FIGURE 9. Maximal (max) and minimal (min) temperature time series of measurements collected at various heights (cm) above (+) or below (-) the soil surface at the field experimental site at Cal Poly with a HOBO Datalogger and temperature probes (lines) relative to the measurements collected by a CIMIS weather station (dots) at the Cal Poly Farm Shop. The Farm Shop and Crops Unit are about 1000m apart.

turf. Sprouts emerge from rhizomes that are partially buried in sandy-loam soils typical of riparian and beach habitat. We downloaded the CIMIS recorded maximum and minimum temperature differences and matched them with the temperatures recorded with a HOBO datalogger and a Campbell 23X datalogger at the exact site of our experiment at depths representative of natural conditions for Arundo rhizomes (FIGURE 9). Correspondence among the different temperature measurement methods except that the CIMIS temperature fluctuations were more accentuated. This is likely due to the fact that the HOBO sensors were much closer to the soil where temperature fluctuations will be buffered relative to the CIMIS sensors, which were perched above the soil surface. That fluctuations occur in synchrony albeit at different amplitudes will likely NOT affect model accuracy. The synchrony is much more important than the amplitude.

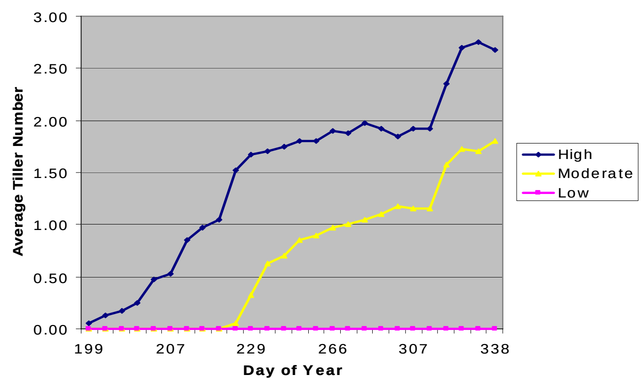


FIGURE 10. Sprouting progression for the various moisture treatments from a field trial in July 2004 but typical for all trials.

- As with the growth chamber trials, Arundo sprouting (1 tiller stage) and tiller development progressed in a manner expected of water-stressed rhizomes (FIGURE 10). In the treatment not receiving water (low), no sprouts and thus no tillers were observed.
- Survival analyses of all field trials were performed in LIFEREG (SAS) which uses partial likelihood to do semiparametric regression analysis on the covariates such as moisture levels and rhizome size. We assumed the time to sprouting followed a log normal distribution in each treatment after testing that assumption against other common distributions such as Weibull, exponential, and log-logisitic. These analyses showed separation according to moisture condition for all trials (FIGURE 11).
- To quantify the effect of each covariate we performed a proportional hazards regression also called a Cox regression using the PHREG procedure in SAS (TABLE 1). The LIFEREG analyses demonstrated that the underlying hazard functions (reciprocal of survival functions) were equivalent among the treatments. Therefore, a proportional hazards regression is appropriate. The analyses found that the variables soil moisture (moisture), the initial number of lateral buds (latbuds) and the initial number of nodes (nodes) had significant (Pr>ChiSq) and positive (Parameter Estimates) effects on time to emergence. This may be interpreted as follows: the more lateral buds or nodes a rhizome has the sooner it will emerge, which is biologically sensible.

An example of the Hazard Ratios computed by Cox regression are presented from the July 2005 trial in TABLE 1. The data can be interpreted as follows: for moisture (a quantitative variable), the percent change in the hazard of sprouting for each unit (% volumetric moisture) increase in moisture is 100(4.282-1)=+382%, so as a rhizome is in higher moisture the hazard of sprouting goes up. For nodes (a quantitative variable), the percent change in the hazard of sprouting for each unit (#/rhizome) increase in nodes is 100(1.096-1)=+9.6%, so as a rhizome has more nodes the hazard of sprouting goes up. For lateral buds (a quantitative variable), the percent change in the hazard of sprouting for each unit (#/rhizome) increase in latbuds is 100(0.797-1)=-20.3%, so as a rhizome has more latbuds the hazard of sprouting goes down, which is not biologically sensible and not a consistent result in all trials.

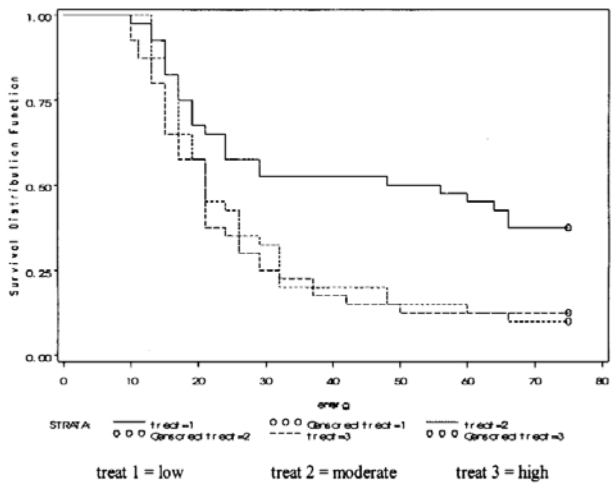


FIGURE 11. Survival curve for the July 2005 planting showing a significant moisture effect between the low and medium/high treatments

TABLE 1. Analysis of maximum likelihood estimates for the July 2005 field trial using the PHREG procedure in SAS. The low p-values (Pr>ChiSq) for moisture indicate there was a significant difference for emergence times attributable to the moisture conditions under which the rhizomes were buried. Other significant effects could be attributed to initial lateral bud numbers (latbuds) and number of nodes (nodes) of the rhizomes prior to planting. Text boxes explain how to interpret the hazard ratios (Haz Ratio) for the significant variables.

Variable	DF	Estimate	Error	Chi-Square	Pr > ChiSq	Haz Ratio
Block	1	0.11940	0.13186	0.8200	0.3652	1.127
moisture	1	1.45437	0.19402	56.1897	<.0001	4.282
mass	1	-0.00762	0.00449	2.8764	0.0899	0.992
length	1	0.10489	0.09405	1.2438	0.2647	1.111
width1	1	0.0008642	0.23086	0.0000	0.9970	1.001
width2	1	-0.02708	0.05284	0.2626	0.6084	0.973
latbuds	1	-0.22731	0.10511	4.6770	0.0306	0.797
termbuds	1	-0.38866	0.24169	2.5859	0.1078	0.678
nodes	1	0.09135	0.03699	6.1000	0.0135	1.096

- ***Parameterization:*** The data from these growth chamber and field trials were used to parameterize an Arundo growth simulation in Objective 3. Parameterization was done as follows:

- For all growth chamber trials, the reciprocal time to median sprouting at 0.00 MPa was regressed on temperature (FIGURE 12). T_{base} is estimated by the x-intercept computed as the negative y-intercept, *a*, divided by the slope of the regression line, *b*, estimated in SAS with the regression procedure. The standard error of the x-intercept, $SE_{x\text{-int}}$, was computed using the following equation from Steinmaus et al. (2000):

$$SE_{x-\text{int}} = \sqrt{\frac{V_{aa}}{b^2} - \frac{2aV_{ab}}{b^3} + \frac{a^2V_{bb}}{b^4}} \quad \text{Eq. 4}$$

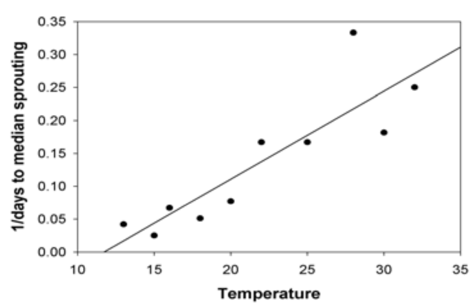


FIGURE 12. Reciprocal time to median sprouting regressed on temperature for 0.00 MPa trials. y = -0.15675 + 0.0133 x. r^2=0.76

where V_{aa} was the variance associated with the estimate of y-intercept, V_{bb} was the variance associated with the estimate of slope, and V_{ab} is the covariance of the estimate of slope and y-intercept. All of these terms were extracted from the variance-covariance matrix generated in SAS using the regression procedure.

- For all field studies, days to emergence was measured for each rhizome. The median time to emergence among the viable rhizomes in each pool was determined. A mean of these medians was them calculated for each moisture level, t_i, in the subsequent equations. To estimate T_{base} three mathematical formulae based on least standard deviation in degree-days (5), least coefficient of variation in degree-days (6), and a regression coefficient (7) were used:

$$T_{base} = \frac{\sum_{i=1}^{n} T_i t_i \sum_{i=1}^{n} t_i - n\sum_{i=1}^{n} t_i^2 T_i}{\left(\sum_{i=1}^{n} t_i\right)^2 - n\sum_{i=1}^{n} t_i^2} \quad \text{Eq. 5}$$

$$T_{base} = \frac{\sum_{i=1}^{n} T_i t_i^2 \sum_{i=1}^{n} T_i t_i - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} T_i^2 t_i^2}{\sum_{i=1}^{n} t_i^2 \sum_{i=1}^{n} T_i t_i - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} T_i t_i^2} \quad \text{Eq. 6}$$

$$T_{base} = \frac{\sum_{i=1}^{n} T_i \sum_{i=1}^{n} t_i T_i - n\sum_{i=1}^{n} t_i T_i^2}{\sum_{i=1}^{n} t_i \sum_{i=1}^{n} T_i - n\sum_{i=1}^{n} t_i T_i} \quad \text{Eq. 7}$$

where T_i is the mean temperature between the start of the trial and the average day of emergence, *n* equals the number of trials (Steinmaus et al., 2000). To minimize the significant interactive effect of moisture, only the high moisture treatment, assumed to be optimal, was used.

- The mathematical approach using equations 5-6 produced consistent estimates across all three formulae. The least standard deviation in degree-days, least coefficient of variation in degree-days, and regression coefficient methods gave estimates of 10.34, 10.22, 10.35°C, respectively, for the field trials and 12.78, 11.46, 11.80°C, respectively, for the laboratory data. There was only a 1.7°C difference between the means for the lab and field trials, 12.01°C and 10.30°C, respectively. Regressing the reciprocal time to median sprouting resulted in an estimate for T_{base} of 11.72°C, SE = 2.37, r2=0.76 (FIGURE 12).

- To estimate Ψ_{base} from lab trials, the 25°C and 30°C trials, assumed to be optimal temperature, were used to eliminate the possibility of an interaction between temperature and moisture at temperature extremes. The median time to sprouting, t_i, was utilized as input as above for establishing T_{base} but water potential in MPa was used as input to T_i in estimating Ψ_{base}. The formulae of equations 5-7 produced estimates of -0.28, -0.82, and -0.79MPa, respectively, with a mean value of -0.63MPa for Ψbase.

- Estimates of T_{base} using the mathematical approach were similar for both lab and field trials, which confirms the regression estimate of 11.72ºC. This value is slightly above a previous estimate of 8ºC (Spencer lab, UC Davis). Unfortunately, the moisture data are not as convincing. Current laboratory data only show a slight moisture effect, particularly at the lower temperatures, due to the small range of moisture levels tested. Estimates of Ψbase using the mathematical approaches gave a reasonable overall estimate of -0.63 MPa, but the variation in the three estimates was large.

- The T_{base} estimate of 11.7 may be used as a stand-alone degree day model at any CIMIS location for Arundo using the University of California Integrated Pest Management Programs degree day calculator (http://www.ipm.ucdavis.edu/WEATHER/ddretrieve.html) . Based on growth chamber data at 20°C when it took 14 days to sprout and a T_{base} of 11.7, the degree day estimate would be 14*(20-11.7)=116 degree days to sprouting.

Objective 3. PREDICT CLIMATIC SUITABILITY USING CLIMEX AND DYMEX

- ***CLIMEX:*** Using the augmented climatic database from Objective 1 and the parameters generated in Objective 2 we were able to construct a CLIMEX model to assess Arundo dispersal throughout California (FIGURE 13). To simulate riparian habitat typical of where Arundo is found, we simulated the additional moisture that would normally be found in waterways using the Irrigation Scenario in CLIMEX by adding 50mm of water per week to the soil moisture module. The predictions show prolific Arundo growth throughout California as long as there is riparian habitat (simulated here under the Irrigation Scenario). Thus, moisture will be limiting growth significantly outside riparian habitat at the locations indicated. For example, when we simulated no additional moisture, and the only inputs were from naturally occurring rainfall, Arundo was not a threat in most of California where the weather stations on which the climatic database is based are located. The exceptions would be in parts of northern coastal California where cold temperature would begin to be a growth limiting factor over moisture. The Sierra Nevada would not be threatened by Arundo because of cold winter temperatures.

- The higher moisture levels in riparian habitat may also buffer those zones from frost that would otherwise occur in the drier regions nearby because of the high heat capacity of water vapor.

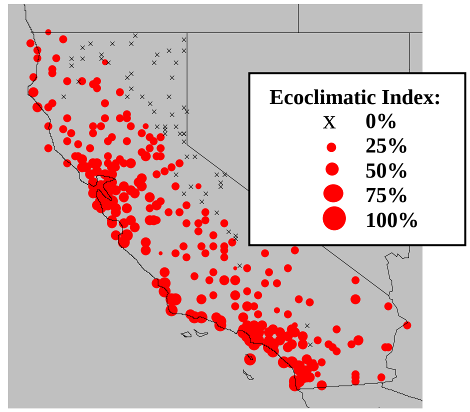


FIGURE 13. Predicted *Arundo donax* distribution using CLIMEX with the Irrigation Scenario set to 50mm of additional moisture per week to simulate riparian habitat in California. Larger red circles correspond to a great ecolimatic match between a species preferences and the climate at that location.

- ***DYMEX:*** A population growth simulation was built for Arundo in DYMEX using parameters generated from the growth chamber and field trials as described in the previous sections, objective 2. In addition to the parameters required by CLIMEX, inputs required for the DYMEX model included the longitude and latitude of the experimental site in San Luis Obispo and the meteorological database from DAYMET which provides daily climatic data as opposed to the augmented database we developed for CLIMEX where monthly averages were utilized (FIGURE 15). The benefit of using actual climatic data rather than averaged data is that the model suffers less from the smoothing effect of averaging which tends to underestimate death of a population. Climatic extremes are the most likely culprits in many failed attempts at naturalization of an alien species, and those extremes are buffered with averaging. We simulated 18 years of Arundo infestation. Only 10 years of simulation are presented in FIGURE 16-18 as it illustrates the salient patterns for the purposes of this report.

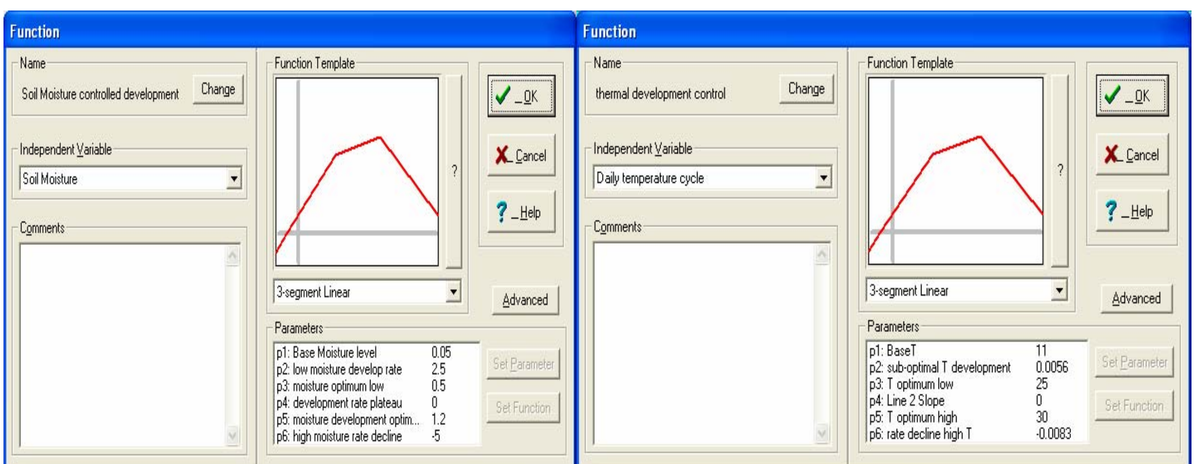


FIGURE 14. Soil moisture and air temperature modules that define and control physiological development of simulated Arundo growth in DYMEX

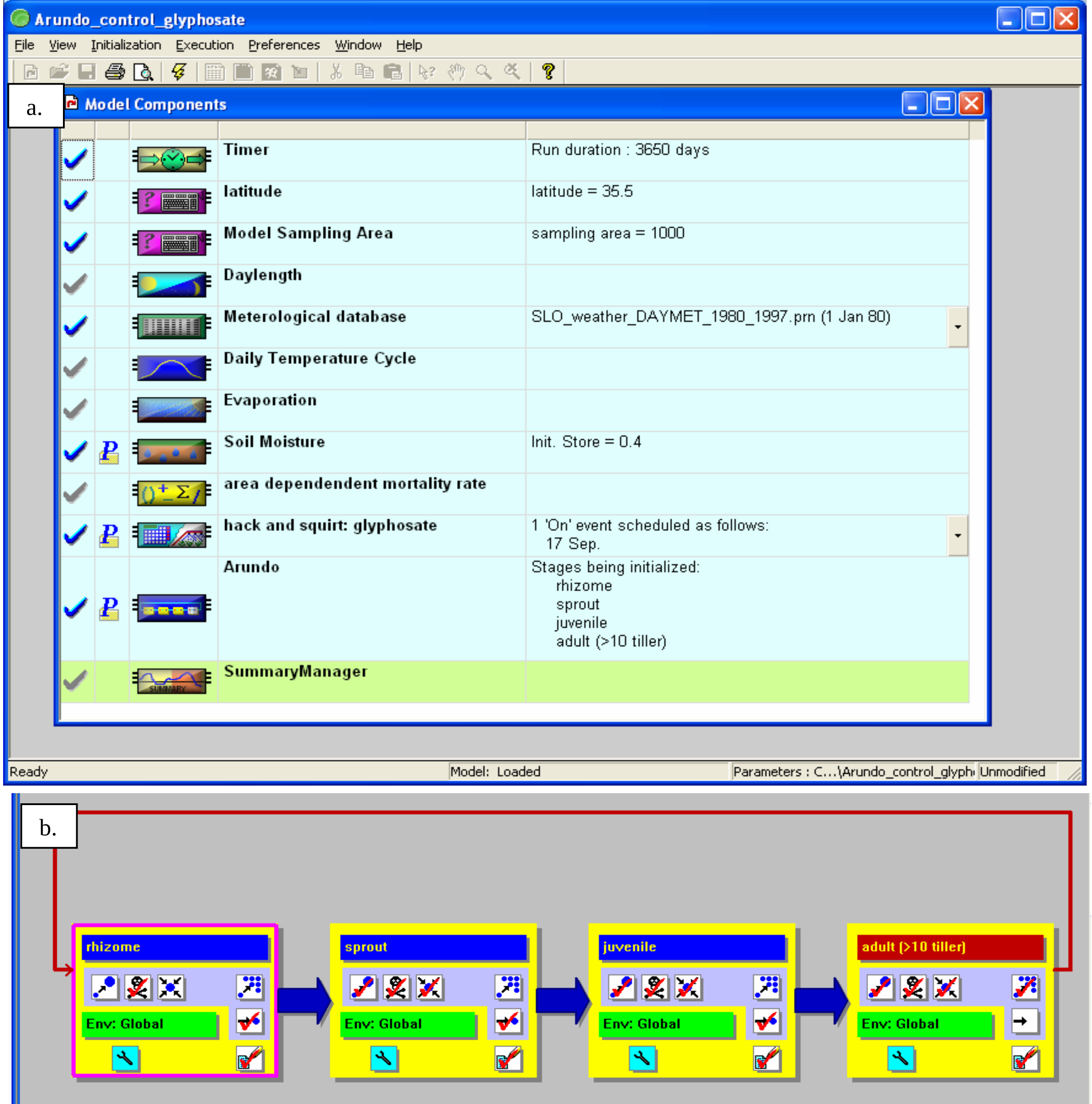


FIGURE 15. A DYMEX simulation for Arundo donax showing the input modules (a) and the climatic response parameters entered into the LifeCycle module, Arundo (b).

- The DYMEX model is a population based model in that it simulates numbers of propagules from each lifestage for a given area, in this case a 10m X 100m plot along riparian habitat in San Luis Obispo County near Cal Poly State University. As a population of individuals at a given lifestage increases in numbers to fill a given area, some individuals will develop into the other lifestage. Some remain at that given lifestage only to transition later to higher lifestages. In natural ecosystems, it will be these individuals that will eventually begin to compete for resources amongst themselves. To simulate this intraspecific competition and self-shading that occurs under densely foliated conditions, the variable, ***canopy cover,*** was attached as a module called a***rea dependent mortality rate***. ***Canopy cover*** is also a good ecological indicator of overall population size and vigor in terms of biomass and how many rhizomes can be produced by the population, which makes for an efficient variable to follow while developing a control program (FIGURE 15).
- The module requiring the most parameterization is the lifestage module, ***Arundo.*** This module is composed of several sub-modules of the significant life stages of Arundo (FIGURE 15b). The climatic response parameters developed in Objective 2 were used to simulate Arundo response to temperature and soil moisture (FIGURE 14). Variables that describe stress were utilized to describe climatic conditions under which Arundo populations at each of the lifestages would die and thus decrease. Any variables not developed in Objective 2 were used from data generated at UC Riverside (J. Holt lab) and at UC Davis in the USDA-ARS aquatic research facility (D. Spencer lab). The model accurately predicted population growth and development for an 18 year period with

total node numbers approaching 18,000 and number of mature adults reaching 1400 at the height of seasonal growth for the 1000m^2 area when no control measures are applied (FIGURE 16).

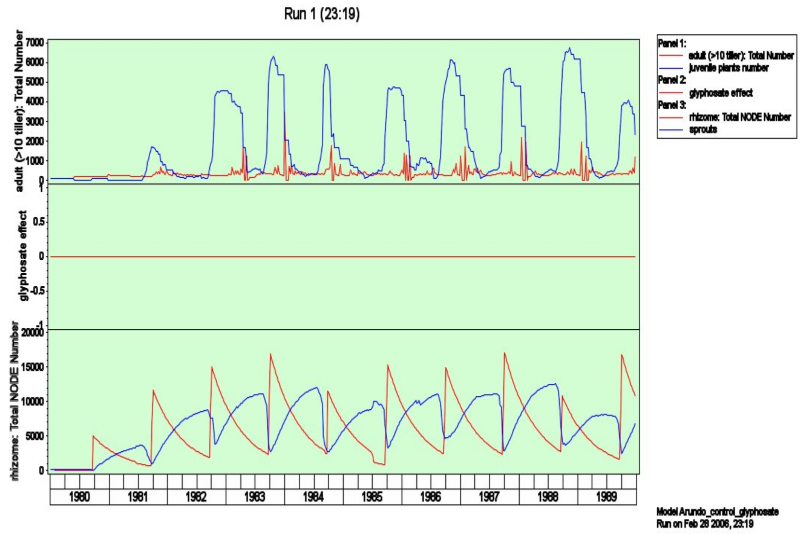


FIGURE 16. A DYMEX simulation module detail showing the Arundo Lifecycle and several simulation runs without herbicide control (Run 1).

- Using DAYMET daily climatic data as input reveals the significance of stochastic events such as the normal day to day temperature or moisture extremes on population establishment and growth. The predictions in FIGURE 16 reveal the unsettled establishment of Arundo as might occur early during its naturalization phase. The population stabilizes about six to eight years after initiation. This pattern of slow establishment, exponential growth to a stable plateau is typical of other successful invasive species. If we had utilized temporally or spatially averaged climatic data we would likely see stabilization after only three to four years, which is less realistic. Contrary to popular thought, alien species more often do not establish stable and spreading populations, and the most likely reason is that climate is not suitable or is sufficiently stochastic. Larger populations and individuals can tolerate climatic extremes better than young newly establishing and emerging populations.

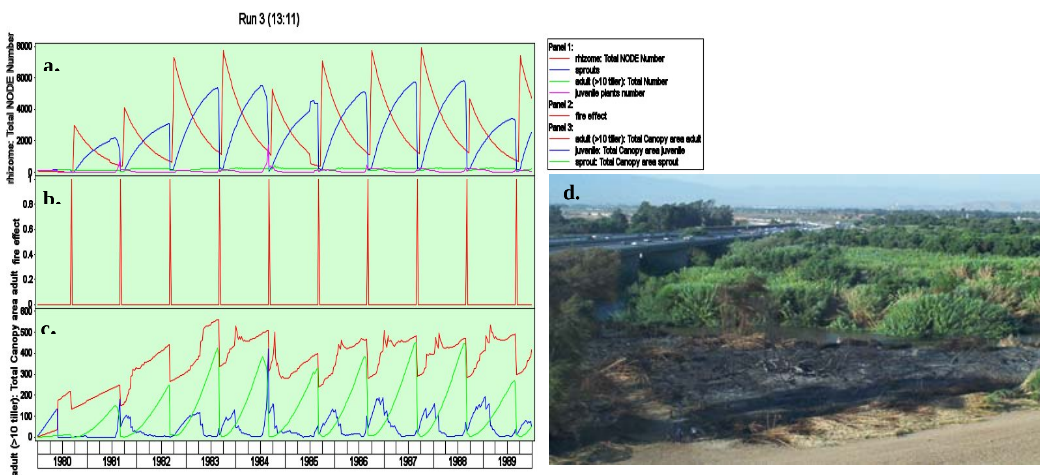
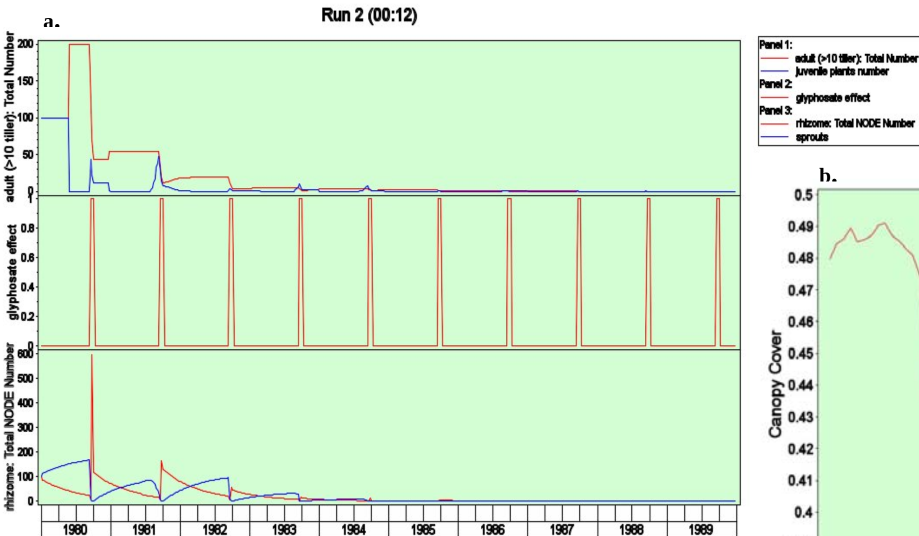


FIGURE 17. Simulating the effect of fire to control Arundo donax in DYMEX. Simulated growth of all lifestages (a) after control by fire applied each summer (b). Plots of the sprout, juvenile, and adult lifestages after control by fire (c). Actual effect of fire on an Arundo population where the Santa Ana River passes under Highway 15 in Norco, California (d).

- Arundo does not produce viable seed in California, therefore, this stage was not included in the lifecycle module. The rhizome stage is the most significant stage that over-winters and tolerates stressful conditions such as drought and frost. It is also the stage that must be controlled if an established population is to be removed. The herbicide, glyphosate (Roundup or Rodeo used in aquatic ecosystems), has been established as an effective tool for killing the rhizome by applying it to the cut stumps of mature Arundo (Bossard et al 2000). This method has been termed ‘hack and squirt’. However, timing of this method is crucial for effective control.
- The control module, ***hack and squirt:glyphosate*** in FIGURE 15a, allowed us to test various control options without having to try them in expensive, time consuming, and sometimes dangerous, experiments in the field. We developed a control module, ***fire effect*** in FIGURE 17, to test how well repeated fire would control Arundo

as it is inexpensive and can be effective in controlling other invasive species. We found that the best timed fire provides suppression of Arundo but not complete control with a decrease to 8000 nodes and about 500 adults for the 1000m^2.

- To achieve complete control we utilized the ***hack and squirt:glyphosate*** control module to test various control scenarios utilizing this method (FIGURE 18). Timing herbicide applications so that the herbicide translocates with photoassimilates to the rhizome is the most effective way to kill the rhizome. To determine the most



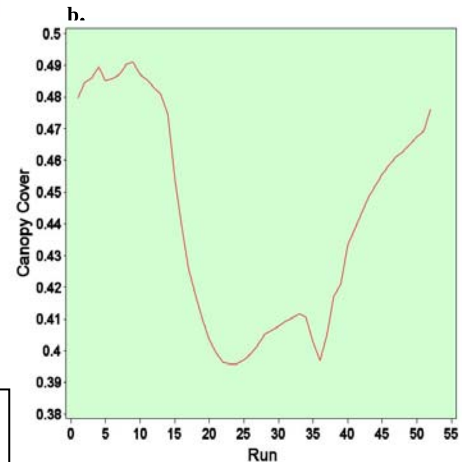


FIGURE 18. Simulated effect of the hack and squirt method on Arundo donax control applied each fall (a). Identifying the week on applying a 'hack and squirt' application to an Arundo population that results in the most significant reduction in canopy cover (b).

efficient timing of glyphosate applications we parameterized the control module with effects we have identified from the literature and from personal observation of Arundo management programs in San Luis Obispo County. We incorporated the typical 90% kill rate that rhizomes will suffer when glyphosate is applied to the cut stumps of 10 leaf stage Arundo. We tested this method by running the complete 18 year model when the 'hack and squirt' method was applied at each week of the year to see which week would provide the greatest reduction in Arundo vigor (FIGURE 18b) ***Canopy cover*** was the best indicator variable for overall population robustness as indicated above. By following ***canopy cover*** with control measures being applied each week of the year for 18 years, we found that there were two periods that showed the greatest promise: May and August/September(FIGURE 18b).

- After testing both possibilities, we found the 'hack and squirt' method to provide the best control in the shortest time when performed in September (FIGURE 18a). The model predicted complete control using the 'hack and squirt' method within three years of initiation. The control measures suppressed Arundo to low numbers and restricted the individuals to the early lifestage, sprouts, which would be susceptible to climatic extremes. The rhizome is very tolerant of climatic extremes, but sensitive sprouts must develop into mature adults before rhizomes can be replenished to produce more nodes.

- These simulations illustrate the importance that control be applied early in population growth, numbers must be decreased, and the surviving individuals must be restricted to young sensitive lifestages. Further, timing of the systemic herbicide is crucial to effective control.

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J. <u>Impact Statements:</u>

- Arundo is a serious invasive plant that is capable of persisting in riparian habitat throughout sub-alpine locations of California
- The persistence of Arundo can be attributed to the rhizome stage which appears to be tolerant of cold and dry stresses that would otherwise kill the population.
- A high resolution climatic database is required to accurately represent the diverse eco-regions typical of California.
- Ability to use stochastic climate data provides more ‘realistic’ predictions than temporally and spatially averaged databases.
- Simulations predict that contact control such as the use of fire is likely insufficient to remove this species.
- Systemic treatment with glyphosate after removing the adult above ground portion (termed ‘hack and squirt’) provides best chance of removing an establishing Arundo population.
- Predictions indicate three years of repeated systemic treatments are likely required

K. <u>Dissemination, publications and presentations of research:</u>

Steinmaus, S. and A. Graziani. Developing temperature and moisture response parameters of Giant Reed (Arundo donax) Journal of Experimental Botany. (manuscript in preparation).

Steinmaus, S. Predicting giant reed (*Arundo donax*) success and control based on response to climate. Journal of Applied Ecology (manuscript in preparation).

Graziani, A. and S. Steinmaus. Assessing the threat and management options for giant reed (Arundo donax). 2006 California Invasive Plant Council Symposium.

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Graziani, A. and S. Steinmaus. 2006. Determination of Temperature and Moisture Parameters for the Development of Giant Reed (*Arundo donax*). Proceedings Western Weed Science Poster Session 59: ## (Presented by A. Graziani March 2006. Reno, NV.)

Steinmaus, S. 2005. CLIMEX and DYMEX-Predicting Weed Invasion using Climatic Factors.
Project 4: Teaching and Technology Transfer. Proceedings Western Society of Weed Science 58:77-78. (Presented by S. Steinmaus March 9, 2005. Vancouver, British Columbia)