Chapter 2
Practical Considerations for Early Detection Monitoring of Plant Invasions

Matthew L. Brooks and Robert C. Klinger

Abstract Invasions by multiple nonnative species into wildland areas require that decisions be made on which species and sites to target for early detection monitoring efforts and ultimately management actions. Efficient allocation of resources to detect invasions from outside of a management unit, and to monitor their spread within a management unit, leaves more resources available for control efforts and other management priorities. In this chapter, we describe three types of monitoring plans that are possible given three typical scenarios of data availability within or adjacent to the management unit: (1) there are *no data* on invasive species, (2) there are *species lists* of invasives, and (3) there are *georeferenced abundance* data for invasive species. In the absence of invasive species data, monitoring must be guided based on the general principals of invasion biology related to propagule pressure and plant resource availability. With invasive species lists, prioritization processes can be applied to narrow the monitoring area. It is also helpful to develop separate prioritized lists for species that are currently colonizing, established but not spreading, and those that have begun to spread within a management unit, because management strategies differ for species at different phases of the invasion process. With georeferenced abundance data, predictive models can be developed for high priority species to further increase the efficiency of early detection monitoring. For the majority of invasive species management programs, we recommend a design based on integrating prioritization and predictive modeling into an optimized monitoring plan, but only if the required species information and resources to process them are available and the decision is based on well-defined management goals. Although the up-front costs of this approach appear to be high, its long-term benefits can ultimately make it more cost-effective than less systematic approaches that typify most early detection programs.

Keywords Modeling • Niche • Prioritization • Prediction • Species distribution models • Vegetation management

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M.L. Brooks(✉) and R.C. Klinger
United States Geological Survey, Western Ecological Research Center, Yosemite Field Station, El Portal Office, El Portal, California 95318,
matt_brooks@usgs.gov [Au1]

Inderjit (ed.), *Management of Invasive Weeds,*

2.1 Introduction

Early detection monitoring forms the foundation of all invasive plant management programs, and is often coupled with rapid response to control incipient populations of undesirable invaders. Collectively, early detection and rapid response provide the first line of defense against plant colonizations. Compared with the spread and equilibrium phases of invasions, the colonization and, to a somewhat lesser degree, establishment phases are typically the only points at which eradication is possible (Rejmanek and Pitcairn 2002). Once invading species have established populations, or are in the process of subsequently spreading into new areas, eradication quickly becomes unfeasible. Thus, prevention of new invasions into a management unit is predicated primarily on an effective early detection and response program.

Invasive plants are managed within local project areas, preserves or agency units, counties, states, nations, and continents. Although priorities and challenges vary among these different types of management units, there are certain issues common to all which we emphasize in this chapter. One major issue is the daunting task of accounting for large numbers of potentially invading species within large areas. Resources will never be sufficient to monitor all invading species in all places. Guidelines are needed on how best to narrow search parameters for the types of species that are poised to invade and focus efforts on areas where they are most likely to invade and/or are most important to protect from invasion.

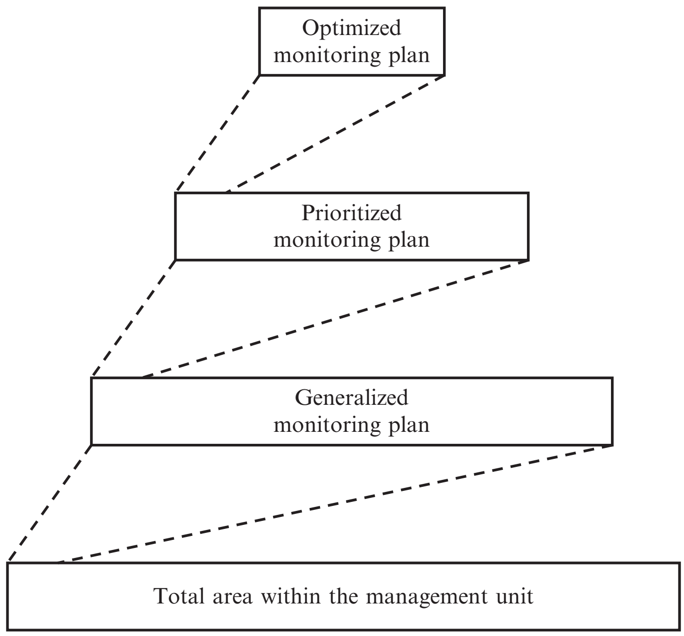

Fig. 2.1 A generalized example demonstrating how the relative proportion of sampling area can decline with each successive monitoring approach

An initial step in any early detection program involves compiling existing information on species and site characteristics to develop an efficient monitoring approach. This information is used to prioritize among species and sites that are most important to monitor, and develop predictive models to optimize monitoring efforts by narrowing their spatial and temporal scope. In this chapter, we discuss the issues associated with compiling and using information to develop and improve the efficiency of early detection monitoring plans. This chapter does not address monitoring tools (e.g., remote sensing) or specific monitoring methodologies (e.g., plot-based sampling), but rather describes a framework for narrowing the search area within which those other tools and methodologies can be applied. The framework we present is structured around three types of monitoring plans that successively reduce the size of the area within which early detection monitoring is conducted: the (1) generalized, (2) prioritized, and (3) optimized monitoring plans (Fig. 2.1) .

2.2 Evaluating Available Data

The information collection stage is perhaps more important than any other step in developing monitoring programs, because all future actions are based on analyses stemming from the information collected. Consequently, we feel it is important not to just supply a “cookbook” of what information to collect and what to do with it, but also to emphasize the importance on thinking about what types of information are most useful for different phases of the invasion process, including colonization, population establishment, and subsequent spread (Groves 1986; Cousins and Mortimer 1995; Rejmanek 2000; Richardson et al. 2000).

Before any information is compiled, the resources available for conducting an early detection program should be realistically evaluated. Time spent compiling vast amounts of information to develop an early detection plan is wasted if there is little hope of supporting the efforts needed to synthesize the information into an implementation plan or to implement the plan itself. Time and money are obvious limitations, but so too are institutional support and the personal commitment of staff. Turn-over rates of personnel can also be a hindrance, since extensive training is often required to develop effective early detection teams (M. Brooks pers. obs.).

Spatial and temporal scales are also very important to consider prior to compiling data. As mentioned above, early detection programs can be developed for areas as small as local projects to as large as continents. Clearly, the amounts and types of information needed vary among these spatial scales. For example, as geographic scale increases, so too do landscape variability, land-use variability, the range of potential sources of nonnative propagules, and many other factors influencing plant invasions, which should be considered when developing early detection programs.

In most cases there is information available on the site characteristics within a management unit. This includes vegetation maps and assessments that can be used to evaluate landscape invasibility, and information on the natural, cultural, recreational, and/or economic values at potential risk due to plant invasions. In contrast, there is a much wider range of information availability regarding invasive species data. In this chapter, we focus primarily on what to do with different amounts of invasive species data.

There are typically three scenarios relative to the availability of invasive species data within or adjacent to a management unit:

1. There are *no data* on invasive species.
2. There are species lists of invasives.
3. There are *georeferenced abundance* data for invasive species.

Because data limitations are a fundamental consideration in developing any monitoring plan, we organized this chapter around these three scenarios. As data quantity and quality increase so too do their range of potential applications for designing early monitoring plans. Accordingly, the sections of this chapter that deal with each of the three scenarios presented above become progressively longer and more detailed. We realize that the most common situation involves having no data or only having species lists. However, we devote significant attention to what can be done with georeferenced data because scientists advising land managers often emphasize the need for this type of data. We feel it necessary to explain just how resource intensive this process of generating and using georeferenced data is, so that those who may be considering this path can better determine whether the effort required is worth the potential improvement in monitoring efficiencies that may result. We hope that this approach will ultimately make it easier to translate the information we present into practice.

2.3 What can be Done in the Absence of Species Data?

It is becoming increasingly rare that there are absolutely no species data available within or near a land management unit, either because most have some sort of species inventory (e.g., plots used to validate vegetation maps) or land managers have access to regional lists of invasive plant species (e.g., invasive plant council lists). Even if species data are present, the resources may not be available to compile, synthesize, and evaluate the data. In the event that species data or resources to process the data do not exist, all efforts to develop efficient monitoring plans must rely on general invasion theory to develop a generalized monitoring plan (Fig. 2.2).

2.3.1 General Invasion Theory

Numerous interacting factors influence rates and extent of biological invasions, and their relative effects have been widely discussed and debated (Hobbs and Huenneke 1992; Lonsdale 1999; Williamson 1999; Davis et al. 2000; Rejmanek et al. 2005).

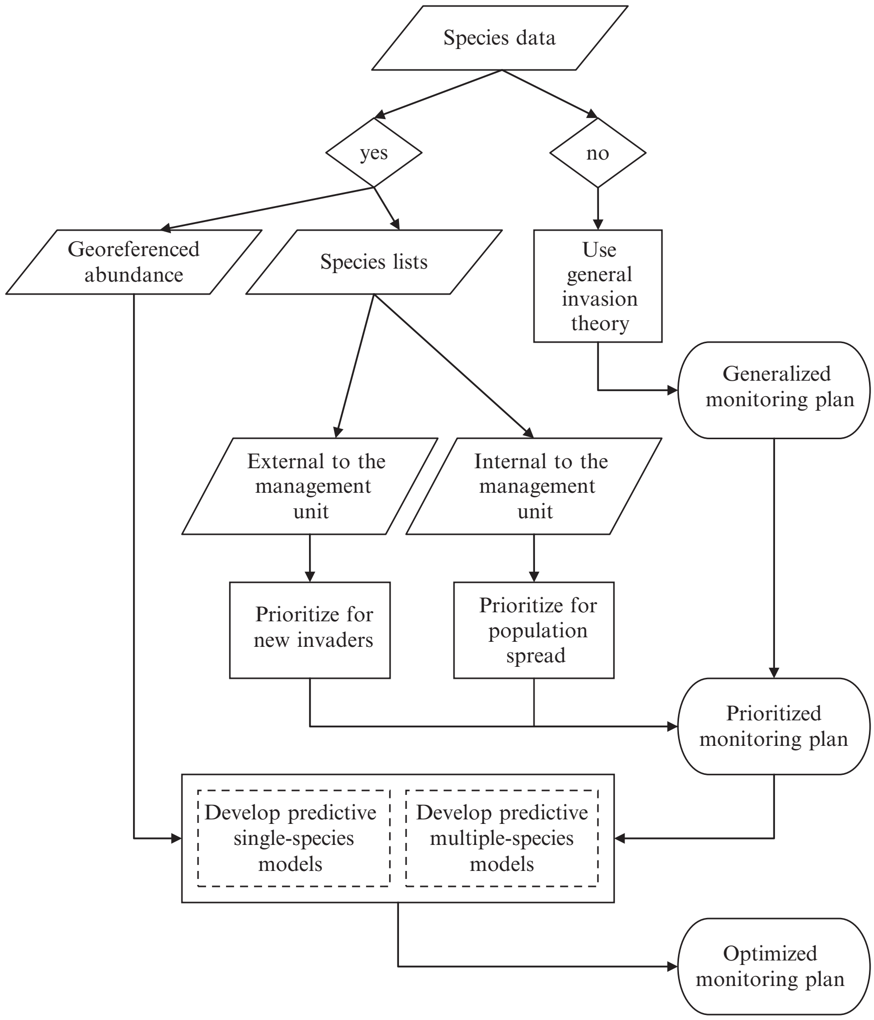

Fig. 2.2 Flowchart linking available species data with synthesis processes resulting in different hierarchical levels of final sampling plans

However, two factors appear particularly important: plant propagule pressure and plant resource availability (Davis et al. 2000; Brooks 2007). Collectively, these two factors can be used to develop a basic program for monitoring specific sites. Information collected during this basic monitoring program can then be used to evaluate and adjust monitoring as needed (Holling 1978).

Plant propagule pressure is related to the number of disseminules (e.g., seeds, rhizomes) introduced into an area per unit time and the species that they represent (Lockwood et al. 2005). Dispersal rates are positively associated with pathways such as roads and trails, vectors such as livestock, land use practices such as seeding burned areas, and the extent of area open to invasion (Forman et al. 2003; Brooks 2007). The species pool is the number of nonnative species in a region, and the larger that pool the greater the likelihood that at least one or several species will invade other areas within the region (Lockwood et al. 2005). Propagules can originate from populations outside of, or within, a management unit.

Plant resource availability is a function of the supply of light, water, and mineral nutrients, and the proportion of these resources that are unused by existing vegetation (Davis et al. 2000; Brooks 2007). Resource availability can increase due to direct additions (e.g., atmospheric nitrogen deposition), increased rates of production (e.g., nutrient cycling rates), or by reduced rates of uptake following declines in plant abundance after they are thinned or removed. Feedback processes from established populations of nonnative plants can also affect resource supply. This can occur by direct increases in nutrient supply (e.g., nitrifying plants) or indirect increases brought about by limiting the growth of other species through competition or inhibition. Areas of high resource availability are often disturbed sites. Fire, landslides, floods, and grazing not only increase the pool of available resources but may also reduce abundance of native species that would otherwise compete with invading species or, conversely, reduce invasion rates by consuming potential colonizers (Marty 2005).

2.3.2 Generalized Monitoring Plan

The role of disturbance in facilitating invasions is well established (Lonsdale 1999; Mack and D'Antonio 1998; Mack et al. 2000), probably because they often lead to increases in both propagule pressure and resource availability. Accordingly, disturbed areas are often high or very high priorities for early detection monitoring. However, disturbances are typically pulsed events that often cannot be predicted. Early detection monitoring plans must, therefore, include two parts: (1) a strategic baseline plan that should be updated periodically (e.g., 5 year intervals) on the basis of an assessment of propagule pressure and resource availability across the entire management unit; and (2) tactical incident plans for each major event that results in major landscape-scale pulses of propagules and/or resources (e.g., a large fire or construction project). Part 1 should be supported by a consistent and predictable source of funding, whereas part 2 should be supported as part of monitoring efforts associated with each major landscape-scale event.

Very high priority areas for early detection monitoring occur where both propagule pressure and resource availability are high (Fig. 2.3). If significant sources of invading species are present, and resources are readily available, then plant invasions have the greatest probability of occurring.

High priority areas for monitoring occur where propagule pressure is high, but resource availability is low (Fig. 2.3). Any time when propagule pressure is high there is a chance that invasive plants can establish following unanticipated

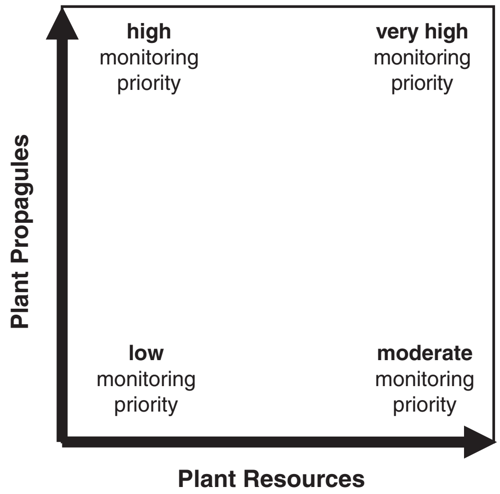

Fig. 2.3 Relative priorities for early detection monitoring relative to propagule pressure of invading plants and resource availability

surges in resource availability that would shift a site to a very high priority from monitoring. These changes can literally occur overnight, most commonly following a major disturbance such as fire, flood, or other agents of vegetation removal.

Moderate priority areas occur where there are few or no vectors and pathways to the site, and thus propagule pressure is low, but resource availability is high (Fig. 2.3). In this case long-distance dispersal is the primary means by which invasions might occur. These types of sites can quickly upgrade in priority following major influxes of propagules, which may occur following revegetation or soil stabilization projects (e.g., in seed mixes or straw mulches) or the establishment of temporary logistical support sites (e.g., fire camps).

Low priority areas occur where both propagule pressure and resource availability are low (Fig. 2.3). However, as mentioned above, these conditions can rapidly change causing a concomitant upgrade in monitoring priority.

The efficiency of generalized monitoring plans is relatively low compared with other approaches described later (Fig. 2.1), but so are the costs necessary to develop them (Fig. 2.4). However, one must remember that time and resources saved up front with generalized monitoring plans may be eclipsed by the time and resources lost due to the inefficiencies of the monitoring efforts that follow. For example, these generalized monitoring plans do not integrate information about the life history characteristics, specific habitat requirements, or potential impacts of invading species which could otherwise be used to further focus monitoring efforts.

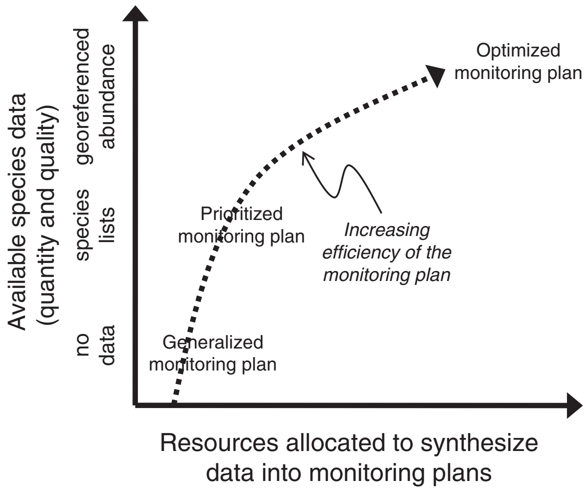

Fig. 2.4 Relationship between available species data and the resources applied to synthesize the data into monitoring plans. Both data and resource investment are required to improve the efficiency of early detection monitoring plans

2.4 What can be Done with Species Lists?

2.4.1 Types of Lists

Species lists provide the fundamental data upon which early detection programs should be based. Even programs designed to monitor sites (as opposed to searching for species; see later) benefit tremendously if species lists are used in the program design. Species lists vary in usefulness depending on their geographic scope, ancillary information, and the time that has passed since they were compiled.

Species lists have been developed for many states or multistate geographic regions within the United States. Examples from the western United States include lists for Arizona (AZ-WIPWG 2005), California (Cal-IPC 2006), and Oregon and Washington (Reichard et al. 1997). Other regions with state lists include Connecticut (Mehrhoff et al. 2003), Florida (Anonymous 1993; Florida Exotic Pest Plant Council Plant List Committee 2005), Illinois (Schwegman 1994), Rhode Island (Gould and Stuckey 1992), Tennessee (Bowen and Shea 1996), and Virginia (Virginia Department of Conservation and Recreation and Virginia Native Plant Society 2003; Heffernan et al. 2001).

Species lists can also be derived from coarse-scale regional surveys, or from finer-scale local studies. Regional lists are generally less useful than site-specific lists for programs focused on local scales, although combining the two can be particularly useful. For example, a site-specific list can be used to target management actions for species already occurring within a management unit, and a regional list can be used to design programs focused on detecting the initial establishment of species that currently occur elsewhere in the region.

Lists that are compiled to specifically document the status of nonnative plants are highly preferable over lists that are compiled for other purposes, such as general botanical surveys or validation of vegetation maps. Monitoring plans vary according to their intended purpose, and there is no single optimal plan for all applications. Consequently, the resulting species lists vary in level of specificity, accuracy, and scope. For example, surveys done to validate vegetation maps are often focused on plant associations, noting only dominant species and other species of interest. Rare occurrences (i.e., the primary targets for early detection) may be left off intentionally or simply overlooked. Accordingly, surveys that are not designed to specifically inventory nonnative plants will most likely underreport the actual number of nonnative species present in the monitoring area.

Numerous types of useful ancillary information can be included in species lists and are almost always useful in designing early detection programs. Estimates of distribution and abundance in the area of concern, even if they are qualitative (e.g., widely distributed but not abundant), are the most basic types of ancillary information that can be included. If the program goal is to monitor areas based on statistical models of the likelihood of a species colonizing a site, then geo-referenced data on environmental conditions where the species is known to occur are highly desirable (see later).

Although it may seem counter-intuitive, it is often useful to also have data on environmental conditions where species do not occur (i.e., absence data). If data on environmental variables are not available, then life history traits (e.g., perennial vs. annual, presence of rhizomatous roots, seed mass, etc.) should be included in the lists. If the program goal is to implement management based on a prioritized list of species, then data on life history characteristics, tendency to be invasive in other geographic regions, known ecological impacts, and feasibility of control are highly desirable. Older species lists (e.g., > 20–30 years) can be useful in documenting occurrence of a species in an area, but data on environmental conditions associated with them may be obsolete.

2.4.2 The Prioritization Process

If species lists exist and resources to evaluate them are available, then the suite of species that early-detection should most optimally focus upon can be developed using a process known as prioritization (Fig. 2.2). The prioritization process initially requires more of an obligation of time and resources than do generalized monitoring methods, but this investment results in monitoring plans of greater efficiency focused on smaller areas (Fig. 2.1) that can be more cost-effective in the long run (Fig. 2.3).

The prioritization process has been typically applied to reduce the number of species targeted for active management, but it can also be used to reduce the number of species targeted for early detection monitoring. In both cases, prioritization addresses the desire to focus management efforts, whether for control or early detection, on a reduced subset of the total species pool where they will be most effective.

2.4.2.1 Prioritization for Control of Nonnative Plants

Prioritization for control efforts has commonly been used to maximize the cost-effectiveness of efforts designed to manage species that are known to reside within a particular management unit. When faced with lists of tens to hundreds of invasive species, land managers need guidance on how best to allocate scarce resources to control them. Randall et al. (2008) recently reviewed 17 examples of systems used to help place nonnative plants into categories to facilitate their management, and compared them to a system that they developed themselves (Morse et al. 2004). Twelve of these systems were designed to prioritize management actions for non-native species that are already established within a management unit. Two prioritized among invaded sites (Timmins and Owens 2001; Wainger and King 2001) and ten prioritized among invaded species within sites, states, or nations (Orr et al. 1993; Weiss and McLaren 1999; Thorp and Lynch 2000; Champion and Clayton 2001; Fox et al. 2001; Heffernan et al. 2001; Virtue et al. 2001; Hiebert and Stubbendieck 1993; Warner et al. 2003; Morse et al. 2004). Only two (Warner et al. 2003; Morse et al. 2004) focus heavily on species' impacts on biodiversity, whereas the rest focus mostly on feasibility of control, or potential effects on agricultural, horticultural, or other economic factors.

Prioritization decisions are typically made based on some combination of the following four factors:

1. The relative ecological and/or economic threats that the species pose
2. Their potential to spread and establish populations quickly (i.e., their "weediness")
3. Their potential geographic and/or ecological ranges
4. The feasibility in which they can be controlled (Timmins and Williams 1987; Hiebert and Stubbendieck 1993, Hiebert 1998, Weiss and McLaren 1999; Fox et al. 2000; Mehrhoff 2000; Warner et al. 2003; Morse et al. 2004)

The scoring systems for these prioritization efforts generally emphasize the threat potential and spread potential over the other two factors, with the weighted sum of the ranks for all four resulting in the net priority assessment.

Although the large number of systems may appear bewildering at first, many can be directly applied to a wide variety of areas and situations. Using an existing system will reduce the cost of developing a new system and provide managers with choices and flexibility. However, it is important to stress the necessity of selecting the system that is most appropriate for a given situation (Randall et al. 2008).

Prioritization is generally done for species that are known to be invasive, or for sites that have high conservation value but may be susceptible to invasion. In some instances, both species and sites can be prioritized for management actions (Timmins and Owens 2001), and if adequate resources and information are available this can be an extremely useful strategy. Prioritization is most often based on a synthesis of preexisting studies, expert opinion, or both (Randall et al. 2001; Hiebert and Stubbendieck 1993; Timmins and Owens 2001). Attributes are then scored on an ordinal scale. For example, the Alien Plant Ranking System (Hiebert 1998) ranks species based on their relative ease of management and their potential impact.

2.4.2.2 Prioritization for Early-Detection of Nonnative Plants

Prioritization for early-detection monitoring has not resulted in the wide range of approaches that have been developed for the task of prioritizing for control efforts. However, the basic premise of both is the same, and there is no compelling reason that systems developed to inform control efforts could not be used (with minor modifications) to help inform early-detection monitoring efforts. They both rely on information related to threat potential, spread potential, range of potential geographic/ecological sites, and feasibility of control. The one primary difference is that species that have low feasibility of control should raise their priority level in terms of early-detection monitoring, but may lower its priority level in terms of control. Basically, species that are more difficult to control should have higher priority in situations where early-detection monitoring is used to identify new populations and keep them from establishing. In contrast, among species already established within a region, those that are more difficult to control may be prioritized lower for control efforts than those which are easier to control.

2.4.3 Information Needed for Prioritization

Relatively few life history characteristics have been found to be consistently good predictors of invasiveness (Kolar and Lodge 2001). Therefore, rather than spending inordinate amounts of time trying to collect as much information as possible on a very large number of species and site attributes (the “shotgun” approach), a more logical and focused approach will produce better (and more timely) results. When prioritizing species, careful attention needs to be given to what phase of the invasion process the rankings are meant to address. Management objectives will differ among the phases as will the relative importance of species attributes.

2.4.3.1 Information for Prioritizing Species

The management objective for species in the colonization phase of invasion is to prevent their introduction and establishment. Developing a list of species with the greatest potential for being introduced into the area of interest is a critical step in any effort to prevent such introductions. In most cases, this phase will be the most difficult to develop a prioritized list for because the pool of potential species will likely be quite large. Once a list of candidate species is developed, useful information for prioritizing includes: (1) invasiveness potential, (2) biogeographic range, (3) land cover types where typically invasive, and (4) potential impacts (Table 2.1).

After invading species have established localized populations, eradication becomes a priority (Rejmanek and Pitcairn 2002). If eradication is not feasible then control of populations (i.e., reducing abundance and/or dispersal pathways and vectors) within the boundaries of local infestations may be an alternative. However, it is important to recognize that even if eradication or control is successful, species could be reintroduced into an area. Clearly, high priority species in this stage would be those that tend to fit the definition of a "transformer species," which cause significant changes in community and ecosystem characteristics (Richardson et al. 2000) and have ecological and life-history characteristics associated with rapid spread potential. Therefore, the primary focus of prioritization at the establishment phase includes: (1) actual and potential impacts, (2) distribution and abundance, (3) life-history characteristics, (4) biogeographic range, and (5) management feasibility (Table 2.1).

Species in the more advanced invasion stages of spread and equilibrium are widely distributed and are often relatively abundant. Eradication is unlikely

Table 2.1 Information needed to develop prioritized lists of species in different phases of the invasion process

A. Colonization phase	
1) Invasiveness potential	Tendency to be invasive elsewhere
2) Biogeographic range	Natural ("native") range
	Nonnative ("invasive") range
3) Land cover types where invasive	
4) Potential Impacts	
B. Establishment phase	
1) Actual and potential impacts	Ecosystems
	Structure
	Species composition
2) Distribution and abundance	Distribution in target sites
	Distribution in adjacent sites
	Abundance in adjacent sites
3) Life history characteristics	Dispersal
	Reproduction
4) Biogeographic range	Regional range
5) Management feasibility	Availability of control methods
C. Spread and equilibrium phases	
1) Management feasibility	Availability of control methods
	Size of infestation
	Accessibility to infestations
2) Distribution and abundance	Trend in target sites
	Distribution in target sites
	Abundance in target sites
3) Life history characteristics	Dispersal
4) Actual impacts	Ecosystems
	Structure
	Species composition

The categories within each phase are ranked in general order of importance

(Rejmanek and Pitcairn 2002), so containment of existing populations or preventing them from becoming established in high priority sites (see next section) are probably the most reasonable management objectives. The likelihood of success for limiting further spread and reducing existing populations will depend on the availability and effectiveness of containment methods and size of existing populations. Data on trends in abundance and distribution and dispersal capability can help distinguish species that are spreading rapidly from those with slower spread rates. Although the general categories of information on species in the spread stage are the same as those in the establishment stage, the specific information that is of most use is generally different (Table 2.1). Information on management feasibility and distribution and abundance are more important than at other phases. Information on impacts can still be useful for prioritizing species in the spread phase, but it is more focused on actual impacts that have been observed than on the potential to cause future impacts. Biogeographic information is not particularly helpful at this phase because it should already be apparent which biogeographic regions (e.g. habitat types) are being invaded by the species.

2.4.3.2 Information for Prioritizing Sites

There are two main categories of information to collect when prioritizing sites: (1) susceptibility to invasion, and (2) the conservation value of the site (Table 2.3). Management feasibility is another consideration, but of lesser importance.

Predicting the susceptibility of vegetation communities to invasion has long been an active area of research (Rejmanek et al. 2005). Success of predictions for general patterns has been elusive, but predictions are often reliable only when done at local scales. Besides basic ecological information on nonnative species and land use within the area of interest (intrinsic factors; Table 2.2), landscape configuration and characteristics are also important (extrinsic factors; Table 2.2). This is because invasive species may initially spread from neighboring lands. Attributes at the landscape scale should also be considered when prioritizing sites, especially patchiness of vegetation communities (some communities are more prone to invasion caused by edge effects; e.g., grasslands) and corridors connecting vegetation types to particular sites. Conservation value includes information on local hotspots of native diversity, endemism, and threatened and endangered species, as well as other cultural or recreational site values.

2.4.4 Prioritized Monitoring Plan

Prioritization can help further reduce the area identified for monitoring in a generalized monitoring plan (Fig. 2.1), and thus increase monitoring efficiency (Fig. 2.4). The specific approach will depend on whether the prioritization was developed for colonizing species, species established in an area but not yet spreading, or species currently spreading through an area. Preventing colonization will require monitoring

Table 2.2 Information needed to develop prioritized lists of sites to protect from invasion by nonnative species

A. Susceptibility to invasion		
1) Intrinsic (site-specific)	Nonnatives richness	
	Nonnative distribution	Spatial
	Nonnative abundance	Vegetation community
	Land use	Disturbance
		Historic
		Contemporary
2) Extrinsic (off-site)	Vectors and pathways	Roads
	Neighbor perimeter	Trails
	Neighbor area	Watercourses
	Land use	Disturbance
		Contemporary
3) Invasion Rates	Temporal trend in nonnative species accumulation	
B. Conservation value		
1) Hotspots		
2) Endemics		
3) T & E species		
4) Rare community types		
5) Sensitive areas of other value	e.g. cultural or recreational	
C. Management feasibility		
1) Management constraints	e.g. in wilderness	
2) Site accessibility		

The categories within each level are ranked in general order of importance

vectors and pathways to the site, as well as areas where the species is likely to become established. Management of established species not yet spreading should be focused on eradication. Attention should be given not just to sites with larger infestations but satellite populations as well which often serve as propagule sources from which larger infestations can develop and spread. Species that are actively spreading are especially hard to deal with. A strategy with dual objectives of containing further spread and reducing density is recommended, but resources may not always allow this. If resources are limited, the decision to focus on containment vs. control will be determined by how rapidly the species is spreading.

2.5 What can be Done with Geo-Referenced Abundance Data?

Geo-referenced abundance data provide the opportunity to develop the most efficient types of early-detection monitoring plans possible. Specifically, these types of data can be used to develop predictive models to help focus monitoring efforts where species, or suites of species, are most likely to appear on the landscape. Because the development of these predictive models can be costly, prioritization is often employed first to narrow a large list of candidate species to a manageable number (Fig. 2.2). This is often done at relatively local scales such as parks and reserves.

The development of predictive models can increase search efficiency by focusing searches on areas that are most likely to be invaded. Predictive models can also be used to estimate the threat posed by specific species and thus can be integrated into the prioritization process. Regardless of scale, the goal of predictive models is to identify sites where invasive species are most likely to occur. Models can be developed for individual species as well as groups of species (Guisan et al. 1999; Underwood et al. 2004; Ferrier and Guisan 2006). Good predictive models substantially reduce the enormous amounts of resources required to detect populations before they become established or before nascent populations begin to expand (Rejmanek and Pitcairn 2002).

The uses of predictive models in wildlife management and other areas of conservation are extensive (Ejrnaes et al. 2002; Scott et al. 2002; Guisan and Thuiller 2005). In contrast, despite a plethora of research predicting what species are likely to be invasive and what communities are likely to be invaded (Rejmanek 1989; Reichard and Hamilton 1997; Daehler and Carino 2000; Kolar and Lodge 2001; Rejmanek et al. 2005; Krivanek and Pysek 2006), and the modeling of invasive species distributions has been relatively limited until only recently (Peterson 2003; Rouget et al. 2004; Underwood et al. 2004; Thuiller et al. 2008).

2.5.1 Types of Predictive Modeling Approaches

There are two general approaches for predicting which species will likely become invasive in an area. One is based on decision trees, usually with binary answers (yes/no) to a series of questions on species biogeography, biology/ecology, and traits generally considered to be legitimate indicators of invasiveness (Daehler et al. 2004; Pheloung et al. 1999; Reichard and Hamilton 1997). The number of questions can range from a few (e.g., 7; Reichard and Hamilton 1997) to many (e.g., 50; Pheloung et al. 1999). In many ways, this approach resembles prioritization with the use of decision trees and ordinal scores. It is simple in concept and has proven effective in predicting species likely to colonize a large geographic area (e.g., a country or state) and become invasive (Krivanek and Pysek 2006).

The other approach is based on statistical models using geo-referenced environmental data at sites where a species is known to occur and, ideally, also where it does not occur. Standard environmental data are correlated with species distribution and abundance patterns including climate, topographic, soil, and land cover variables (Table 2.3). Some of these variables directly influence species distribution patterns (e.g., soil pH, light), while others indirectly influence patterns (e.g., elevation, aspect). In addition, invasive species biologists have identified other variables that

Table 2.3 Information needed to develop predictive models of invasive species in different phases of the invasion process

A. Pre-introduction and introduction phases		
1) Species data	Biogeographic	Native range
		Nonnative range
	Tendency to be invasive elsewhere	
2) Environmental data	Climate	Temperature
		Precipitation
	Productivity	
	Evapotranspiration	
B. Establishment and spread phases		
1) Species data	Distribution	
	Abundance	
2) Environmental data	Topography	Elevation
		Slope
		Aspect
	Soils	Structure
		Chemistry
	Land cover	Vegetation association
		Land use
3) "Invasion Theory" data	Disturbance	Grazing
		Fire
		Logging
		Roads & trails
	Species pool	
	Propagule pressure	Site-specific land use
		Off-site land use
	Neighboring land perimeters	
	Neighboring land area	
	Vectors (sources of transport)	

The categories within each level are ranked in general order of importance

are often correlated with invasive plant species (Mack and D'Antonio 1998; Lonsdale 1999). These include factors such as disturbance, propagule pressure, and the species pool of potential invaders.

2.5.2 Preintroduction Prediction Models for Single Species

Many studies have focused on predicting the likelihood of a species being introduced and becoming established in an area in which it does not yet occur. Until recently, there has been a great deal of pessimism regarding the success of these studies (Williamson 1999). However, important advances have been made in recent years, and there do appear to be traits that have some generality for predicting invasiveness (Kolar and Lodge 2001; Rejmanek et al. 2005), especially for particular taxa (Rejmanek and Richardson 1996; Grotkopp et al. 2002).

A number of models have been developed that attempt to predict the likelihood of different species becoming invasive if they are introduced in an area (e.g. Rejmanek and Richardson 1996; Reichard and Hamilton 1997; Pheloung et al. 1999; Daehler et al. 2004). Some of these models have good predictive ability even outside geographic areas in which they were developed (Krivanek and Pysek 2006; Pauchard et al. 2004). A potential limitation is that both the decision tree and statistical models require a large amount of detailed information which is not always available, such as species life-history characteristics or environmental conditions. On a more fundamental level, the models have often been applied at much larger scales (e.g., countries, bioregions, or even continents) than the effective scale of most early detection programs (i.e., local or designated management units). Although they may be useful for predicting *what* species might become invasive over a large geographic region, they generally do not predict *where* species are most likely to become established at a scale appropriate for most early detection programs.

Early detection programs are generally targeted at species early in the colonization phase of invasion and implemented at local or, perhaps, regional scales. However, in some instances, there may be a need to develop an early detection program for a large geographic area. In these cases, there is a group of predictive models known as climatic-envelope models (CEM) that form a bridge between the preintroduction models discussed above and postintroduction models. CEMs are based on general relationships between climate and species biogeographic patterns (Rouget et al. 2004), and require little if any detailed species life-history information or environmental characteristics. Predictions are for large geographic areas, but they have the flexibility to be applied to species in either preintroduction or postintroduction phases. Information needed for developing CEMs includes the native and nonnative ranges of the species, basic climatic data for where the species occurs, productivity (which rainfall can often be a surrogate for), and evapotranspiration (Table 2.3).

2.5.2.1 Postintroduction Prediction Models for Single Species

Postintroduction predictive models are often developed with preexisting data from plant surveys and GIS data. The fundamental ecological concept that is the foundation of most predictive modeling studies is the ecological niche (Grinnell 1917; Hutchinson 1957; MacArthur 1968). A species' fundamental niche is determined by a large number of abiotic, biotic, and behavioral factors. Where species actually occur is best conceptualized as its realized niche (e.g., Austin and Meyers 1996). Although a species could have greater ranges of distribution, biotic interactions (e.g., competition, predation, pathogens), the lack or limitation of important resources (e.g., moisture, light), and/or the inability to cross barriers restricts its actual distribution. Consequently, predictive models are based on data of a species' realized niche. Differentiation between the fundamental niche and the realized niche has important practical considerations for evaluating the scale to which model predictions can be extended and for the information collected for developing models (Thuiller et al. 2005). Because environments are dynamic and heterogeneous, factors that influence a species' realized niche can be expected to vary unpredictably, both spatially and temporally. Therefore, a good rule of thumb is to assemble data on species (e.g., distribution, abundance) and environmental variables (e.g., elevation, soils) from areas in close geographic proximity to where the early detection program will be applied. It is also very important that the environment has not substantially changed since the time when the data were collected.

2.5.3 Postestablishment Prediction Information for Single Species

Models of species in the spread and equilibrium phases are focused on local scales (e.g., a reserve, national park, or state forest). At this phase of invasion, nonnative species have a proven ability to establish themselves and survive regional climatic conditions. The objective of modeling efforts then becomes predicting where the species can reproduce, persist, and disperse.

For obvious reasons, developing statistical models for species that are in the equilibrium phase would not be a good investment of financial or human resources. Therefore, statistical models are most appropriate for species in the establishment and, to a lesser degree, the spread phase of invasion. Even then, the usefulness of these models may be limited. Data might be too sparse for developing models for species in the establishment phase, because populations are restricted in distribution and/or abundance. Although species known to be spreading are better suited for modeling, they may be beyond the point of practical control efforts.

Basic information to gather on species in the establishment and spread phases are estimates of distribution and abundance (Table 2.3). Predictive models are often based on presence–absence (incidence) of species in an area, but abundance data (e.g., cover, density) give a far more ecologically meaningful correlation of the species along environmental gradients (Austin 2002; Klinger et al. 2006). Although incidence-based models have utility, we strongly recommend the use of abundance data if they can be obtained. Models based on incidence data essentially give equal weight for species relationships along environmental gradients; a species that occurs at 10%, 30%, 50%, and 70% values for a given predictor variable provides the same amount of information at each value (it simply occurs there, but in what amount we do not know). A species with densities of 10, 40, 60, and 30 at 10%, 30%, 50%, and 70% values for the predictor variable provides much more ecological information and has greater predictive value.

Standard environmental data to correlate with species distribution and abundance patterns include topographic, soil, and land cover variables (Table 2.3). In addition to these standard environmental variables, invasive species biologists have identified other variables that are often correlated with the occurrence of invasive plant species (Mack and D'Antonio 1998; Lonsdale 1999). These factors include disturbance, propagule pressure, and the species pool of potential invaders (Rouget and Richardson 2003).

Invasions can be facilitated by biological interactions such as pollination and seed dispersal. Theoretically, incorporating these processes into predictive models could be very useful, but in most instances it would be extremely difficult to do in a meaningful way (Araujo and Luoto 2007). Lack of data on the processes, what metric to use in the models, and matching the scale of the process to the scale where species and environmental data have been collected would be problematic. The issue of matching scales where predictor variables and species data are collected is a general issue that confronts even models found to have reasonable predictive value (Underwood et al. 2004).

In developing a useful predictive model, it is essential to only include predictor variables that are available in the management unit's database, especially in the case of spatial data. Although other predictors may be very important, if spatially explicit information is not available for the management unit, the model cannot be used to predict areas of the unit that should be searched for invasives. It may be possible to include some important predictors, such as propagule pressure, through the use of available surrogates such as vectors and pathways.

2.5.4 Predicting Risk of Occurrence Using Multispecies Models

Information that can be used for modeling species assemblages is essentially the same as that for individual species. The main difference is the statistical methods used to develop the models, not the data themselves (Guisan et al. 1999; Underwood et al. 2004; Ferrier and Guisan 2006). Most landscapes have been invaded by multiple species, so an approach focused on assemblages may be very efficient (Underwood et al. 2004). Because of computerized databases, the time required to collect information on species assemblages is not much greater than for a single species. Nevertheless, care must be taken with assemblage-based models. Because species tend to respond individualistically to environmental gradients, predictions of distribution patterns could either be narrower or broader depending upon the shape of the species response curves (Austin 2002). In an early detection program, this could result in areas not being monitored where invasive species do occur, or spending time searching areas where few if any occur. An additional consideration is that within an assemblage only one or a few species are truly prone to be problematic. In these instances, it is more useful to predict where the problem species occur rather than the entire assemblage (Zimmerman and Kienast 1999; Ferrier and Guisan 2006).

Multiple species models assume that species within an assemblage respond similarly to environmental gradients. Numerous studies have shown this assumption is tenuous, so great care needs to be used when using these models. Careful analysis of species distribution data is needed before developing models to determine whether the assumption of similar niche responses among species is justified. Even if the assumption appears justified, the results need to be interpreted cautiously.

2.5.5 Predictive Models Applied to Multiple Sites

Predictive models can be applied to multiple sites. However, models developed at one site may have poor prediction success at other sites, because the relative importance of different realized niche dimensions can change between areas (see above). For this reason, multisite models should be based on information for species and predictor variables from each site. If this is not possible, then predictions of invasive species distributions in areas where the models could not be validated should be interpreted very cautiously. It is also a strong argument for the need to validate predictions in the field before full implementation of an early detection program.

2.5.6 Optimized Monitoring Plan

An optimized monitoring plan allows for a further reduction in the search area required for early detection monitoring (Fig. 2.1) and an increase in efficiency (Fig. 2.4). It integrates the results of a generalized monitoring plan, prioritized monitoring plan, and predictive modeling (Fig. 2.2). After a generalized monitoring plan is used to identify areas most susceptible to invasion, prioritization is employed to narrow the search range within this area and to identify the species most important to monitor for. Predictive modeling is then applied to these high priority species to develop efficient monitoring plans for those species. In some instances, it may make sense to first predict which species are most likely to be introduced to a site or spread into areas of high conservation value. In either case, this would be the most efficient use of resources at both the planning and implementation stages of a monitoring program. These considerations are typically overlooked in most early detection programs (M. Brooks pers. obs.).

The payoff from investing in the optimized monitoring plan would be in implementation. Obviously, it would result in a minimum area being targeted for monitoring (Fig. 2.1). However, it will also increase the probability that the species most likely to be problematic and the sites where the species are most likely to occur and/or have the most negative effects have been identified. This would help identify the best type of monitoring and control efforts needed to reduce the likelihood of colonization, spread, and impacts of those high priority species.

2.6 An Example of How to Apply the Monitoring Framework

The framework described in this chapter can be used to increase the overall efficiency of early detection monitoring programs. With the addition of each successive monitoring approach, the extent of the area which is the focus of monitoring efforts can be reduced (Fig. 2.1). An example of how this process can work is presented below for a hypothetical management unit composed of typical landscape features (Fig. 2.5).

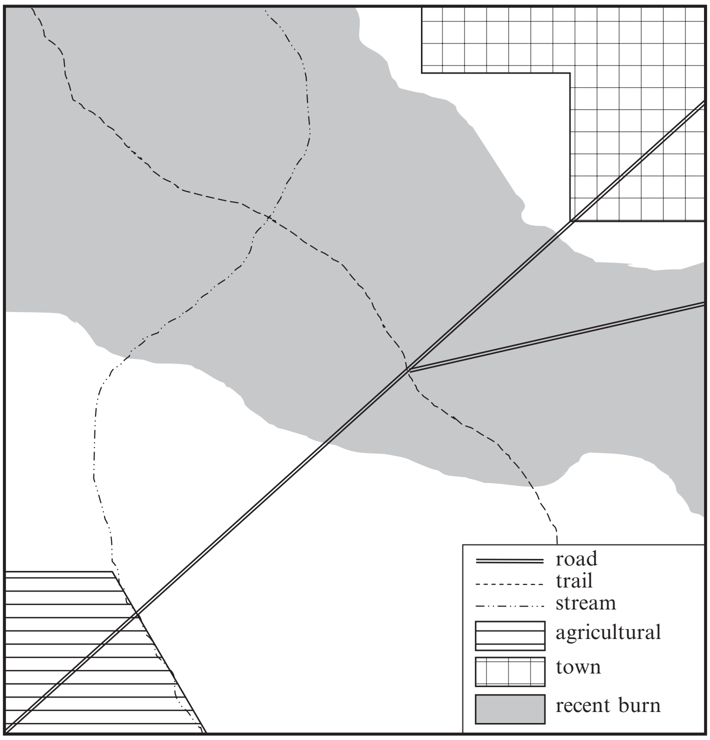

Fig. 2.5 A worked example of how the three types of monitoring plans can be applied to a management unit composed of common landscape features

If there are no species data available in or near the management unit, then a generalized approach is required (Fig. 2.2). The landscape features in this hypothetical management unit are associated with typical levels of propagule pressure and resource availability, which can be used to develop a generalized monitoring plan. Propagule pressure would be very high in the town and agricultural area, high along the roads, moderate along the trail and stream, and low elsewhere (Fig. 2.5). Resource availability would be very high in the town, high in the agricultural area, recent fire, and roadsides, moderate along the trails, and low elsewhere. The generalized monitoring priorities in this case would be as follows: *very high priority* in the town and agricultural area; *high priority* along the roads and in the burned area, especially where to two meet; *moderate priority* along the trail and stream; and *low priority* elsewhere. Thus, the areas of very high priority would comprise about 10% of the total area within the management unit, and if the high priority areas were added, the monitoring area would be about 50% of the total area.

If a species list is available, then a prioritized monitoring plan can be built upon the generalized plan (Fig. 2.2). The specifics of this plan will depend on the types of species that rank as highest priorities. For example, assuming that the species pool is dominated by highly invasive riparian plants, then monitoring efforts should be focused on the stream corridor, especially where it passes through the recent burn, agricultural field, and crosses the road (Fig. 2.5). This would reduce the monitoring area to less than 5% of the total management unit.

If georeferenced abundance data are available for the high priority riparian species in this example, then an optimized monitoring plan can be developed (Fig. 2.2). Assuming that habitat modeling indicates that these riparian species are typically associated with agricultural areas, then the monitoring effort can be focused even further on the stream corridor where it passes along the edge of the agricultural area, especially where it crosses the road. Accordingly, the monitoring areas would be reduced to < 1% of the total management unit (Fig. 2.5).

In most situations there will not be just one set of characteristics associated with potential invaders (e.g. riparian plants with affinities for agricultural areas). However, the process outlined above can be applied for each group of high priority species with similar characteristics to produce multiple components of an optimized monitoring plan. For example, assume that in addition to riparian plants of agricultural areas, the above example included high priority species that are often used as ornamentals in landscaping and others that are typical of roadsides in post-fire landscapes. In that more complicated example, the optimized monitoring plan would additionally include monitoring in the town (especially its interface with wildlands) and along the roadside within the burned area. This would increase the sampling area to about 5% of the management unit, but still well below the 10–50% associated with a generalized monitoring plan.

The strength of the early detection monitoring framework presented in this chapter is in improving not only the efficiency of monitoring efforts, but also the efficiency of developing the monitoring plans themselves. In particular, by first developing a prioritized list of potential invaders, subsequent resources to develop predictive models can be most effectively allocated to those species that pose the greatest threat of invading and negatively affecting resource values. The framework also allows for realistic consideration of the extra effort needed to develop prioritized or optimized plans, so that more informed decisions can be made regarding the allocation of resources to develop early detection monitoring plans, implement them, and respond to new invaders with control treatments.

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Author Query:

[Au1]: Please check whether the corresponding author information is OK as typeset.