# Prioritizing Weed Populations for Eradication at a Regional Level: The California Department of Food and Agriculture's A-rated Weeds

By

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## ABSTRACT

California has many pioneer weed infestations worthy of eradication, but too few resources to respond to all. Traditionally, weed lists guide eradication efforts in the state. However, species evaluation systems have limitations when applied to prioritizing individual populations for eradication. Therefore, I developed a science-based, transparent, decision-making tool to help prioritize weed *populations* for eradication using the California Department of Food and Agriculture's A-rated weeds as test populations. This ranking tool assessed the relative impact, potential spread, and the cost and feasibility of eradication for each population. Species-wide population scores indicated that conspecific populations do not necessarily group together in the final ranked output, which supports a system where occurrences of the same species should not be given the same priority for management. This tool will help land managers systematically target weed infestations by putting their limited resources into populations known to cause the highest impacts and are most feasible to eradicate. This thesis is the first attempt to prioritize noxious weed populations for eradication on a statewide scale using a spatially explicit ranking tool.

# INTRODUCTION

California's uniquely diverse flora includes non-native plants from around the world, especially from other Mediterranean climates (Hickman 1993, CNPS 2001, CDFG 2003, DiTomaso and Healy 2007). Many non-native plant species fulfill horticultural and agronomic purposes. However, some non-native plant species spread aggressively and are able to disrupt agricultural production and ecological systems (Richardson et al. 2000, Cal-IPC 2006). These noxious (state-listed) and invasive (i.e., Cal-IPC-listed) species are known to cause harmful impacts including lowering agricultural productivity, altering ecosystem functions (e.g., nutrient cycles, hydrology, and wildfire frequency), outcompeting and excluding native plants and animals, and adding to maintenance costs of roads, parks and waterways (Bossard et al. 2000, CDFA 2005, Duncan and Clark 2005). Noxious and invasive weeds infest over 20 million acres in the state and result in hundreds of millions of dollars in control costs and lost productivity (Duncan and Clark 2005, Pimentel et al. 2005). Fortunately, many Federal, State, and local land managers have invested in protecting California from the harmful impacts caused by noxious and invasive weeds.

The California Department of Food and Agriculture (CDFA) and County Agricultural Departments have been eradicating noxious weeds for over 100 years. Eradication is the elimination of every individual or propagule of a species or population by deliberate management from an area to which re-colonization is unlikely to occur (Bomford and Obrien 1995, Myers et al. 1998). The California State Legislature designated the CDFA as the state's lead agency in noxious weed control in the California Food and Agriculture Code (California 2008). Successful eradication has been attained in

California for several weed species including *Halimodendron halodendron* (L.) Voss (Russian salt tree) and *Orobanche ramosa* L. (branched broom-rape) (DiTomaso and Enloe 2008). The Legislature provides some financial resources, but available funding is insufficient for intensive management of all potential eradication targets (CDFA 2005).

Funding cuts to the CDFA's noxious weed eradication programs since the late 1970s have significantly decreased the number of CDFA biologists in the field, while county eradication programs have experienced similar cuts. During this period the number of new weed populations has been increasing (Schwartz et al. 1996). California has many pioneer weed infestations worthy of eradication, but detection biologists have too few resources, i.e., time and funding, to respond to all listed plant species.

The CDFA's Integrated Pest Control Branch hosts the noxious weed eradication program. This program maintains a staff of biologists with expertise in eradication and containment programs directed at noxious weeds of limited distribution (A-rated weeds). The CDFA's Integrated Pest Control Branch developed and maintains a GIS database with location, acreage, and treatment data on A-rated weed populations in California. Of the 52 listed A-rated noxious weed species, 13 have been eradicated statewide along with hundreds of individual populations. The remaining 1,700 discrete populations, plus a number of large, dense infestations, pose a daunting problem.

Traditionally, CDFA biologists and County Agricultural Department staff prioritize weed eradication projects using the best available information, but often without linkage to a regional framework. Due to efforts by the CDFA, University of California Cooperative Extension, County Agricultural Departments and local Weed Management Areas, information exists on the biology of these weed species, effective control methods, and maps of infestation locations. A prioritization system is needed to ensure the CDFA and other large land managers direct resources to weed infestations of highest priority.

**Risk Management**

Eradicating weeds at the earliest stages of invasion is widely recognized as the more cost-effective and efficient strategy compared with the commitment of indefinite resources to ongoing containment or living with the costs of established weeds (Rejmánek and Pitcairn 2002, Cunningham et al. 2004, Hester 2004). The imperative then becomes: which of the weed populations in California should receive the highest priority for eradication? High priority is assigned to controlling weed species that have substantial impacts on agriculture, the environment, human health, and that are more easily managed. High priority should be given to managing weed species that presently may not cause major impacts to agricultural or environmental resources, but are known to cause major impacts elsewhere and would be expected to cause damage should their populations spread in California. Low priority should be assigned to species that currently, or have the potential to, cause little impact, or are virtually impossible to control (Hiebert 1997, Virtue et al. 2006).

Risk management can assist in reducing negative impacts. Increasing worldwide concern with weed invasions has generated many weed risk management systems, both as screening tools and quarantine protocols (pre-border) and as prioritization tools for existing infestations (post-border) (Hiebert and Stubbendiek 1993, Reichard and Hamilton 1997, Pheloung et al. 1999, Williams and Newfield 2002). Decisions made using a science-based, analytical risk management tool are transparent, repeatable, and consider a full array of significant factors. By documenting the reasoning process, decisions are defensible if challenged, and proposals for funding are justified. Consistent use of an analytical tool reduces some of the problems associated with decisions based on judgment and precedent (Hiebert and Stubbendiek 1993). Agencies in charge of weed control would benefit from an assessment tool to assist in making decisions when new invasions are discovered (Cacho 2004).

Currently, land managers may choose weed control projects based on a post-border weed risk assessment (WRA). Many existing post-border WRA tools address species-level priorities and employ an all-or-nothing approach, i.e., either a weed species is considered for management or it is not. Two such species-level lists used in California are the CDFA Pest Plant Rating System (DiTomaso and Enloe 2008) and the California Invasive Plant Inventory (Cal-IPC 2006).

The CDFA Pest Plant Rating System identifies noxious weeds known to cause ecological and economic damage, and/or be human health risks (DiTomaso and Enloe 2008). It was in use as early as 1959[*] and was the first list of priority species in California. The rating system, including how plants are added or removed from the list, was formalized in a CDFA Quarantine Circular No. 213 in 1989 (CDFA 2005). However, the decision-making process used to create and update the list is neither fully documented nor transparent. Traditionally, A-rated and quarantine (Q-rated) species are recommended for statewide eradication by the CDFA. B-rated species are widely distributed in some regions of the state but not others, and are recommended for regional eradication within California. C-rated species are widespread throughout the state and are recommended for

[*] Archive CDFA Memorandum dated 3 July 1961. From: Division of Plant Industry, Weed and Vertebrate Pest Control, Weed Circular No. 48. To: all County Agricultural Commissioners. Re: Rating Classification of Noxious Weed Species.

local eradication. Management action on B- and C-rated weeds is at the discretion of the County Agricultural Commissioner (DiTomaso and Enloe 2008).

The California Invasive Plant Council (Cal-IPC) has maintained a wildland weed list since 1994. In 2006, Cal-IPC published the revised *California Invasive Plant Inventory*, based on the transparent system developed by Morse et al. (2004). The Inventory is the result of assessing over 300 wildland weed species based on the biology, ecological impacts, and distribution of the species, and ranks those species as High, Moderate, Limited, and Alert High or Moderate (Cal-IPC 2006).

Other notable post-border species-level assessment tools are widely used to discriminate weeds from non-weeds amongst naturalized floras and to rank weeds by their potential impact or need for control. Randall et al. (2008) summarized these tools in a recent publication. Hiebert and Stubbendieck (1993) prepared the *Handbook for Ranking Exotic Plants for Management and Control* for the National Park Service. This was the first decision-making tool in the United States to prioritize weed species for control based on the impact of the species and feasibility of control. The *National Post-Border Weed Risk Management Protocol* in Australia guides land managers in using risk assessment systems to determine high priority weed species based on invasiveness, impacts, potential distribution and feasibility of containment (Virtue et al. 2006). The *Invasive Species Assessment Protocol*, developed by The Nature Conservancy, NatureServe, and the U.S. National Park Service, is a tool for assessing invasive plants based on their impact to biodiversity (Randall et al. 2008).

However, these species-level prioritization systems have limitations when applied to ranking individual populations for eradication. For example, these systems assign a priority to each species, which is then applied to all occurrences of that species and assumes that level of impact, potential for spread, and feasibility of control are uniform across the landscape. This categorization of the species should not be expected to be equally applicable across all of California. At state and nationwide scales, assigning the same priority to all infestations of a particular weed is not the most efficient method to address the growing problem of invasive weeds.

After choosing high-priority weed species using a species-level prioritization tool, land managers find that even among the highest priority species, eradicating all infestations may not be realistic. The New Zealand Department of Conservation recognizes both a weed-led and site-led approach to managing invasive weeds (Timmins and Owen 2001). The Analytical Hierarchy Process (Saaty 1980) has been used by the Department of Natural Resources and Environment in Victoria, Australia to determine the invasive potential of 112 pest plant species (Weiss and Iaconis 2002). Subsequently, a prioritization process was developed specifically for the Santa Monica Mountains National Recreation Area to address infestations of nine pest plant species within the park (Althoen et al. 2007). Recently, a theoretical population prioritization framework has been suggested by Rew *et al.* (2007) to aid non-indigenous species management. These studies show that management of all species, and all populations of a species, is impractical and unnecessary; however, they do not address eradication specifically as a management goal. Management of noxious and invasive weed populations needs to be prioritized at a regional level. Eradication efforts should be focused on weed populations with the greatest potential to cause negative impacts, to spread, and to affect high-value assets (e.g., rare species habitat, agriculture, important recreation areas). Thus, land managers will allocate eradication resources wisely.

### Research Objectives

The objective of this study was to address the need for a population-level weed prioritization tool for use by land managers through the development of a science-based, transparent, decision-making model. This prioritization model was designed to rank eradication projects at a regional level. To accomplish this, I used the CDFA A-rated weeds as a model data set to develop the tool. The prioritization score varied by population, allowing land managers to consider each infestation individually for eradication. This population-level prioritization system does not replace existing species-level prioritization tools, but further refines the weed risk management decision-making process.

## MATERIALS & METHODS

### Building the Ranking Tool

I used a six-step approach to building the weed population prioritization tool. First, I identified high-priority species and utilized a geographic information system (GIS) inventory of those species in California compiled by the California Department of Food and Agriculture (CDFA). Second, I chose ranking criteria and arranged those criteria into a decision hierarchy. Third, I weighted the criteria using the Analytical Hierarchy Process (Saaty 1980). Concurrently, I researched and scored each criterion for each sample population. Fifth, I combined the criteria weights and scores to calculate the overall priority score for each population. And lastly, I made recommendations for how the ranked output could be used by land managers.

**Step 1: Identify and inventory (GIS) populations of high priority species**

The first step was to choose populations of high-priority species to develop the prioritization tool. In this study, the CDFA's A-rated weed species were used as the test dataset for the model. The A-rated weeds are high-priority eradication targets for CDFA, but there are too many populations to focus eradication efforts on all. Pre-assessment conditions were set to eliminate large, dense infestations (containment zones) and populations under successful biological control. Tracking the location and extent of weed populations is essential to running the populations through this prioritization tool. CDFA maintains a GIS database of A-rated weed locations in the state; therefore, this step of data gathering was already completed.

**Step 2: Choose ranking criteria for prioritizing populations for eradication**

Many factors contribute to the decision to eradicate a weed population. I reviewed the scientific literature and engaged in discussions with experts to compile a list of criteria used in making the decision to undertake an eradication program. From the eradication literature, feasibility criteria (e.g., factors contributing to cost and effective control techniques) are well documented (Cunningham et al. 2004, Panetta and Timmins 2004, Woldendorp and Bomford 2004, Cacho et al. 2006). I also reviewed existing prioritization protocols, which emphasized the major criteria of ecological impact, invasiveness potential, current and potential distribution, and feasibility of control (Hiebert and Stubbendiek 1993, Cal-IPC 2006, Virtue et al. 2006, Randall et al. 2008). I narrowed the list to those criteria that most commonly influence the decision to eradicate, based on the emphasis placed upon them in the literature. This assured that the ranking tool was neither too cumbersome nor impractical in the decision-making process.

I vetted feasibility criteria at a Science Advisory Workshop held at UC Davis in August 2007, which included 20 researchers, federal, state and county agency representatives all with substantial experience in weed eradication. After discussion with the participants, I added an impact section because all A-rated species are not equally damaging. Furthermore, a restoration component was suggested at the workshop. I did not add this because most A-rated weed sites are in disturbed areas, which are not a high priority for restoration. Furthermore, the CDFA does not often eradicate weeds to protect the immediate site, but rather to prevent the weed from spreading to the surrounding region. However, a restoration criterion may be appropriate for other land managers, such as the US Forest Service or a Weed Management Area, who may wish to adapt this tool to their needs.

I further narrowed the number of criteria due to insufficient data. I did not include suitability of nearby habitat for spread nor animal migration routes because sufficient GIS data layers were not available. These factors may be subsequently included in the decision-making process as the data become available.

I organized the final major and sub-criteria (Table 1) into a hierarchy (Appendix A). For a detailed explanation of all criteria see Appendix B – Model Criteria Explained. The major criteria were:

- ❖ **Impact –** This criterion assesses relative impact to wildlands, agriculture, and human health of the species in question. Regional site value is estimated by calculating the population's proximity to agricultural commodities at risk, rarity occurrences of threatened and endangered species, National and State parks, and US Forest Service land.

- ❖ **Invasiveness –** This criterion assesses the likelihood of spread based on maximum rate of spread in California, distance to propagule sources of the same species, and proximity to vectors of spread (e.g., major roadways, rivers, and mining operations).
- ❖ **Feasibility of Eradication –** This criterion assesses the likelihood of success of an eradication project based on population size, reproductive ability (e.g., seed set, vegetative reproduction, seed longevity, lengths of juvenile and reproductive phases), detectability, accessibility, and control effectiveness and estimated cost.

**Step 3: Assign weights using the Analytical Hierarchy Process**

We often consider multiple factors when making a decision (e.g., safety and aesthetics when purchasing a new car). Those factors do not necessarily weigh equally on that decision. The Analytical Hierarchy Process (AHP) is a mathematical decision-making method that utilizes subject matter experts' judgments to quantitatively reduce a complex decision to its component parts (Saaty 1980). I used the weighting concept to divide the entire decision into its component criteria where the weights are the proportion each criterion contributes to the decision. This method is more objective than assigning weights when considering all criteria at once.

Weed eradication experts in California and Australia were surveyed and requested to rank criteria in each tier in order of importance; consider pairs of criteria within each tier of major, sub- and sub-sub-criteria, indicate which of the two contributes more to the decision to eradicate, and indicate how much more important on the Saaty Scale from 1 to 9, where larger values indicate higher importance (Saaty 2008) (Appendix C – AHP Worksheet). I collected and averaged 15 expert responses using the geometric mean for group responses (Saaty 2008), and calculated weights and consistency measures using Saaty's method. The exact mathematical calculations are very complex, so I used an accepted approximation (Saaty 1980).

An important consideration when calculating weights via the AHP is the consistency of the pair-wise judgments made by the experts, especially when averaging group responses. For example, if the group average indicates that criterion A is more important than criterion B, and that criterion B is more important than criterion C. Therefore, the group average must also indicate criterion A is more important than criterion C to have consistent judgment. A measure of consistency used for the AHP is the Consistency Ratio (Saaty 1980). Please see Appendix D for an AHP sample calculation.

**Step 4: Gather information and score populations**

For the species-level criteria, information was gathered from Cal-IPC Plant Assessment Forms (Cal-IPC 2006), *Weeds of California and Other Western States* (DiTomaso and Healy 2007), and other published resources. Expert opinion was used when published information was not available (e.g., seedbank longevity). The species-specific score consists of information about the species regardless of population size and location. This score was applied to all populations of a given species and is a default score, which populated an attribute table such that every occurrence of a particular species received the same value. These default scores may be altered if known to differ among sites (Appendix E – Species Criteria Scores).

For the population-level criteria, I assessed a sample of 100 weed populations from the CDFA's GIS database; stratified by species to avoid over-representation of more common weed species. With the assistance of the CDFA GIS staff, I created and implemented geoprocessing models using ArcGIS 9.3 (McCoy 2004, McCoy et al. 2004) to answer population-level spatial questions. The population-specific score consists of information particular to an individual site. These scores allow the model to vary spatially, while existing species-level ranking systems assume that levels of impact, invasiveness, and feasibility of control are uniform across all occurrences of the species (Appendix F – Population Summary Form).

In the decision hierarchy, only criteria at terminal branches were assigned scores. For example, under the Impact major criterion, impact to wildlands, agriculture and humans received scores, and distance to each high-value asset received a score. However, the Regional Site Value criterion score is a composite of the criteria scores below it in the hierarchy. Higher branches help organize the criteria, and their weights are used to calculate the final result.

Each criterion was scored as very high (10 points), high (6 points), medium (3 points), low (1 point), or very low (zero points). This scale was designed to resolve the high priority populations from others by placing more weight (points) on high priority attributes. For example, when scoring distance to high-value assets, a population within 0.1 mile of an asset received 10 points (highest priority), a population between 0.1 and 1 mile received 6 points, a population between 1 – 10 miles received 3 points, between 10-25 miles received 1 point, and a population greater than 25 miles from a high-value asset received zero points for that criterion. In the case of an unknown (e.g., impact or seed set), an expert's best estimate was used to assign a middle score (6 or 3) so as not to bias the population towards very high or very low priority.

**Step 5: Calculate overall priority score**

Finally, to calculate the overall priority I multiplied each score by the corresponding weight for that criterion and added the weighted criteria scores using a summary table. The final score is the sum of all criteria priority point scores weighted by their percent contribution to the overall decision to eradicate, with a maximum possible score of 10 points. In the following series of equations, 'S' indicates Score, 'Wt' indicates Weight, and subscripts indicate the corresponding criterion from Table 1. Calculating the scores for reproductive ability and cost effectiveness sub-criteria follow the same pattern. Populations were ranked according to the overall priority score.

$$\text{Overall Priority} = S_{IMP}Wt_{IMP} + S_{INV}Wt_{INV} + S_{FEAS}Wt_{FEAS};\ \text{where} \sum Wt = 1$$

$$S_{IMP} = S_{WILD}Wt_{WILD} + S_{AG}Wt_{AG} + S_{HU}Wt_{HU} + S_{REG}Wt_{REG};\ \text{where} \sum Wt = 1$$

$$S_{REG} = S_{GR}Wt_{GR} + S_{RARE}Wt_{RARE} + S_{REC}Wt_{REC} + S_{FS}Wt_{FS};\ \text{where} \sum Wt = 1$$

$$S_{INV} = S_{PR}Wt_{PR} + S_{RATE}Wt_{RATE} + S_{VEC}Wt_{VEC};\ \text{where} \sum Wt = 1$$

$$S_{VEC} = S_{RD}Wt_{RD} + S_{RIV}Wt_{RIV} + S_{MINE}Wt_{MINE};\ \text{where} \sum Wt = 1$$

$$S_{FEAS} = S_{SI}Wt_{SI} + S_{RE}Wt_{RE} + S_{DE}Wt_{DE} + S_{AC}Wt_{AC} + S_{CE}Wt_{CE} + S_{\$}Wt_{\$};\ \sum Wt = 1$$

**Step 6: Assess resource availability and choose eradication projects**

The final step for a land manager using this prioritization protocol is to assess resource availability and choose eradication projects. External circumstances may need to be considered once populations are ranked in order of priority, e.g., landowner cooperation or socio-political environment for control. A land manager may choose to focus 60% of their budget on the highest priority infestations, and spend the remaining budget on populations in the vicinity of, or en route to, those first tier infestations, thus maximizing the efficiency of staff time. Populations ranking lower may be targets for containment or biological control.

**Initial Assessment of the Ranking Tool**

To test the performance of the population-level prioritization tool I developed, I compared subject matter experts' rank of a sample of the weed populations to model results. This method is commonly used to verify risk assessment and prioritization tools (Pheloung 1999). To detect a strong correlation ($r^2 \geq 0.7$), approximately 100 sample points are needed for 90% power, assuming a 0.05 level of significance. The Fisher test (1921) was assumed, and the power was calculated using the methods of Kendall et al. (1994) via the POWER procedure in SAS for Windows Version 9.1. I chose a random sample of 100 weed populations (5% of the total) to be assessed by the model and the experts; these were stratified by species (Table 2) to avoid over-representation of more common weed species.

Experts classified each sample site as relatively very high, high, medium, or low priority for eradication based on their judgment. However, experts were not given all the information that was considered in the model, but were given all the information they would otherwise have on hand. I provided maps of the locations of each site along with nearness to major highways and rivers, size of the population, and the CDFA's Encycloweedia Web page with information on each species (DiTomaso and Enloe 2008). I asked for their rationale in categorizing each population.

Pair-wise scatter plots were used to provide a graphical assessment of the correlation between the experts and the model results. I formally assessed the association of the expert categorization with the model ranking by calculating Kendall's $\tau$ coefficient, a non-parametric statistic used to measure the degree of correspondence between two rankings and assessing the significance of this correspondence (Hollander and Wolfe 1973). I also used Kendall's $\tau$ coefficient to compare the major criteria scores of Feasibility, Impact and Invasiveness to each other and to the overall priority score.

## RESULTS

The weed population prioritization tool was designed to evaluate individual populations for eradication within a defined region. I chose CDFA A-rated weeds in California. It includes preliminary screening questions, species-level assessment questions, and population-level assessment questions. The significant result of this study is the successful development of the six-step weed population prioritization method.

### Criteria Weights via Analytical Hierarchy Process

Criteria weights were calculated using responses from 15 subject matter experts (Table 3). Higher weights indicate greater importance to the eradication decision. Within a given tier on the hierarchy (Appendix A), weights sum to one. The major criteria were weighted 39.3% for Feasibility of Eradication, 37.8% for Impact, and 22.9% for

Invasiveness (likelihood of spread). Under Feasibility of Eradication, the Size (25.3%) and Control Effectiveness (19.0%) sub-criteria received the most weight. Under Impact, Impact to Wildlands (33.6%) and Regional Site Value (31.3%) received the most weight, and the Rarity Occurrence sub-criterion (51.8%) was weighted the most under Regional Site Value. Under Invasiveness, the Maximum Rate of Spread (39.3%) sub-criterion was weighted the highest, with Nearness to Propagule Source (37.8%) also weighted heavily. The combined weight of the species-level criteria (54.3%) is slightly greater than the combined weight of the population-level criteria (45.7%). The comparison matrices all have acceptable consistency ratios ($CR < 0.10$), except for the 'Nearness to Spread Vector' sub-criterion ($CR = 0.17$).

**Ranking Tool Components**

The major criteria scores of Impact, Invasiveness, and Feasibility of Eradication were not significantly correlated (Figure 1). Impact scores were not significantly correlated with Invasiveness scores ($\tau = 0.129$, $p = 0.0615$). Impact and Invasiveness scores were not correlated with Feasibility scores ($\tau = 0.0951$, $p = 0.176$; $\tau = -0.0668$, $p = 0.337$, respectively). Impact, Invasiveness and Feasibility were all positively correlated with the overall priority score ($\tau = 0.569$, 0.343, 0.412, respectively, $p < 0.0001$).

**Ranking Tool Output**

The mean overall priority score was 6.052 points ± 0.834 (SD) with a median score of 5.887, and ranged between 3.7 and 7.7 (Figure 2). Because scores are relative, there is no threshold for "high" or "low" priority. The distribution of score residuals from the stratified sample was normal (Shapiro-Wilk $W = 0.991$, $p = 0.7726$). An analysis of variance showed a range of variances for conspecific populations, with change in variance reflected by the range in scores (Figure 3). Levene's tests for homogeneity of variance showed variances are not equivalent ($p=0.0003$). Tukey pair-wise comparison shows meadow knapweed's mean score is significantly different from the rest (Table 4). However, mean score significance groupings overlap for all other species.

**Initial Assessment of Ranking Tool**

I compared the ranked list to expert opinion by Kendall $\tau$ coefficient to determine how closely the model matched five experts' assessments of the sample populations (Figure 4). Model output was strongly positively correlated with one expert ($\tau=0.209$, $p=0.00573$), weakly positively correlated with two experts ($\tau=0.149$ for both, $p=0.0531$ and $p=0.0526$), negatively correlated with another expert ($\tau=-0.160$, $p=0.0399$), and did not correlate with a fifth expert ($\tau=0.0916$, $p=0.233$). Among pair-wise comparisons of experts, $\tau$ ranged from $-0.419$ to 0.344.

## DISCUSSION

The goals of this study were to create a method for prioritizing weed population eradication projects, to illustrate the method using a sample of CDFA A-rated weed populations, and to suggest a strategy for implementing the prioritization tool. This protocol was developed to prioritize weed populations that have already been identified as high-priority species with the ultimate goal of eradication. The protocol is not designed to predict species most likely to invade an area or to determine target species for control from a list of unknowns. The tool ranked weed populations in order of priority according to a carefully chosen set of criteria. The most important result from the study is that prioritizing populations, rather than species, has been shown to be feasible and produces a useful ranking. This addressed the needs of the California Department of Food and Agriculture (CDFA) with regard to the eradication of noxious weeds and would apply to any entity performing early detection and rapid response activities.

**Interpretation of Weights**

Experts gave higher weight to criteria they felt were of greater importance in an eradication decision. Among the major criteria, Feasibility of Eradication (39.3%) and Impact (37.8%) received the most weight. The CDFA's A-rated weed species are statewide eradication targets because they are known to be damaging; therefore, the feasibility of managing these weeds is the primary concern for the Department. However, all A-rated weeds are not equally damaging, and level of impact should play an important role in the decision to eradicate. Once a weed has been determined to be causing negative impact and is designated as feasible to control, then the decision to target specific populations should consider those most likely to spread. Under Feasibility of Eradication, the Size (25.3%) and Control Effectiveness (19.0%) sub-criteria received the most weight. This makes sense because these two sub-criteria greatly affect the overall cost of an eradication project, which is a major consideration with a limited budget.

The CDFA is mandated to protect agriculture and the environment (CDFA 2007). The subject matter experts, many of whom were CDFA and County Agricultural Department staff, placed emphasis on impact to wildlands and nearness to rarity occurrences. Under the major criterion of Impact, Impact to Wildlands (33.6%) and Regional Site Value (31.3%) received the highest weight. The Rarity Occurrence sub-sub-criterion (51.8%) was weighted highest under Regional Site Value. Granted, the model does not take into account whether the weed in question would actually threaten the rare species in the vicinity. An assumption built into the model is that the weed could potentially adversely affect the surrounding habitat and is, therefore, an very high priority for eradication.

The comparison matrices all have acceptable consistency ratios (CR< 0.10), indicating that the experts were consistent among themselves when ranking criteria in order of importance. However, the ‘Nearness to Spread Vector’ sub-criterion consistency ratio was 0.17, but because the criterion is low in the hierarchy, the score will not likely compromise the overall priority score.

**Interpretation of Scores**

The major criteria scores of Impact, Invasiveness, and Feasibility of Eradication were not correlated with each other, which indicates that they varied independently making the model more robust. I was concerned that populations scoring high in one criterion might always score high in another, but that was not the case. If this was the case, then a slightly complex multivariate scoring system such as this might not have been necessary. Impact, Invasiveness and Feasibility of Eradication all positively correlated with the overall priority score. This suggests that a single major criterion score may be as predictive of the overall score as the full model. A sensitivity analysis could determine the predictive power of the major component criteria to further minimize the number of model inputs.

If weeds were more appropriately considered for management at the species-level, I would expect the conspecific population scores to be significantly clustered, without much overlap with populations of other species. However, an analysis of variance of overall priority scores grouped by species showed that conspecific populations did not necessarily group together and need to be considered individually for management. Some clumping of conspecific population scores is understandable given the species-level criteria did contribute substantially (weight 54%) to the overall score. For example, all meadow knapweed populations exist along the same corridor in the northwest corner of the state, wherein contains a concentration of rarity occurrences, which resulted in clumping of model output scores. Some species have a wider distribution and, as expected, the conspecific population scores were more varied (e.g., rush skeletonweed, musk thistle, and leafy spurge).

The environment and site logistics (e.g., detectability, accessibility) where a weed population is located can vary tremendously statewide. When combined together, the population-level assessment criteria comprise just below 50% of the overall decision, which has a strong enough impact to increase conspecific population score variance. The overlap in Tukey significance groupings for species suggests that the variance in the range of scores for con-specific populations is sufficient for each population to be considered individually for management.

Because scores are relative, there is no threshold for “high” or “low” priority. However, the fact that populations are numerically ranked provides the ability to objectively set a cut-off once resources for eradication are allocated. Ultimately, the overall priority score is reasonably objective and provides insight into why a given population may or may not be a high priority for eradication. The model was designed to consider all criteria consistently. For example, one might not consider the meadow knapweed populations in the northeastern corner of the state to be a very high priority, until we consider the easy accessibility, high potential for spread, and nearness to a concentration of rarity occurrences.

**Initial Assessment**

Because the protocol was built by experts, the output should be consistent with experts' rankings of weeds within an area, rather than produce a reordering of priority infestations for management (Hiebert 1997, Pheloung et al. 1999). The output from the prioritization system should generally agree with present knowledge and understanding, which will be required to gain acceptance and be implemented. However, the prioritization tool may realign priorities of the current experts' opinions. The model explicitly assesses the decision factors, while the experts do so implicitly. If the tool's output does not agree with expert rankings, this may be because a component of the tool is not optimal (e.g., criteria selection, hierarchy arrangement, weights, scores, etc.) or because the tool identified a factor or suite of factors not previously considered analytically. The system can be revised based on experience and recommendations from users and expert reviewers.

Five experts were asked to perform assessments of sample populations using their judgment as to whether a given site was a high or low priority for eradication. Using Kendall's $\tau$ correlation coefficient, experts' assessments generally correlated positively with the model output. During the survey, the subject matter experts did not have all the factors considered by the model, such as data on rare taxa. Also, experts considered factors that were not included in the model, e.g., treatment history at the site and landowner cooperation.

While not all experts agreed with the model, they also did not agree with one another. Using Kendall's τ correlation coefficient, correlations among expert assessments varied from strongly positive to strongly negative. Weak or no correlation in this initial assessment does not mean the model is invalid. The tool is science-based, removes objectivity inherent in expert opinion, and can dynamically respond to new information and future validation.

This initial assessment of the model output is not a validation because experts were not given full details. A future validation exercise might entail giving experts all the information used by the model, which will give a better understanding of the model's capabilities, limitations, and appropriateness for identifying eradication targets. I expect the correlations of experts and the model will then be stronger.

**Significance of Results**

Consideration of spatial criteria for each infestation sets this prioritization protocol apart from previous prioritization methods. Spatial characteristics of the infestations include: nearness to vectors of spread (Cacho et al. 2006); distance to propagules sources (Dewey et al. 1995); and nearness to high-value assets (Hiebert pers. comm. 2007), i.e., vulnerable agricultural commodities, threatened and endangered species, popular recreation areas. In creating a population-level prioritization system, I enhanced existing species-level prioritization systems by employing both species and population-level information.

Statewide eradication as a goal is sometimes limited. Some weeds are prevalent in regions of California, but they are still rare and eradicable in small sub-regions of the state. The quote, "Eradication should be attempted whenever feasible," is one of the major themes identified in the California State Weed Action Plan (CDFA 2005). Local eradication, removing every individual and its propagules from the region, can substantially reduce the long-term control costs and protect natural resources from impacts associated with the weed.

In California, control efforts should focus on prevention of further spread and on local eradication. A land manager may focus their noxious weed activity on reducing infestation levels in areas where the plants are abundant. However, weeds may potentially spread into non-infested regions of the state. Large areas, including private land and public forests and parks, can still be protected from the presence of harmful weeds. Land managers now have a prioritization tool to rank potential eradication targets. At the end of the prioritization process, land managers have a list of infestations ranked in order of priority based on a transparent, analytical system. Along with the list of ranked infestations, the land manager also has a record of the decision-making process. All are important and useful tools to justify program authorization and funding. Infestations ranked at the bottom of the list may be good candidates for biological control trials, provided the populations are large enough for establishment of appropriate agents. Agencies and private landowners need better information on where to prioritize eradication to make the most effective use of limited budgets.

**Weaknesses, Problems, and Uncertainty**

Several issues arose during development of the prioritization model that may have affected the results. One issue was defining and scoring criteria consistently. I found that the criteria and scores evolved as I learned more about the decision-making process and the species in question. Also, the scale of the area under consideration was possibly too large. Often the data were unavailable to answer questions for some populations, such as size, accessibility and detectability. For example, missing data in the CDFA A-weed database on acreage precluded many sites from being run through the model. With more complete data, the model results would be more realistic. Furthermore, the CDFA does not track weed populations outside the California border, which may act as propagule sources. Applying this prioritization method to smaller scales may alleviate the problem of poor data resolution.

Dealing with various sources of uncertainty is a major challenge in developing and using weed risk management and prioritization systems (Akçakaya et al. 2000, Regan et al. 2002, Burgman et al. 2005, Regan et al. 2005). One problem was that no one individual is familiar with every species or every site, which makes comparisons among sites difficult. I chose to implicitly deal with uncertainty in scoring by using the taxonomy approach – even if the answer to each question is a little off target, by combining the scores of many criteria, the final score is very likely to be meaningful. The best available information went into the model for consideration.

The model has several limitations. The model criteria do not capture every factor in the decision to eradicate. During the model assessment surveys, experts used criteria not considered by the model, such as treatment history at the site and landowner cooperation. Also, factors such as suitability of nearby habitat for spread and nearness to migratory routes were considered but not included due to lack of data. Not all potential vectors of spread were included, e.g., animal dispersal, because they were not as relevant to the test set of weed species, but would be relevant for berry-producing species. Disadvantages of using a prioritization tool are that it is time-consuming and there are data availability and quality issues. However, the protocol is adaptable to many different scales and can be revised based on experience and recommendations from users and expert reviewers. During the survey process, experts commented that considering all criteria was challenging but a very useful exercise.

**Future Directions**

Further analyses of this model could include a sensitivity analysis, rerunning the populations with more data of higher quality, and testing the model on different scales (e.g., county level and National Forests). Several Weed Management Areas have expressed interest in using this prioritization protocol. The model would benefit from an integrated cost function to estimate the first year and lifetime cost of proposed eradication projects, similar to the Australian WeedSearch™ tool (Cacho and Pheloung 2007). A future collaboration with colleagues in Australia would help to combine hierarchical decision-making with decision points (Steele pers. comm. 2008) and explore the possibility of multiplying the major criteria scores, as opposed to totaling them, to give greater separation of population scores and investigate whether there is better agreement with expert categorizations (Virtue pers. comm. 2008).

**Conclusions**

As non-native species become widely established, management options become more limited and more expensive. Even in the rare cases in which the knowledge and methods exist to fully control a widely established species, such efforts are expensive and must be practiced indefinitely. For example, if cost inflation were considered, economic impacts (e.g., forage loss and reduced livestock production) in the western United States from spotted and diffuse knapweed would be about $164.5 million annually based on seven million acres infested (Duncan and Clark 2005). Quantitative prioritization protocols that identify weed populations most likely to spread quickly and impact on California's resources could enable targeted eradication to help prevent future environmentally damaging and expensive infestations.

This prioritization tool will help land managers systematically target the highest priority weed populations by putting their limited resources into the populations known to cause the highest impacts and are the most feasible to eradicate. This tool results in a ranked list of infestations based on a transparent, analytical system with a record of the decision-making process, which will help to justify program authorization and funding (Hiebert 1997). The results presented here are not specific to the state of California and the CDFA's A-rated weeds. This approach to prioritizing weed populations may be applied to a diversity of plant species on a range of regional scales.

Regional eradication achieves clear benefits in a state as large and ecologically diverse as California. Weed prioritization protocols are now becoming a common approach in focusing activity and resources**.** However, from the standpoint of eradication programs, species-level statewide priorities do not allow for regional and population-level considerations. The prioritization scheme can be designed to look at eradication of discrete infestations. By strategically targeting weed populations using the limited resources available, we minimize future spread and mitigate future impacts.

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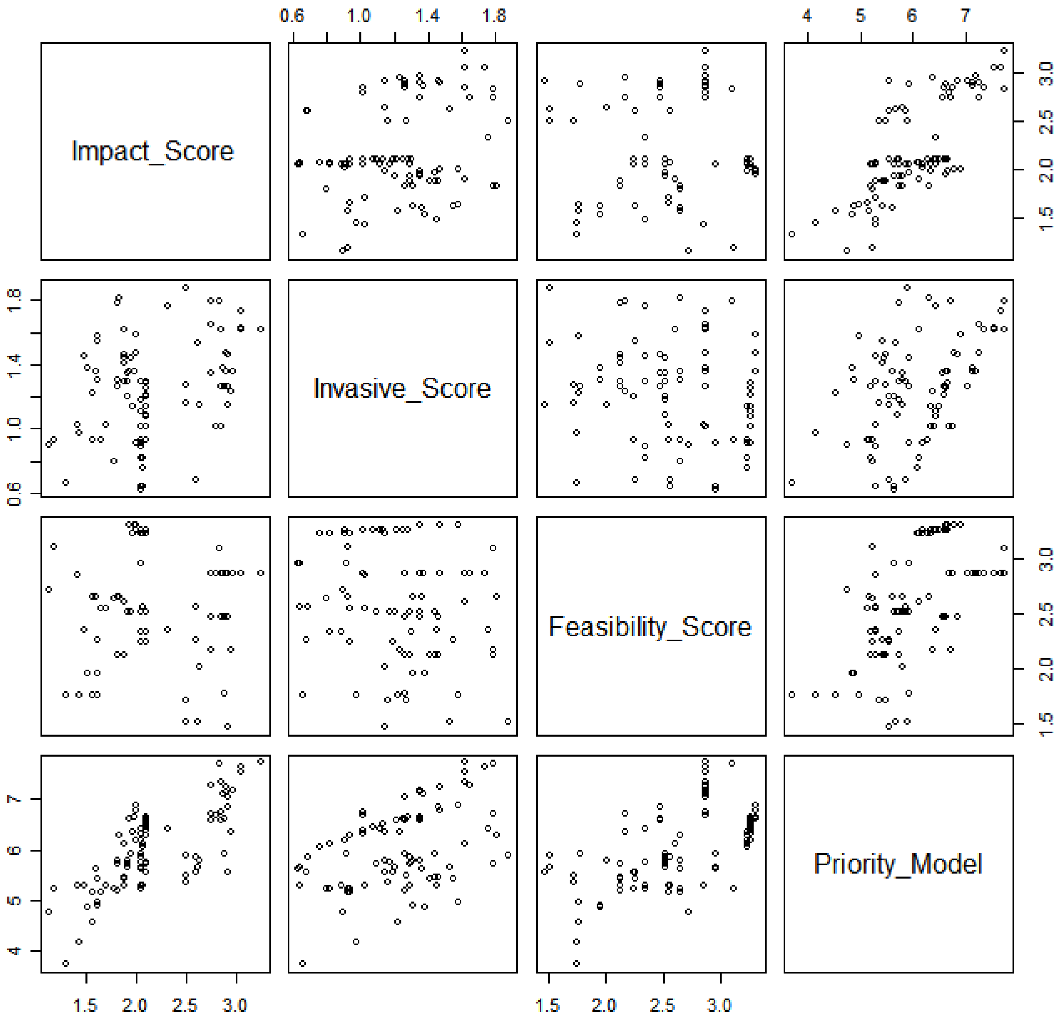



Figure 1. Matrix of scatter plots of major criteria and overall priority scores. Major criteria scores are not significantly correlated ($p > 0.05$). Each component score is significantly correlated with the overall priority score ($p < 0.0001$).

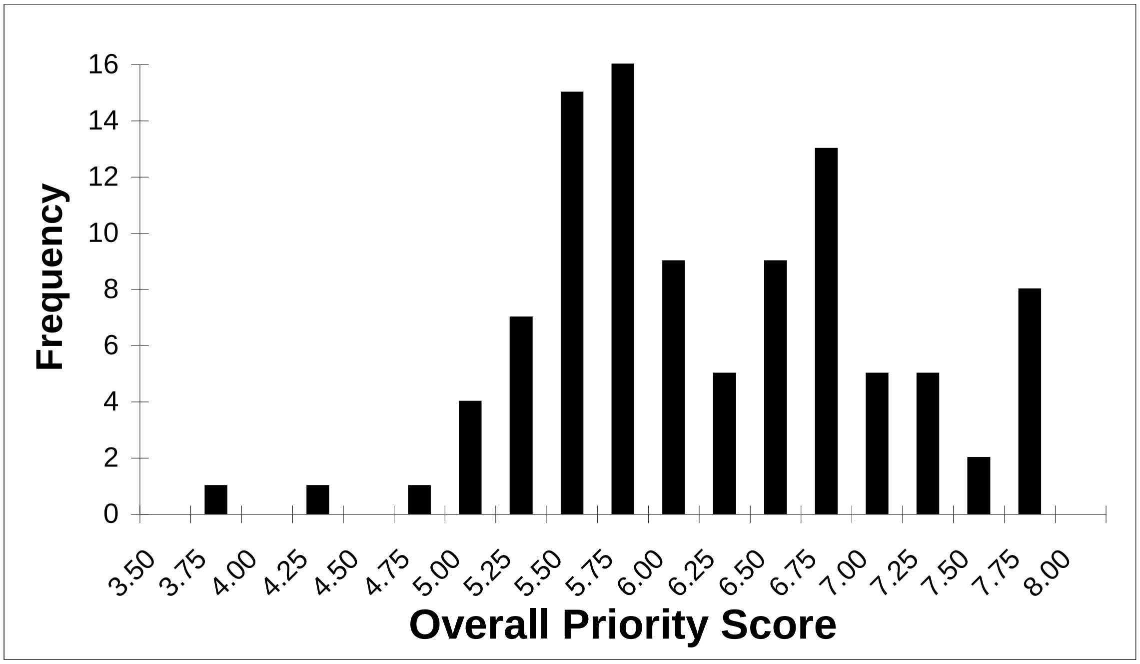



Figure 2. Distribution of Overall Priority Scores for 100 sample A-rated weed populations stratified by 19 species.

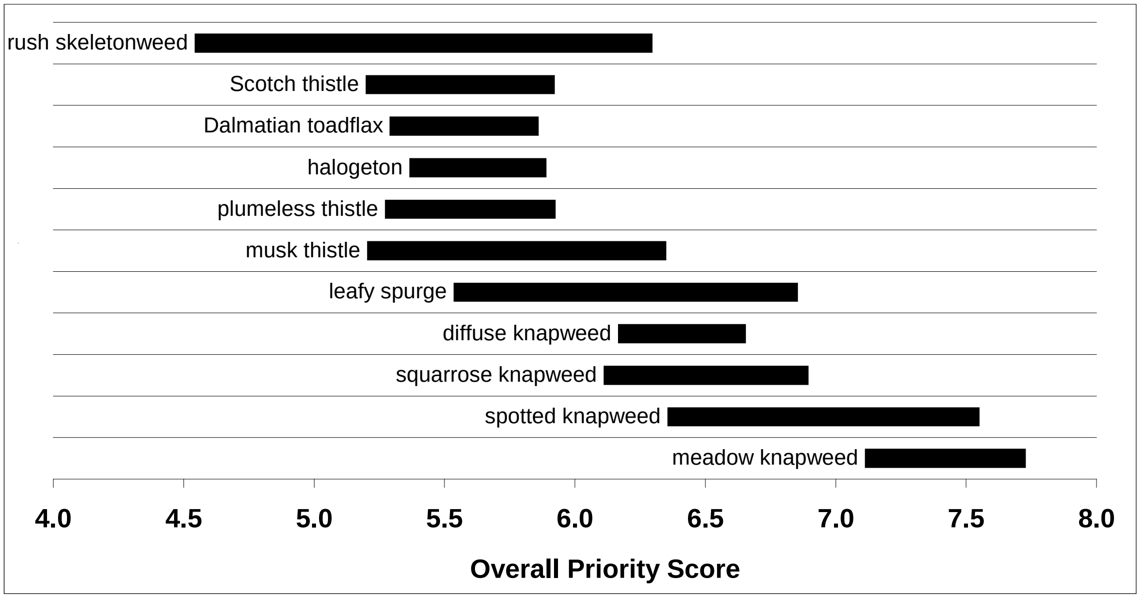



Figure 3. Range of overall priority scores for species represented by more than two populations.

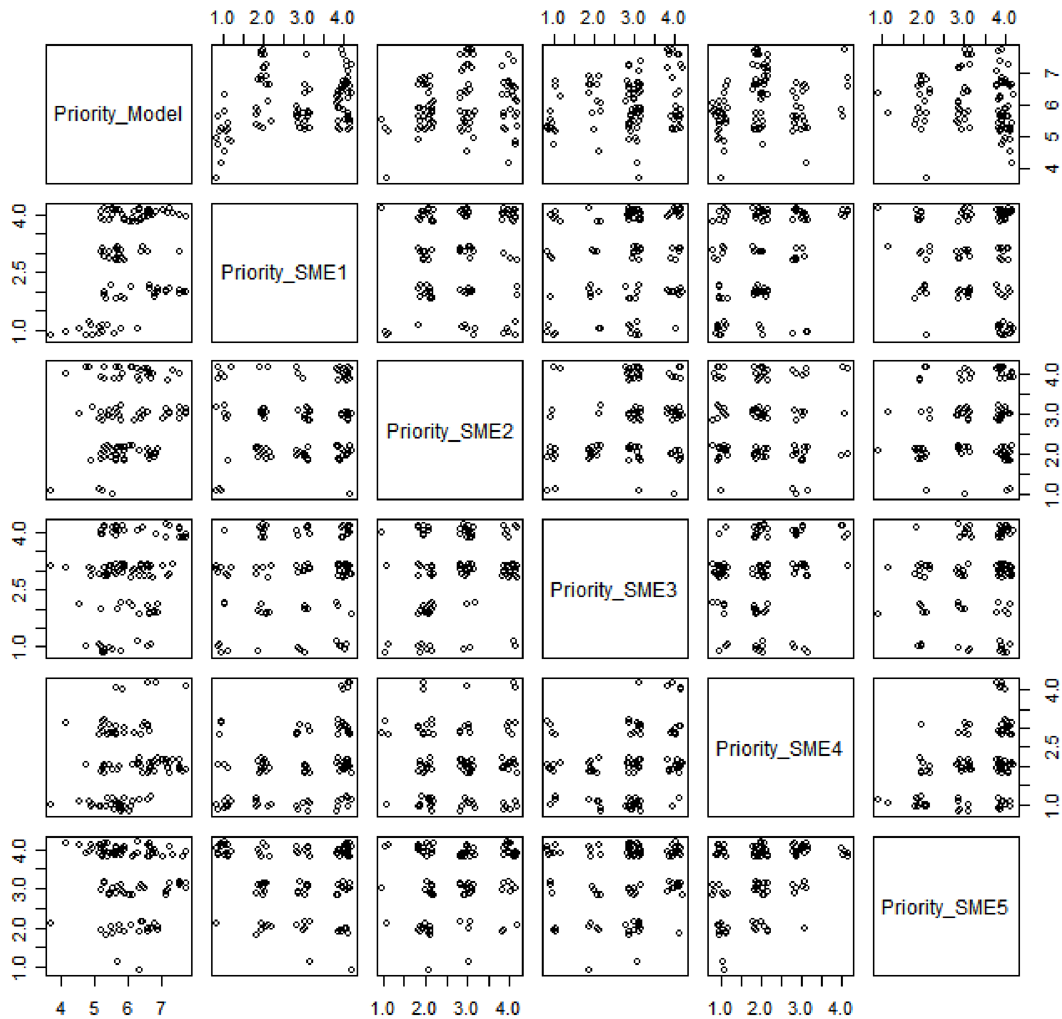



Figure 4. Matrix of scatter plots of model population scores compared to subject matter expert (SME) assessments of the corresponding population. Model scores range from 3.7 to 7.7. Expert assessments were 'very high priority' (4), 'high' (3), 'medium' (2), and 'low' (1). Expert assessments were 'jittered' in order to see the concentration of populations receiving the same score.

Table 1. Major and sub-criteria used to rank weed populations organized in a hierarchy with species-level questions designated 'S' and population-level questions designated 'P.'

Preliminary Screening Questions

1. High-priority species (S)
2. Not included in containment zone (P)
3. Not a biological control agent release site (P)
4. Accessible during control season (P)

Impact $_{\mathbf{(IMP)}}$– Major Criterion

- Impact to Wildlands $_{(WILD)}$ (S)
- Impact to Agriculture $_{(AG)}$ (S)
- Impact to Humans $_{(HU)}$ (S)
- Regional Site Value $_{(REG)}$(AKA Nearness to high-value assets)(P):
  - Agricultural commodities at risk (grazing land) $_{(GR)}$
  - Rarity occurrences $_{(RARE)}$
  - National and State Parks $_{(REC)}$
  - US Forest Service land $_{(FS)}$

Invasiveness $_{\mathbf{(INV)}}$– Major Criterion

- Distance to conspecific propagule source $_{(PR)}$ (P)
- Rate of spread with no management $_{(RATE)}$ (S)
- Nearness to vectors of spread $_{(VEC)}$ (P):
  - Major roadways $_{(RD)}$
  - Major rivers $_{(RIV)}$
  - Mining operations $_{(MINE)}$

Feasibility of Eradication $_{\mathbf{(FEAS)}}$– Major Criterion

- Size of infestation (gross acreage) $_{(SI)}$ (P)
- Reproductive ability $_{(RE)}$ (S):
  - Seed set
  - Vegetative reproduction
  - Seedbank longevity
  - Length of juvenile phase
  - Length of reproductive phase
- Detectability $_{(DE)}$ (S)
- Accessibility $_{(AC)}$ (P)
- Control effectiveness $_{(CE)}$ (S)
- Cost estimate $_{(\$)}$ (P):
  - Driving time to site
  - On-site control cost per acre
  - Follow-up visits
  - Special considerations

Table 2. 19 species were chosen from the CDFA A-weed database to test the prioritization tool. Sample populations were chosen stratified by species so as not to over-represent the more common species in the database.

| ***Scientific name*** | **Common Name** | **No. Sample Populations** |
|---|---|---|
| *Acaena novae-zelandiae* | biddy-biddy | 2 |
| *Achnatherum brachychaetum* | punagrass | 1 |
| *Alhagi maurorum* | camelthorn | 1 |
| *Alternanthera philoxeroides* | alligatorweed | 1 |
| *Arctotheca calendula* | fertile Capeweed | 1 |
| *Carduus acanthoides* | plumeless thistle | 9 |
| *Carduus nutans* | musk thistle | 10 |
| *Centaurea diffusa* | diffuse knapweed | 9 |
| *Centaurea maculosa (= C. bieberstenii)* | spotted knapweed | 11 |
| *Centaurea x pratensis* | meadow knapweed | 9 |
| *Centaurea squarrosa* | squarrose knapweed | 8 |
| *Chondrilla juncea* | rush skeletonweed | 9 |
| *Cirsium ochrocentrum* | yellowspine thistle | 2 |
| *Euphorbia esula* | leafy spurge | 4 |
| *Halogeton glomeratus* | halogeton | 5 |
| *Linaria genistifolia* spp. *dalmatica (= L. dalmatica)* | Dalmatian toadflax | 9 |
| *Onopordum acanthium* | Scotch thistle | 7 |
| *Onopordum tauricum* | Taurian thistle | 1 |
| *Peganum harmala* | harmel | 2 |

Table 3. Weights (eigenvectors) and consistency measures for major and sub-criteria. All have acceptable consistency ratios (CR < 0.1), except one*.

| **Weights - Major Criteria** | |
|---|---|
| Impact | 0.378 |
| Feasibility of Eradication | 0.393 |
| Invasiveness | 0.229 |
| **Consistency Measures** | |
| Maximum Eigenvalue ($\lambda_{max}$) | 3.005 |
| Consistency Index (CI) | 0.003 |
| Random Index (RI) | 0.580 |
| Consistency Ratio (CR) | 0.005 |

| **Weights - Impact Sub-criteria** | |
|---|---|
| Wildlands | 0.336 |
| Agriculture | 0.238 |
| Humans | 0.113 |
| Region | 0.313 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 4.014 |
| CI | 0.005 |
| RI | 0.900 |
| CR | 0.005 |

| **Weights - Invasiveness Sub-criteria** | |
|---|---|
| Propagule Sources | 0.378 |
| Max Rate of Spread | 0.393 |
| Nearness to Spread Vector | 0.229 |
| **Consistency Measures** | |
| M $\lambda_{max}$ | 3.012 |
| CI | 0.006 |
| RI | 0.580 |
| CR | 0.010 |

| **Weights - Feasibility Sub-criteria** | |
|---|---|
| Size | 0.253 |
| Reproduction | 0.177 |
| Detectability | 0.125 |
| Accessibility | 0.150 |
| Control Effectiveness | 0.190 |
| Control Cost | 0.105 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 6.110 |
| CI | 0.022 |
| RI | 1.240 |
| CR | 0.018 |

| **Weights - Regional Sub-criteria** | |
|---|---|
| Ag Commodity at Risk | 0.261 |
| Rarity Occurrences | 0.518 |
| Recreation Areas (Parks) | 0.100 |
| USFS Land | 0.121 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 4.043 |
| CI | 0.014 |
| RI | 0.900 |
| CR | 0.016 |

| **Weights - Spread Vector Sub-criteria** | |
|---|---|
| Major Roadways | 0.333 |
| River Systems | 0.425 |
| Gravel Operations | 0.243 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 3.204 |
| CI | 0.102 |
| RI | 0.580 |
| CR* | 0.175 |

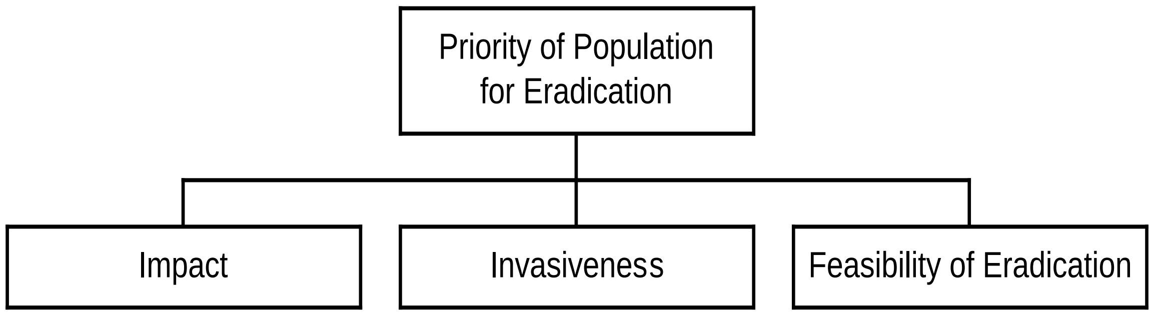
| **Weights - Reproductive Sub-criteria** | |
|---|---|
| Seed Set | 0.159 |
| Vegetative Reproduction | 0.154 |
| Seed/Propagule Longevity | 0.448 |
| Juvenile Phase | 0.132 |
| Reproductive Phase | 0.106 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 5.068 |
| CI | 0.017 |
| RI | 1.120 |
| CR | 0.015 |

| **Weights - Control Cost Sub-criteria** | |
|---|---|
| Driving Time | 0.132 |
| On-Site Control | 0.338 |
| Monitoring | 0.347 |
| Special Considerations | 0.182 |
| **Consistency Measures** | |
| $\lambda_{max}$ | 4.112 |
| CI | 0.037 |
| RI | 0.900 |
| CR | 0.042 |

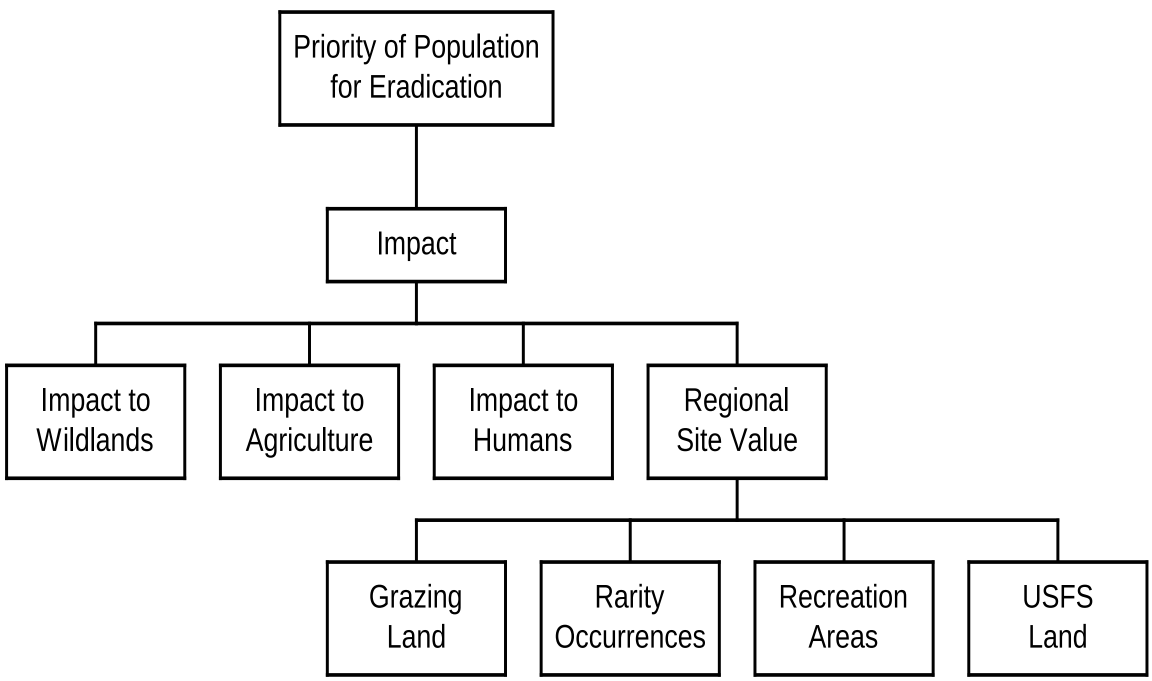
Table 4. The overlap and variance of species groups indicates that scores are spread across species and conspecific populations, and should be considered separately for management.  Species means with the same Tukey significance grouping letters are not significantly different.

| Species (represented more than twice) | No. populations in sample | Mean Score | Standard Deviation |
|---|---|---|---|
| meadow knapweed | 9 | 7.469 | 0.243 (A) |
| spotted knapweed | 11 | 6.910 | 0.382 (B) |
| squarrose knapweed | 8 | 6.668 | 0.250 (BCD) |
| diffuse knapweed | 9 | 6.453 | 0.153 (C) |
| leafy spurge | 4 | 6.227 | 0.607 (BCD) |
| musk thistle | 10 | 5.800 | 0.456 (D) |
| plumeless thistle | 9 | 5.641 | 0.182 (D) |
| halogeton | 5 | 5.639 | 0.213 (D) |
| Dalmatian toadflax | 9 | 5.614 | 0.213 (D) |
| Scotch thistle | 7 | 5.498 | 0.247 (D) |
| rush skeletonweed | 9 | 5.280 | 0.548 (D) |

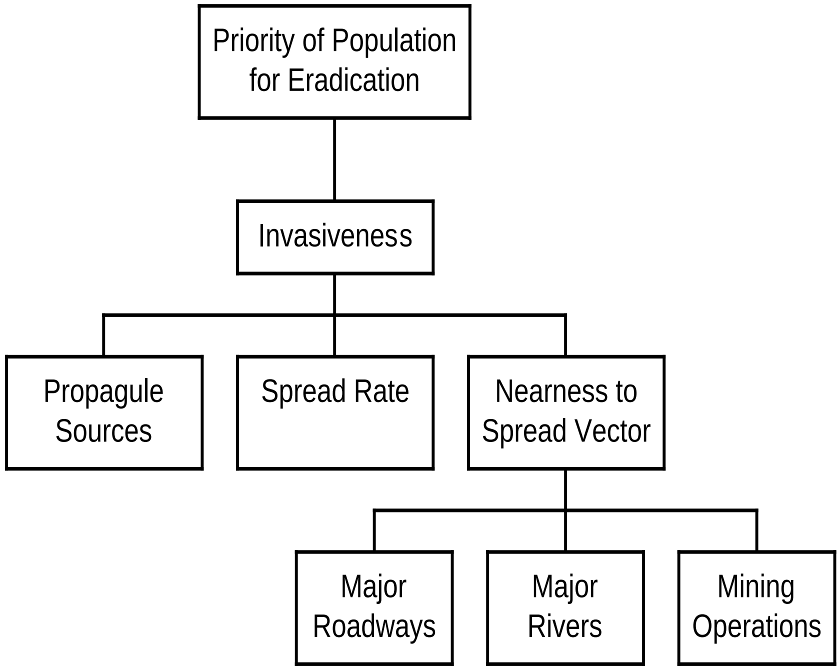
**APPENDIX A– Hierarchy Used for Prioritization Analysis**



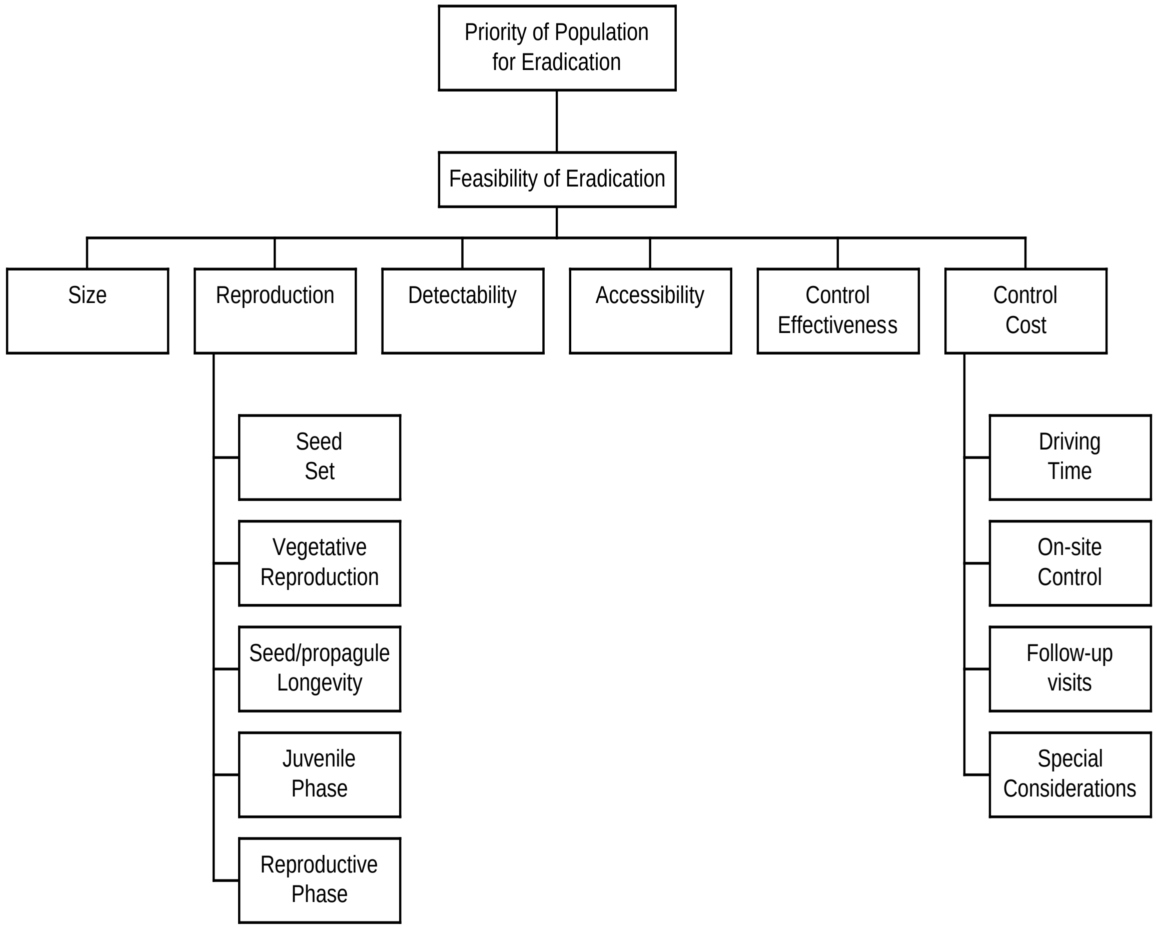

The overall priority of the population for eradication is divided into three major criteria, AKA Tier 1: Impact, Invasiveness, and Feasibility of Eradication.




The Impact major criterion is further broken down into sub-criteria, AKA Tier 2: Impacts to wildlands, agriculture, humans, and regional site value. The regional site value sub-criterion is further broken down into sub-sub-criteria, AKA Tier 3.




The Invasiveness, or potential for spread, major criterion is further broken down into sub-criteria, AKA Tier 2: observed spread rates, distance to propagule sources, and nearness to vectors of spread. The spread vector value sub-criterion is further broken down into sub-sub-criteria, AKA Tier 3.




The Feasibility of Eradication major criterion is further broken down into sub-criteria, AKA Tier 2. The reproduction and control cost sub-criteria are further broken down into sub-sub-criteria, AKA Tier 3.

## APPENDIX B – Model Criteria Explained

To prevent range expansion and to mitigate potential damage in the future with limited available resources, land managers need to have worked on minimizing the extent of spread and minimizing potential impact by strategically selecting eradication targets.

After reviewing the weed risk management and eradication literature and hosting discussions with experts (County Agricultural Department Interviews, 6/07; Science Advisory Workshop, 8/07; 2nd International Weed Risk Assessment Workshop, Perth, Australia, 9/07; Dane Panetta visit, 5/08), I chose criteria that contribute most to the success of eradication projects and, therefore, the decision to eradicate. I recognize many factors contribute to eradication success and cost, but decided on this subset to prevent the tool from becoming unmanageable.

**Scoring:** Each criterion at a terminal node in the hierarchy is scored on a scale of 0 to 10, with 10 points given for an attribute lending itself to being a very-high priority for eradication; 6 points for high priority, 3 points for medium, 1 point for low, and zero points for none. I placed emphasis (more points) on higher priority attributes to parse out top tier populations since those will be getting a land manager's attention.

### Eradication Prerequisites

Pre-assessment criteria are employed to screen potential candidates for eradication. In the case of the California Department of Food and Agriculture (CDFA), these conditions include:

1) The weed has to be a species previously identified as a high-priority via a species-level risk assessment protocol. In this case, the weed must be a CDFA A-rated species identified by the CDFA Pest Plant Rating List (CDFA 2008a).
2) The population must not be within a CDFA designated containment zone, an area of many, dense infestations, at which point CDFA is concerned about the leading edge of the infestation and not individual sites. i.e. *Onopordum acanthium* L. in the northeastern California counties (CDFA 2007).
3) The weed must not be under successful biological control at the site, i.e. some *Centaurea squarrosa* Willd. sites in California.
4) The site must be accessible during the optimal control season: i.e. no locked gate, landowner permission granted, no pot farming.
5) The site must be delimited with net and gross acreage recorded in the database.
6) The species must not have its own funding source tied to a law mandating its eradication, i.e. *Hydrilla verticillata* (L. f.) Royle and *Cuscuta japonica* in California.

**Impact**

Species were initially chosen for eradication based on the potentially high negative impacts that would result from their spread across the California landscape. However, among those species chosen, impacts varied widely. This section was designed to identify weeds causing relatively high impacts of species already known to cause negative impacts. These criteria assess the relative negative impact of each A-rated weed population based on known species impacts to wildlands, agriculture, human health and the potential of weed populations to impact the regional site value. Species and populations determined to have relatively high, negative impacts will be a higher priority for eradication.

Impact to Wildlands

The Cal-IPC Inventory Impact Score aims to assess cumulative impact of the species on the wildlands where it typically occurs in California and takes into account: 1) impact on abiotic ecosystem processes; 2) impact on plant community composition, structure, and interactions; 3) impact on higher trophic levels; and 4) impact on genetic integrity (Cal-IPC 2006). In the cases of species not evaluated by Cal-IPC, Joseph DiTomaso and I gathered information and assigned an appropriate score. For the purposes of simplifying the prioritization tool, negative impact to the environment is a species-level consideration and scores are from plant assessment forms, which resulted from the California Invasive Plant Council's (Cal-IPC) weed assessment system (Cal-IPC 2006). University of California Cooperative Extension Specialists assessed impact to agriculture and human health for each species and environmental impact for those species not assessed by Cal-IPC.

*Scoring*: Species known to cause greater negative impact are a higher priority for eradication. Species receiving an A or equivalent from the Cal-IPC Plant Assessment Form criteria get 10 priority points; B get 6 points; C get 3 points; D get 1 point. No species received zero points.

Impact to Agriculture

Costs to agricultural production are viewed in terms of both reduced yield and the control costs incurred to maintain yield (Virtue et al. 2006). I gathered information and

UC Cooperative Extension specialists scored the level of relative potential negative impact on agriculture (crops, rangeland, timber) in California if CDFA did not manage the weed and it achieved a density typical of the worst California infestation.

*Scoring*: Species known to cause greater negative impact are a higher priority for eradication. Species causing a relatively very high impact get 10 priority points; a high impact get 6 points; a moderate impact get 3 points; a low impact get 1 point; and a species determined not to cause any negative impacts would receive zero points; however no species received zero points.

Impact to Human Health

If the weed affects health of people, it is a problem (Virtue et al. 2006). This criterion considers the potential of poisoning, allergic reactions and/or physical injuries from thorns or spines. Joe DiTomaso and I gathered information on each species and scored level of negative impact.

*Scoring*: Species known to cause greater negative impact are a higher priority for eradication. Very toxic plants receive 10 priority points; very spiny plants receive 6 points; allergen-producing plants receive 3 points; mildly irritating plants receive 1 point; and plants not likely to affect human health receive zero points.

Regional Site Value

Proximity to high-value assets was used to estimate risk of a noxious weed population affecting the region. The value of infested site to the surrounding region was approximated via distance to high-value assets in ArcGIS 9.3: 1) agricultural commodities at risk; 2) rarity occurrences; 3) important recreation areas; and 4) USFS land. Based on the distance to each of these high-value assets, a score was assigned using GIS geoprocessing models (Appendix F) and an attribute table was populated.

1) Agricultural Commodities at Risk - most weed species under consideration affect grazing lands, and we created a grassland layer for California using data from The California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP) (http://frap.fire.ca.gov/).
2) Rarity occurrences of threatened and endangered species and rare plant communities layer was created using element occurrence concentrations by topographical quads from California’s Natural Diversity Database (CNDDB). We included element occurrences from CNDDB’s backlog in order to estimate the rarity value of a region. Neighborhood statistics were calculated using ArcGIS 9.3 Spatial Analyst.
3) We used a layer of National and State Parks to represent important recreation areas.
4) USFS land (layer). Control options are limited on USFS lands so in an effort to prevent future spread, higher priority sites are close to USFS land

*Scoring*: The closer a population is to each of these high-value assets, the higher the priority for eradication and the more points it received. For grazing land, parks and USFS layers, a very close population (in or within .1 mile) gets 10 priority points; close (between .1-1 mile) gets 6 points; far (between 1-10 miles) gets 3 points; very far (10-25 miles) gets 1 point; and too far, not likely to invade (25+ miles) gets zero points. For the Rarity Occurrences layer, the score was calculated using neighborhood average of the quad a population was found in and the 8 surrounding quads. A rarity value of 500 or more received 10 priority points; a value of 300-500 received 6 points; a value of 100 - 200 received 3 points; a value of 1 – 100 received 1 point; and a value of zero received zero points.

**Feasibility of Eradication**

These criteria assess relative feasibility of eradicating a weed population. Higher-feasibility projects (sites) require relatively lower cost and effort and received higher priority for eradication.

Size

Total area (net and gross acreage) of the population is relates to eradication cost and effort, propagule pressure, and detectability (Dewey et al. 1995, Rejmánek and Pitcairn 2002, Panetta and Timmins 2004, Cacho et al. 2006, Virtue et al. 2006, Randall et al. 2008). Gross acreage is the amount of area that needs to be surveyed in order to detect every individual at the site. Net acreage is the amount of area the weeds occupy on the landscape and the amount of area that gets treated. Smaller sites are less expensive to manage due to less search area, less chemical and increased likelihood of detection. Mapping of a weed's distribution is needed in order to address this criterion. Population sizes are maintained as part of CDFA's A-rated Weed Database.

*Scoring*: The smaller the population, the more feasible it is to eradicate, and the higher priority. A population less than 0.1 gross acre gets 10 priority points; a population between 0.1-1 acre gets 6 points; a population between 1-10 acres gets 3 points; a population between 10 - 100 acres gets 1 point; and a population over 100+ acres gets zero points.

Reproduction

Reproductive ability is well documented as an important consideration when deciding on an eradication project (Hiebert 1997, Cunningham et al. 2004, Hester 2004, Woldendorp and Bomford 2004, Cacho et al. 2006, Virtue et al. 2006, Randall et al. 2008). This criterion assesses the relative ability of the species to reproduce and persist at the site regardless of infestation size via: 1) seed set; 2) ability to reproduce vegetatively; 3) seed bank/propagule longevity; 4) length of juvenile phase; and 5) length of reproductive (adult) phase. Biological information was unavailable for some species so I deferred to expert opinion or inferred from congeners and families.

1) Seed set is the relative amount of viable seed per unit area (typical density seeds/$m^2$/yr). The fewer seeds a plant produces per unit area in a typical density situation, the greater chance of eradication from the site. Information was gathered from the literature and photos from the CDFA Weed Image Database (CDFA 2008b).
2) Vegetative reproduction allows a plant population to spread locally and long-distance. A plant unable to produce vegetative propagules will be easier to eradicate.
3) Seedbank longevity is the major determinant of the time to achieve eradication. A shorter-lived seedbank will facilitate eradication of the population.
4) Juvenile phase is also time to seeding. Weeds that take less than one year to reproduce (i.e. annuals) are more likely to escape treatment. In contrast,

preventing reproduction is much easier for weeds that take a number of years before they produce propagules.

5) Length of reproductive phase is the time during the season the plant is flowering. The longer a plant's blooming season, the less likely each will be controlled prior to setting seed.

*Scoring*:

1) Seed set - plants producing no seed get 10 points; 1-100 seeds/m2/yr get 6 points; 100 - 1,000 seeds get 3 points; 1,000 - 10,000 seeds get 1 points; 10,000+ seeds get 0 points.
2) Vegetative reproduction: None, not clonally (resprouts from perennials don't count), 10 points; Yes, but infrequently (mostly reproduces by seed), 6 points; Yes, frequently, but in conjunction with few viable seed (mostly by veg), 3; Yes, frequently and in conjunction with lots of viable seed, 1; Yes, aggressively, and in conjunction with viable seed, 0.
3) Seedbank longevity: < 2 yr, 10 points; 2-5 yrs, 6 points; 5-10 yrs, 3 points; 10-20 yrs, 1 point; 20+ yrs, 0 points.
4) Juvenile phase: 2+ yrs, 10 points; 1-2 yrs, 6 points; 6 mo - 1yr, 3 points; 1-6 mo, 1 point; < 1mo, 0 points.
5) Reproductive phase: 6+ mo, 10 points; 3-6 mo, 6 points; 1.5-3 mo, 3 points; <1.5 mo, 1 point.

**Logistical Considerations.** On-site logistics and practical considerations also play a role when making the decision to commit to an eradication project. These considerations include 1) *Detectability,* ability to see all individuals of the population at the site prior to reproduction (Panetta and Timmins 2004, Cacho *et al.* 2006); 2) *Accessibility,* remoteness, ease of access, safety (Dewey *et al.* 1995, Cunningham *et al.* 2004, Panetta and Timmins 2004, Cacho *et al.* 2006); 3) *Cost*, control method and labor (Dewey *et al.* 1995, Cacho *et al.* 2006, Panetta and Timmins 2004,), and 4) *Effectiveness* of control (Cacho *et al*. 2006).

Detectability

Weeds that are easy to detect will require less search effort to find and kill every individual. For the purposes of this model, I am considering the detectability to a trained eye (CDFA detection biologists) of a weed at a site that has already been identified, not the likelihood of finding a new site. Is the weed readily visible to a trained eye against the background of typical existing vegetation before the weed flowers? How likely is it to find all individuals at a typical site? Distinguishing features may be plant height above other vegetation, or the color or shape of foliage. A weed that is non-emergent and not distinct from other vegetation prior to reproduction will be more likely to reproduce before it can be controlled. The more detectable the weed is, the higher priority for eradication. Species will receive a default score based on the typical individual in the typical setting. However, the district biologists may change the score based on local knowledge of the site and when the ideal time to treat is.

*Scoring*: Is the weed detectable before reproducing: Highly visible (cannot miss it), 10 points, Visible (miss a few here and there), 6 points; Moderately visible (likely to miss as many as can find), 3 points; somewhat visible (likely to miss more than find); Cryptic (not likely to see unless standing on top of the plant), 0 points.

Accessibility

Assess how difficult it is to access the weed population once driven to the site. Does accessing the site require a special vehicle/equipment (i.e. boat, ATV, repelling, helicopter)? How difficult is it to traverse the terrain (topography, vegetation, safety, landowner)? For example, an infestation may be difficult to access due to the site being on a slope, rocky, dense vegetation, and/or presence of water. I will assign a default score based on topography due to incomplete knowledge of all the sites. However the score may be changed upon consultation with the district biologists. I recommend this data be recorded when surveying a site and entered into the notes for the population in the CDFA A-weed geodatabase.

*Scoring*: The easier a site is to access, the higher priority for eradication. Require special vehicle: No, roadside or equivalent gets 10 priority points; Yes, 4x4 truck or equivalent, 6; Yes, ATV or equivalent, 3; Yes, boat or equivalent, 1; Yes, repelling, helicopter, or equivalent, 0. Difficulty of traversing terrain: Very easy, i.e. open roadside, little traffic, 10; Easy, i.e. roadside moderate to heavy traffic, 6; Medium, i.e. rough topography, poison oak, 3; Difficult, i.e. steep terrain, rattle snakes, 1; Very difficult, accessible, but unsafe, 0.

Control Effectiveness

The number of treatments required to kill a mature plant determined effectiveness of the choice control techniques for each species. Weeds with a strong capacity for vegetative regeneration are often difficult to kill and will require multiple treatments.

*Scoring*: Weeds with more effective tools will receive higher priority for eradication. The number of treatments required to kill a typical, mature individual: 1

treatment, 10 points; 2 treatments, 6 points; 3 treatments, 3 points; 4 treatments, 1 point; and 5+ treatments, 0 points.

<u>Cost Estimate</u>

The total cost of a successful coordinated control program will be a function of total area infested, annual control cost per unit area, and number of years required to achieve the desired level of control (Virtue et al. 2006). I assessed factors contributing to total cost including: 1) Driving time to the site from the district office; 2) On-site control (labor x chemical/equipment x duration); 3) number of follow-up and monitoring visits required per year; and 4) special considerations, i.e., anything that will drive up the cost. Treatment of weed infestations (i.e. herbicides, physical removal) varies with weed species and land use. I gathered information and assigned a default score for the species. However, the district biologists may change the score based on local knowledge of the site.

*Scoring*: Less expensive projects received higher eradication priority. Driving time from district office: <0.5 hr, 10; 0.5-1 hr, 6; 1-3hrs, 3; 3-8 hrs, 1; 8+hrs, 0. On-site control method per unit area + labor: < 10$, 10; $10-50, 6; $50-100, 3; $100-500, 1; $500+, 0; Follow-up monitoring within treatment season: 1 return after treatment, 10; return twice/season after treatment, 6; return 3x/season, 3; return 4/season, 1; return 5+x/season, 0. Special Considerations: none = 10 points.

**Invasiveness**

Invasiveness is defined as the ability to establish, reproduce, and disperse within an ecosystem (Richardson et al. 2000). These criteria assess the relative potential of each

A-rated weed species and population to spread and establish new satellite populations based on known species spread rates and likelihood of long-distance dispersal due to proximity to known spread vectors. While spread is dependent on dispersal characteristics, I decided to generalize across species for this first iteration of the model. To mitigate future spread, species and populations determined to have relatively high likelihood of spreading long distances will be a higher priority for eradication. An assumption is that each weed population has the potential to spread; whereas in reality, some population may be geographically isolated.

Distance from Propagule sources

The more isolated a weed population is from conspecific infestations, the lower the probability of reinvasion of the region and the lower the probability of new acreage being infested in the future, which increases the likelihood of eradication of the species from California (Moody and Mack 1988). A goal is to decrease number of infestations. Studies have shown that by eradicating outlier populations, spread is minimized (AKA fire-fighter strategy) (Dewey et al. 1995). For example, if a population of Scotch thistle occurs in southern California when the densest infestations occur in northern California, then the southern California site would get a higher priority than the populations in the northeastern counties. In any other ranking system Scotch thistle as a species would rank low due to its density in the north. We might miss the opportunity to eradicate the outlier populations that could one day create huge, unmanageable infestations. A more isolated infestation, further from conspecific propagule sources, would receive higher priority. Distance to propagules sources is not related to accessibility. I calculated distance to the nearest conspecific propagule sources in the CDFA A-weed database in ArcGIS 9.3 using

Hawth's Tools for Spatial Analysis (Beyer 2004). I measured straight-line distance from each random selection point up to the nearest neighboring population of the same species.

*Scoring*: 1) Further populations from conspecific propagules sources (outliers with potential to invade new landscapes) will get higher priority. Beyond 25 miles, 10 points; Within 10 - 25 miles, 6 points; Within 1-10 miles, 3 points; Within 1 mile, 1 point; within 0.1 mi, 0 points.

<u>Spread</u>

Maximum rate of current spread with no management (Cal-IPC Inventory Invasiveness score) is a species-level score. UC Cooperative Extensions specialists scored species not evaluated by Cal-IPC.

*Scoring: 2) Faster* spreading species received a higher priority. Cal-IPC scores A or equivalent gets 10 points; B gets 6 points; C gets 3 points; D gets 1 point; no species received zero points.

<u>Nearness to vectors of spread</u>

This criterion uses distance to known vectors of spread to assess the likelihood of spread. Vectors of spread include major roadways, river systems, and mining operations. We used the 2006 mining operation database provided by the California Department of Conservation's Office of Mine Reclamation. We calculated nearness to vectors of spread using ArcGIS geoprocessing models.

*Scoring:* Closer populations to a spread vector will get higher priority. Very close (in or within .1 mile) gets 10 points; close (between .1-1 mile) gets 6 points; far (between 1-10 miles) gets 3 points; very Far (10-25 miles) gets 1 point; and too far (25+ miles) gets 0 points.

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## APPENDIX C – Analytical Hierarchy Process Worksheet

**Analytical Hierarchy Process**
**Internal Weighting Worksheet**

**Reviewer:**
**Amount of time spent filling out this worksheet:**
**Instructions:** Within each tier, rank criteria from most to least important to help with consistency. Use this worksheet to go through each pair of criteria and indicate which criterion is most important and by how much. For assistance, contact Gina Darin.

| | **When choosing an A-rated weed population eradication project, which criterion weighs more heavily on that decision?** | **Choice 1 or 2?** | **By how much (Saaty scale 1-9)?** |
|---|---|---|---|
| Major | 1) Impact vs. 2) Feasibility of Eradication | | |
| Criteria | 1) Impact vs. 2) Invasiveness | | |
| | 1) Feasibility of Eradication vs. 2) Invasiveness | | |

| | | | |
|---|---|---|---|
| Impact | 1) Wildlands vs. 2) Agriculture | | |
| Sub-criteria | 1) Wildlands vs. 2) Social | | |
| | 1) Wildlands vs. 2) Regional Site Value | | |
| | 1) Agriculture vs. 2) Social | | |
| | 1) Agriculture vs. 2) Regional Site Value | | |
| | 1) Social vs. 2) Regional Site Value | | |

| | | | |
|---|---|---|---|
| Regional | 1) Ag Commodity at risk vs. 2) Rarity Occurrences | | |
| Site value | 1) Ag Commodity at risk vs. 2) Recreation areas | | |
| Sub-criteria | 1) Ag Commodity at risk vs. 2) USFS Land | | |
| | 1) Rarity Occurrences vs. 2) Recreation Areas | | |
| | 1) Rarity Occurrences vs. 2) USFS Land | | |
| | 1) Recreation Areas vs. 2) USFS Land | | |

| | | | |
|---|---|---|---|
| Feasibility | 1) Size vs. 2) Reproduction | | |
| Sub-criteria | 1) Size vs. 2) Detectability | | |
| | 1) Size vs. 2) Accessibility | | |
| | 1) Size vs. 2) Control Effectiveness | | |
| | 1) Size vs. 2) Control Cost | | |
| | 1) Reproduction vs. 2) Detectability | | |
| | 1) Reproduction vs. 2) Accessibility | | |
| | 1) Reproduction vs. 2) Control Effectiveness | | |
| | 1) Reproduction vs. 2) Control Cost | | |
| | 1) Detectability vs. 2) Accessibility | | |
| | 1) Detectability vs. 2) Control Effectiveness | | |
| | 1) Detectability vs. 2) Control Cost | | |
| | 1) Accessibility vs. 2) Control Effectiveness | | |
| | 1) Accessibility vs. 2) Control Cost | | |
| | 1) Control Effectiveness vs. 2) Control Cost | | |

| | | | |
|---|---|---|---|
| Feasibility | 1) Seed Set vs. 2) Vegetative Reproduction | | |
| Reproduction | 1) Seed Set vs. 2) Seed/Propagule longevity | | |
| Sub-criteria | 1) Seed Set vs. 2) Juvenile Phase | | |
| | 1) Seed Set vs. 2) Reproductive Phase | | |
| | 1) Vegetative Reproduction vs. 2) Seed/Propagule longevity | | |
| | 1) Vegetative Reproduction vs. 2) Juvenile Phase | | |
| | 1) Vegetative Reproduction vs. 2) Reproductive Phase | | |
| | 1) Seed/Propagule longevity vs. 2) Juvenile Phase | | |
| | 1) Seed/Propagule longevity vs. 2) Reproductive Phase | | |
| | 1) Juvenile Phase vs. 2) Reproductive Phase | | |

| | | | |
|---|---|---|---|
| Feasibility | 1) Driving Time vs. 2) On-site Control | | |
| Control Cost | 1) Driving Time vs. 2) Monitoring | | |
| Sub-criteria | 1) Driving Time vs. 2) Special Considerations | | |
| | 1) On-site Control vs. 2) Monitoring | | |
| | 1) On-site Control vs. 2) Special Considerations | | |
| | 1) Monitoring vs. 2) Special Considerations | | |

| | | | |
|---|---|---|---|
| Invasiveness | 1) Propagule Source vs. 2) Max Rate of Spread | | |
| Sub-criteria | 1) Propagule Source vs. 2) Nearness to Spread Vector | | |
| | 1) Max Rate of Spread vs. 2) Nearness to Spread Vector | | |

| | | | |
|---|---|---|---|
| Nearness | 1) Major Roadways vs. 2) River Systems | | |
| Spread Vector | 1) Major Roadways vs. 2) Gravel Operations | | |
| Sub-criteria | 1) River Systems vs. 2) Gravel Operations | | |

| Saaty Scale | | |
|---|---|---|
| Intensity of Importance | Definition | Explanation |
| 1 | Equal Importance | The two criteria contribute equally to the decision to eradicate. |
| 2 | Weak or Slight | |
| 3 | Moderate Importance | Experience and judgment slightly favor one criterion over the other. |
| 4 | Moderate Plus | |
| 5 | Strong Importance | Experience and judgment strongly favor one criterion over the other. |
| 6 | Strong Plus | |
| 7 | Very strong or demonstrated importance | A criterion is favored very strongly over the other; its dominance is demonstrated in practice. |
| 8 | Very, very strong | |
| 9 | Extreme Importance | The evidence favoring one criterion over another is of the highest possible order of affirmation. |

## APPENDIX D – Analytical Hierarchy Process Sample Calculation

This section is adapted from notes by Rob Klinger, US Geological Survey. For a complete discussion of the procedure and mathematics involved, see Saaty's *The Analytic Hierarchy Process* (1980).

### Step 1. Collected and Averaged Responses

AHP Worksheet – Hypothetical Example

| | When choosing an A-rated weed population eradication project, which criterion weighs more heavily on that decision? | Choice 1 or 2? | by how much (Saaty scale 1-9)? |
|---|---|---|---|
| Tier 1 | 1) Impact vs. 2) Feasibility of Eradication | 2 | 4 |
| | 1) Impact vs. 2) Spread | 2 | 3 |
| | 1) Feasibility of Eradication vs. 2) Spread | 1 | 2 |

| | | | |
|---|---|---|---|
| Impact | 1) Wildlands vs. 2) Agriculture | 1 | 1 |
| Tier 2 | 1) Wildlands vs. 2) Social | 1 | 3 |
| | 1) Wildlands vs. 2) Regional Site Value | 2 | 4 |
| | 1) Agriculture vs. 2) Social | 1 | 3 |
| | 1) Agriculture vs. 2) Regional Site Value | 1 | 1 |
| | 1) Social vs. 2) Regional Site Value | 2 | 5 |

The scores above would populate the matrix below. Each criterion is equally important when compared with itself; therefore, the main diagonal of each matrix consists of 1s. The item in the left column is compared to the item in the top row. Reciprocal scores are used below the diagonal for the reverse comparison.

Saaty Matrix – Hypothetical Example

| | Impact | Feasibility | Spread |
|---|---|---|---|
| **Impact** | 1 | 1/4 | 1/3 |
| **Feasibility** | 4 | 1 | 2 |
| **Spread** | 3 | 1/2 | 1 |

| | Wildlands | Agriculture | Humans | Region |
|---|---|---|---|---|
| **Wildlands** | 1 | 1 | 3 | 1/4 |
| **Agriculture** | 1 | 1 | 3 | 1 |
| **Humans** | 1/3 | 1/3 | 1 | 1/5 |
| **Region** | 4 | 1 | 5 | 1 |

However, I first averaged the scores using the geometric mean (n=15) for each pair-wise comparison and then populated the Saaty matrix below. The geometric mean is required given that the Saaty Scale of Importance is 1/9 – 9, with zero not being an option (Saaty 2008).

Saaty Matrix – Group Averages

| | Impact | Feasibility | Spread |
|---|---|---|---|
| **Impact** | 1 | 0.8729 | 1.7459 |
| **Feasibility** | 1.1456 | 1 | 1.6129 |
| **Spread** | 0.5728 | 0.6200 | 1 |

| | Wildlands | Agriculture | Humans | Region |
|---|---|---|---|---|
| **Wildlands** | 1 | 1.4179 | 3.1282 | 0.9344 |
| **Agriculture** | 0.7053 | 1 | 2.2146 | 0.6651 |
| **Humans** | 0.3197 | 0.4515 | 1 | 0.4046 |
| **Region** | 1.0702 | 1.5035 | 2.4715 | 1 |

A matrix was prepared for each level in the hierarchy.

**Step 2. Computation of a vector of priorities from each matrix, AKA the principal eigenvector is computed, and when normalized, becomes the vector of priorities.**

One way to estimate the eigenvector is to sum the elements in each row and normalize by dividing each sum by the total of all the sums. Therefore all the results add to one.

Comparison Matrix

| | Impact | Feasibility | Spread | Sum of GeoMeans | Resulting Vector |
|---|---|---|---|---|---|
| **Impact** | 1 | 0.8729 | 1.7459 | 3.6188 | 0.3781 |
| **Feasibility** | 1.1456 | 1 | 1.6129 | 3.7585 | 0.3927 |
| **Spread** | 0.5728 | 0.6200 | 1 | 2.1928 | 0.2291 |
| | | | | 9.5701 | 1.0000 |

Comparison Matrix

| | Wildlands | Agriculture | Humans | Region | Sum of GeoMeans | Resulting Vector |
|---|---|---|---|---|---|---|
| **Wildlands** | 1 | 1.4179 | 3.1282 | 0.9344 | 6.4805 | 0.3360 |
| **Agriculture** | 0.7053 | 1 | 2.2146 | 0.6651 | 4.5850 | 0.2377 |
| **Humans** | 0.3197 | 0.4515 | 1 | 0.4046 | 2.1758 | 0.1128 |
| **Region** | 1.0702 | 1.5035 | 2.4715 | 1 | 6.0452 | 0.3134 |
| | | | | | 19.2865 | 1.0000 |

**Step 3. Estimate Consistency**

Multiply each matrix by its eigenvector to obtain a new vector of weighted sums.

| Comparison Matrix | Impact | Feasibility | Spread | | Priority Vector | | Weighted Sums |
|---|---|---|---|---|---|---|---|
| **Impact** | 1 | 0.8729 | 1.7459 | | 0.3781 | | 10.7279 |
| **Feasibility** | 1.1456 | 1 | 1.6129 | * | 0.3927 | = | 11.4409 |
| **Spread** | 0.5728 | 0.6200 | 1 | | 0.2291 | | 6.5958 |

| Comparison Matrix | Wildlands | Agriculture | Humans | Region | | Priority Vector | | Weighted Sums |
|---|---|---|---|---|---|---|---|---|
| **Wildlands** | 1 | 1.4179 | 3.1282 | 0.9344 | | 0.3360 | | 1.3189 |
| **Agriculture** | 0.7053 | 1 | 2.2146 | 0.6651 | * | 0.2377 | = | 0.9330 |
| **Humans** | 0.3197 | 0.4515 | 1 | 0.4046 | | 0.1128 | | 0.4544 |
| **Region** | 1.0702 | 1.5035 | 2.4715 | 1 | | 0.3134 | | 1.3093 |

Divide the first component of this new Weighted Sums vector by the first component of the Priority vector, the second component of the Weighted Sums vector by the second component of the Priority vector and so on, to obtain another vector.

| Weighted Sums | / | Priority | = | Vector A |
|---|---|---|---|---|
| 10.7279 | / | 3.6188 | = | 2.9645 |
| 11.4409 | / | 3.7585 | = | 3.0440 |
| 6.5958 | / | 2.1928 | = | 3.0080 |

| Weighted Sums | / | Priority | = | Vector B |
|---|---|---|---|---|
| 1.3189 | / | 0.336012 | = | 3.9251 |
| 0.9330 | / | 0.237732 | = | 3.9247 |
| 0.4544 | / | 0.112816 | = | 4.0278 |
| 1.3093 | / | 0.313439 | = | 4.1772 |

Sum the components of this vector and divide by the number of components to approximate the maximum eigenvalue, $\lambda_{max}$. The closer $\lambda_{max}$ is to $n$ (the number of columns in the matrix), the more consistent the result. Deviation from consistency is measured by the Consistency Index: $(\lambda_{max} - n)/(n - 1)$.

| A |
|---|
| 2.9645 |
| 3.0440 |
| 3.0080 |

$\lambda_{max}$ = 3.0055

CI = (3.0055 – 3)/(3-1) = 0.0027

CR = CI/RI = 0.0027/0.58 = 0.0047

| B |
|---|
| 3.9251 |
| 3.9247 |
| 4.0278 |
| 4.1772 |

$\lambda_{max}$ = 4.0137

CI = (4.0137 – 4)/(4-1) = 0.0046

CR = CI/RI = 0.0046/0.90 = 0.0051

The ratio of the Consistency Index (CI) to the average Random Index (RI) for the same order matrix is called the Consistency Ratio (CR). A consistency ratio of 0.10 or less is considered acceptable. A list of average random indexes is provided by Saaty (1980).

## APPENDIX E – Species-level Criteria Scores

| Scientific name | Common Name | Impact to Wildlands | Impact to Ag | Impact to Humans | Seed Set | Seedbank/ Prop Longevity | Veg Repro | Length Juvenile | Length reproductive | Detectability | Control effective | Cost estimate | Follow-up | Spread Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Acaena novae-zelandiae* | biddy-biddy | 3 | 3 | 6 | 1 | 3 | 1 | 6 | 6 | 1 | 6 | 6 | 6 | 6 |
| *Achnatherum brachychaetum* | punagrass | 1 | 6 | 1 | 3 | 0 | 10 | 3 | 6 | 6 | 6 | 10 | 3 | 6 |
| *Alhagi maurorum* | camelthorn | 6 | 10 | 6 | 3 | 6 | 3 | 6 | 6 | 3 | 6 | 3 | 3 | 10 |
| *Alternanthera philoxeroides* | alligatorweed | 10 | 10 | 6 | 6 | 6 | 3 | 6 | 6 | 10 | 6 | 3 | 1 | 10 |
| *Arctotheca calendula* | Fertile Capeweed | 6 | 3 | 1 | 6 | 6 | 1 | 6 | 6 | 6 | 10 | 6 | 3 | 6 |
| *Carduus acanthoides* | plumeless thistle | 6 | 6 | 6 | 3 | 3 | 10 | 6 | 6 | 6 | 6 | 6 | 6 | 3 |
| *Carduus nutans* | musk thistle | 6 | 6 | 6 | 1 | 3 | 10 | 6 | 6 | 6 | 10 | 6 | 6 | 6 |
| *Centaurea diffusa* | diffuse knapweed | 6 | 6 | 6 | 3 | 3 | 10 | 6 | 6 | 6 | 10 | 6 | 6 | 6 |
| *Centaurea maculosa (= C. bieberstenii)* | spotted knapweed | 10 | 10 | 3 | 1 | 3 | 6 | 6 | 3 | 6 | 6 | 6 | 6 | 10 |
| *Centaurea x pratensis* | meadow knapweed | 6 | 6 | 3 | 3 | 6 | 6 | 6 | 6 | 6 | 10 | 6 | 6 | 10 |
| *Centaurea squarrosa* | squarrose knapweed | 6 | 6 | 6 | 3 | 3 | 10 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| *Chondrilla juncea* | rush skeletonweed | 6 | 3 | 1 | 1 | 6 | 1 | 6 | 10 | 6 | 3 | 3 | 3 | 6 |
| *Cirsium ochrocentrum* | yellowspine thistle | 3 | 1 | 6 | 3 | 1 | 3 | 6 | 6 | 6 | 10 | 6 | 6 | 1 |
| *Euphorbia esula* | leafy spurge | 10 | 10 | 6 | 0 | 3 | 1 | 0 | 6 | 10 | 1 | 0 | 3 | 10 |
| *Halogeton glomeratus* | halogeton | 6 | 10 | 10 | 1 | 1 | 10 | 1 | 6 | 6 | 1 | 6 | 3 | 10 |
| *Linaria genistifolia* spp. *dalmatica (=L. dalmatica)* | Dalmatian toadflax | 6 | 6 | 3 | 0 | 1 | 3 | 3 | 10 | 6 | 3 | 6 | 3 | 10 |
| *Onopordum acanthium* | Scotch thistle | 10 | 6 | 6 | 1 | 0 | 10 | 6 | 6 | 10 | 10 | 6 | 3 | 10 |
| *Onopordum tauricum* | Taurian thistle | 6 | 3 | 6 | 1 | 0 | 10 | 6 | 6 | 10 | 10 | 6 | 6 | 3 |
| *Peganum harmala* | harmel | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 10 | 6 | 3 | 10 | 6 | 3 |

# APPENDIX F –Population Summary Form

## Example Prioritization Summary Form

| Priority | Points |
|---|---|
| Super High | 10 |
| High | 6 |
| Medium | 3 |
| Low | 1 |
| None | 0 |

**Species:** Alhagi maurorum camelthorn
**PopCode:** CMT1300001
**PopName:** Oasis gate 29 CMT
**County:** Imperial

S – Species Score
P – Population Score

| Category | Criteria | Sub-Criteria | Points | x Weight | = Score |
|---|---|---|---|---|---|
| **Impact** | | | **6** | **0.3781** | **2.3234** |
| | Impact to Wildlands (S) | | 6 | 0.3360 | 2.0161 |
| | Impact to Agriculture (S) | | 10 | 0.2377 | 2.3773 |
| | Impact to Human Health (S) | | 6 | 0.1128 | 0.6769 |
| | Regional Site Value (P) | | 3 | 0.3134 | 1.0740 |
| | AKA Nearness to: | Grazing Land | 10 | 0.2609 | 2.6086 |
| | | Rarity Occurrences | 1 | 0.5176 | 0.5176 |
| | | Recreational Areas | 3 | 0.1001 | 0.3002 |
| | | USFS Land | 0 | 0.1215 | 0.0000 |
| **Feasibility of Eradication** | | | **6** | **0.3927** | **2.3455** |
| | Size (P) | | 6 | 0.2531 | 1.5184 |
| | Reproductive Ability (S) | | 5 | 0.1774 | 0.8974 |
| | | Seed Set | 3 | 0.1594 | 0.4783 |
| | | Vegetative Reproduction | 3 | 0.1541 | 0.4624 |
| | | Seed/Propagule Longevity | 6 | 0.4482 | 2.6894 |
| | | Juvenile Phase length | 6 | 0.1321 | 0.7923 |
| | | Reproductive Phase length | 6 | 0.1062 | 0.6369 |
| | Detectability (S) | | 3 | 0.1248 | 0.3745 |
| | Accessibility (P) | | 10 | 0.1495 | 1.4948 |
| | Control Effectivness (S) | | 6 | 0.1902 | 1.1412 |
| | Control Cost (P) | | 5 | 0.1050 | 0.5460 |
| | | Driving Time (P) | 10 | 0.1317 | 1.3165 |
| | | On-Site Control (S) | 3 | 0.3385 | 1.0156 |
| | | Follow-up Visits (S) | 3 | 0.3475 | 1.0425 |
| | | Special Considerations (P) | 10 | 0.1823 | 1.8231 |
| **Invasiveness** | | | **8** | **0.2291** | **1.7598** |
| | Propagule Sources (P) | | 10 | 0.2535 | 2.5353 |
| | Spread Rate (S) | | 10 | 0.3600 | 3.6001 |
| | Nearness to Vectors of Spread (P): | | 4 | 0.3865 | 1.5451 |
| | | Major Roads | 6 | 0.3327 | 1.9963 |
| | | River Systems | 3 | 0.4247 | 1.2741 |
| | | Mining Operations | 3 | 0.2426 | 0.7278 |
| **Overall Priority Score** | | | | | **6.4287** |

### Example Calculation – Invasiveness Major Criterion and Overall Score

Scores are assigned at the terminal nodes in the hierarchy and added up the hierarchy to calculate the overall priority score. Propagule Sources = 10 points = this population is an outlier (greater than 25 miles from the nearest conspecific population in the GIS database), and thus a high priority. Multiplying this score by the criterion's weight (0.2535) gave a score of 2.535 points. Spread Rate is a species-level consideration = 10 points = this species is known to double its distribution in less than 10 years. Multiplying this score by the criterion's weight (0.3600) gave a score of 3.6001 points.

Nearness to vectors of spread is a composite score of the sub-sub-criteria scores below it in the hierarchy. This population is within 1 mile of a major roadway = 6 points. Multiplying this score by the criterion's weight (0.3327) gave a score of 1.9963 points. This population was within 10 miles of a major waterway and a mining operation = 3 points each. Multiplying these scores by the respective weights (0.4247 and 0.2426) gave 1.2741 points and 0.7278 points. Totaling the sub-sub-criteria points equaled 3.998, which became the Nearness to Vectors of Spread score. The Nearness to Vectors of Spread score (shown in the Summary Form as 4) was multiplied by the criterion's weight (0.3865) and gave a score of 1.5451.

Totaling the Invasiveness sub-criteria scores (Propagule Sources = 2.535; Spread Rate = 3.6001; and Nearness to Vectors of Spread = 1.5451) gave a score of 7.6805 (shown in the Summary Form as 8). This score was multiplied by the criterion's weight (0.2291) and gave a Invasiveness score of 1.7596 points. The three major criterion scores (Impact = 2.3234, Feasibility = 2.3455, and Invasiveness = 1.7598) were summed to give the overall priority score = 6.4287.