Controlling invasive species in complex social landscapes

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Control of biological invasions depends on the collective decisions of resource managers across invasion zones. Regions with high land-use diversity, which we refer to as "management mosaics", may be subject to severe invasions, for two main reasons. First, as land becomes increasingly subdivided, each manager assumes responsibility for a smaller portion of the total damages imposed by invasive species; the incentive to control invasives is therefore diminished. Secondly, managers opting not to control the invasion increase control costs for neighboring land managers by allowing their lands to act as an invader propagule source. Coordination among managers can help mitigate these effects, but greater numbers – and a wider variety – of land managers occupying a region hinder collective action. Here, we discuss the challenges posed by management mosaics, using a case study of the yellow starthistle (*Centaurea solstitialis*) invasion in the Sierra Nevada foothills of California. We suggest that the incorporation of management mosaic dynamics into invasive species research and management is essential for successful control of invasions, and provide recommendations to address this need.

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Despite substantial investment in control technologies, biological invasions are becoming ever more problematic. Suggested reasons for control failures include insufficient policy, inadequate funding, and gaps in scientific knowledge (Simberloff *et al*. 2005). A less-recognized barrier to control is the increasingly complex social landscape in which invasions occur. Habitats worldwide are continually being subdivided and managed as smaller areas, reducing the likelihood that invasions will be controlled. We use the term *management mosaics* to refer to landscapes comprising many individually managed properties with a variety of uses.

In a nutshell:

- Regional control of biological invasions requires collective effort by all affected resource managers
- Lack of control of invasives by any one manager can reduce nearby managers' incentives by increasing their costs of controlling the invasion
- Land managers should coordinate control efforts to increase effectiveness and reduce costs by eliminating reinvasion sources
- Coordination may be facilitated by top-down and middle-out approaches that promote education, regulation, incentives, and increased communication among all stakeholders

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In a management mosaic, each manager's control decisions directly impact his/her neighbors' decisions, by affecting the spread of species across boundaries. However, landholders within an invaded management mosaic tend to make control decisions based only on damages occurring on their own land, leading to a lack of control and increased invasion of the landscape. Furthermore, managers who choose not to control invasive species impose extra costs on others by allowing their lands to serve as propagule sources. Thus, management mosaics exemplify a classic collective action problem (Olson 1965), requiring resource managers to cooperate and agree on control levels.

Here, we examine the role of management mosaics in biological invasion control. We contend that subdivision of the landscape into greater numbers and types of management units reduces managers' incentives to control invasions and hinders the cooperation necessary to overcome this collective action problem. We support this premise with a case study on rancher responses to yellow starthistle (*Centaurea solstitialis*), a widespread invader in California. This focal system exemplifies a complex management mosaic. Finally, we offer recommendations for incorporating socioecological principles into invasive species control and research, to combat the constraints imposed by management mosaics.

Management mosaics: mechanisms and examples

Management mosaics have been shown to impede invasive species control in many regions of the world, including Australia and New Zealand (Williams and West

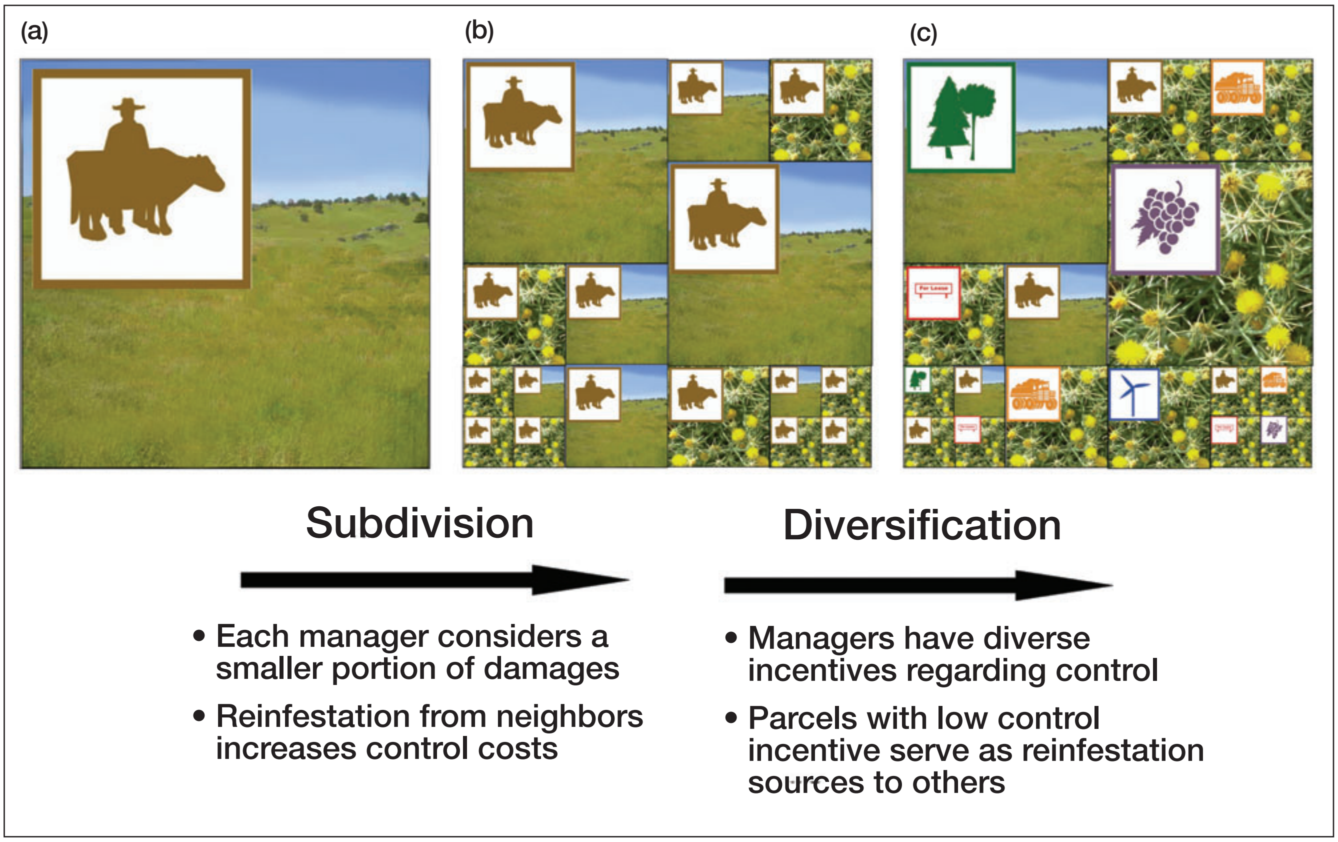

Figure 1. *The complexity of a management mosaic (a) increases as it is subdivided into more and smaller parcels (b) and as land use diversifies (c). Increasing complexity of this social landscape can reduce managers' incentives to control invasions, leading to over-invasion of the landscape.*

2000), Britain and Ireland (Dehnen Schmutz *et al.* 2004; Stokes *et al.* 2006), and the US (Fiege 2005; Hershdorfer *et al.* 2007). Furthermore, theoretical studies have shown reduced pest control in regions divided among multiple managers (Bhat *et al.* 1996; Wilen 2007). As management mosaics become more complex, invasive species control becomes more difficult, for two main reasons: subdivision of the landscape reduces managers' incentives to control an invasion (subdivision effect), and differing control incentives, resulting from diverse land-use goals, increase the likelihood that uncontrolled patches will perpetuate reinfestation of neighboring lands (diversity effect; Figure 1).

Within a single, contiguous management unit (eg a national park or very large ranch), managers can estimate control costs and evaluate invasion damage for the entire area and then implement appropriate control measures (Figure 1a). However, subdivision into multiple management units reduces control incentives in several ways (subdivision effect; Figure 1b). First, each manager considers damages specific to his/her lands, rather than the damages resulting from invasion spread across the entire landscape. Second, the ratio of edge to surface area for each parcel increases with landscape division, making transboundary spread more likely and raising the relative cost of excluding invasion from any parcel. As the numbers of land uses and types of managers in a region increase, the existence of different control incentives can exacerbate the effects of transboundary spread, because regions managed by individuals with little incentive to control are likely to serve as reinfestation sources for adjacent areas (diversity effect; Figure 1c).

Given the effects that increasing subdivision and diversification can have on control incentives, it seems apparent that regional invasions are as much a social challenge as an ecological one.

Yellow starthistle

Yellow starthistle (*Centaurea solstitialis*; Figure 2) infests over 14 million acres (over 5.5 million hectares) across California (DiTomaso *et al.* 2006). This non-native annual spreads in spite of enormous resources and research directed toward its control, a strong network of agricultural advisors, and nearly universal antipathy for it among land managers. Aslan *et al.* (2009) identified many practical challenges to yellow starthistle control. In addition, we suggest that socioecological factors, including subdivision and diversity effects, also hinder control of this species.

Our exploratory study targeted the western foothills of California's Sierra Nevada Mountains, an area composed primarily of privately owned parcels of land and scattered public lands. Yellow starthistle heavily infests this region

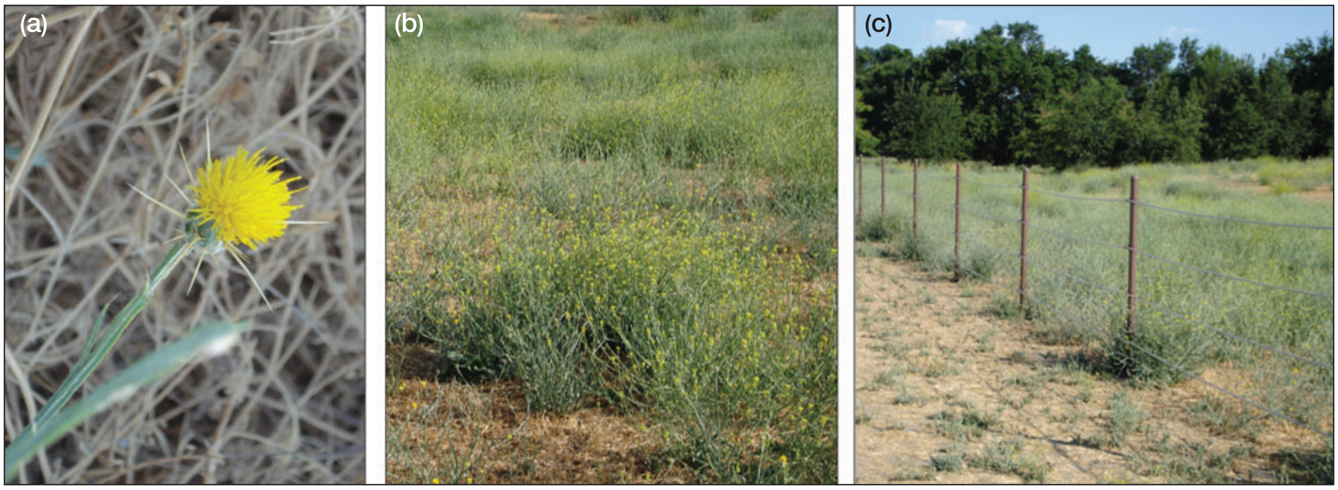

Figure 2. *Yellow starthistle (*Centaurea solstitialis*) is an aggressive and tenacious invader. (a) The plant's sharp spikes can pierce the eyes of grazing cattle. (b) Starthistle spreads quickly and forms dense infestations. (c) Managers must contend with the spread of yellow starthistle across fencelines from neighbors who do little to control this noxious weed.*

(DiTomaso *et al.* 2006), decreasing rangeland forage, reducing wildlife habitat quality, displacing native species, and diminishing groundwater availability (DiTomaso 2005). The region's demographics are changing, as human migration to rural areas and escalating land prices drive rangeland conversion (Standiford *et al.* 1996). Former ranchlands now support diverse land-use goals in an increasingly complex management mosaic.

We surveyed ($n = 162$) and interviewed ($n = 40$) ranchers in Amador, Calaveras, Tuolumne, and Mariposa counties (see Aslan *et al.* [2009] for full methodology; Figure 3a). Ranchers are the primary land managers in these four counties (Figure 3b); approximately 1.2 million acres, or about 0.5 million hectares (35% of total land area), are managed for domestic cattle (US Department of Agriculture–National Agricultural Statistics Service 2005). Ranchers in this region operate within a management mosaic: 93% of those surveyed report neighboring land under multiple management types (with diverse land-use goals), with 47% of respondents' ranches bordered by three or more types. Ninety percent of ranches are bordered by other ranches, 86% by state or county roads, 38% by residential land, and 22% by public land.

Sampled ranchers described frustration resulting from both subdivision and diversity effects. Three-quarters of interviewed ranchers stated that yellow starthistle from neighboring land negatively affected them; 25% of interviewees also reported that neighboring weed sources reduced their investment in control efforts, because of the cost associated with continual reinvasion. A sample quotation describes this effect: "If [my neighbors] don't control [yellow starthistle], there's no hope for me to…I usually don't try to fight it…I can't afford to do that year after year".

Most ranchers are motivated to control yellow starthistle because it directly affects their livelihood by reducing cattle forage. Eighty-five percent of surveyed ranchers who had yellow starthistle on their land had attempted control, a trend that did not vary by rancher age, education, and income, or by ranch size. However, not all ranchers owned the land that their livestock depended on for grazing. Although 58 of 60 survey respondents who owned all of their pasture controlled the weed, none of the seven ranchers who leased all of their pasture had attempted control. Without the long-term commitment of ownership, leased ranchlands provide little incentive for control and are probable sources of reinvasion.

Diversity effects may arise any time an invasion spreads between properties that have different incentives or control policies. In our study, differences in control effort between roads (mostly managed by state and county agencies) and ranchland were of greatest concern to ranchers. Of interviewees with land adjacent to roads, 76% (26) reported roadside infestations, 74% (25) considered those roads as the sources of yellow starthistle on their land, and only 38% (10) believed that roadside infestations were controlled. Furthermore, 39 survey respondents provided unsolicited comments expressing frustration about lack of control along roadsides.

Another example of diversity effects is evidenced by interviewees' comments on lack of control on private land. Nine (56%) of 16 interviewees with land adjacent to residential land reported yellow starthistle invasion from those neighbors. A prevalent opinion among sampled ranchers was that "hobby" ranchers, non-ranchers, and newcomers to the region were unfamiliar with yellow starthistle or lacked control incentives. This trend has also been observed elsewhere (Klepeis *et al.* 2009).

To reduce the impacts of the diversity and subdivision effects and to improve invasive species control in management mosaics, system-wide coordination of control efforts is needed. Many ranchers recognize this necessity. Sixty-eight percent of the interviewees unequivocally called for coordination of control efforts, and 22 survey respondents provided unsolicited comments addressing this, such as: "I do not think that we can eradicate it, because it's all along the highways. Until the state [imple-

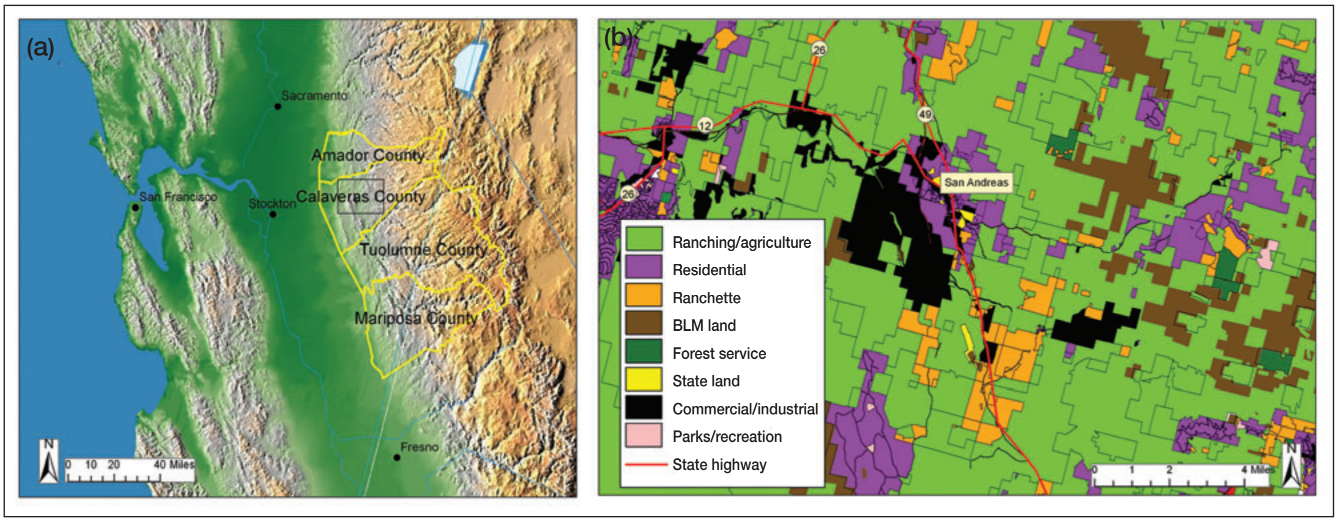

Figure 3. *The yellow starthistle management mosaic in the Sierran study region. (a) Locator map showing study counties in the foothills of California's Sierra Nevada Mountains. (b) Mosaic of land uses in a representative portion of our study region.*

ments controls along roadways], it's going to come into my field…If we declare war, we gotta [sic] be united", and, "We get rid of [yellow starthistle] here, and our neighbor has it, and – before you know it – you have it again; so everybody's got to control it or…you [will] never get rid of it".

Coordinating control efforts in a management mosaic

Our case study exemplifies the challenges posed by management mosaics and the need for collective action to protect ecosystems against invasion. There are three levels at which environmental protection is generally undertaken: top-down (regulation by centralized government), bottom-up (grassroots, self-governing efforts), and middle-out (civic environmentalism) (John *et al.* 2006). We evaluate the relevance of these three strata for guiding coordinated invasive species control, in our case study and in general.

Top-down approaches attempt to resolve collective action problems by controlling individual actions through policy. Hardin (1968) famously argued that commons threatened by pollution (akin to biological invasions) require this approach. In the US, as in Australia and New Zealand, invasive species legislation occurs at multiple levels of government. These policies and their effectiveness vary greatly across subregions (Fiege 2005; Hershdorfer *et al.* 2007; Higgins *et al.* 2007), but many mandate control of high-priority noxious weeds on private lands and permit government to impose control on non-compliant lands at the landowner's expense (eg California, Colorado, Utah, and Montana; California Department of Food and Agriculture [www.cdfa.ca.gov/phpps/ipc/encycloweedia/winfo_weedlaws.htm]; Montana Weed Control Association [www.mtweed.org/faq.html]; Hershdorfer *et al.* 2007). However, command-and-control policies often falter when problems span political and administrative boundaries (Lubell *et al.* 2002), a constraint certainly applicable to biological invasions in management mosaics. Furthermore, noxious weed laws are frequently not enforced, as a result of resource constraints (eg counties in Montana; Montana Weed Control Association) or to avoid antagonistic relationships with landowners (Fiege 2005; Hershdorfer *et al.* 2007). Top-down approaches are rarely sufficient for regional invasion control (Fiege 2005; Hershdorfer *et al.* 2007), but they are, nevertheless, a valuable component thereof (Lodge *et al.* 2006; Hershdorfer *et al.* 2007; Higgins *et al.* 2007), encouraging cooperation among managers even when not strictly enforced (Lubell *et al.* 2002; Hershdorfer *et al.* 2007).

With respect to our case study, yellow starthistle control is not assisted by top-down approaches in California, because the state does not require control of species that are too widespread to be deemed eradicable (S Schoenig pers comm). Although this stance acknowledges that eradication is unlikely, targeted policies to prevent or slow the spread of yellow starthistle could still be beneficial.

Collective action problems can also be managed by bottom-up, self-governing institutions, such as local cooperatives (Ostrom 1990). For example, a small group of Montana landowners united to cooperatively control knapweed (*Centaurea* sp) on neighboring lands (Fiege 2005). Similarly, a few interviewees in our case study cooperated with other ranchers, either by sharing control costs or by informally agreeing to coordinate control. Other ranchers coordinated efforts with non-ranchers, such as the US Forest Service or the state agency responsible for road management. Despite these examples, cooperative efforts to control yellow starthistle in our study region are insufficient to halt invasion spread and currently fail to include stakeholder groups such as residential homeowners and hobby ranchers.

Bottom-up coordination is most likely to occur when the costs of developing, monitoring, and enforcing the institutions are low and potential gains from coordination are substantial (Ostrom *et al.* 1999; Lubell *et al.* 2002). The large number of stakeholders and heterogeneity of incentives in our study region increased coordination costs, decreasing the likelihood that local institutions will resolve coordination problems (Hackett 1992; Ostrom *et al.* 1999; Lubell *et al.* 2002). In this way, complex management mosaics not only lower incentives to control invasions, but also reduce the ability of local institutions to overcome the collective action problem. Bottom-up approaches to management are further hindered in our study system by rapid human population growth and turnover, which reduce individuals' connection to the local community, knowledge of the natural systems (including awareness of the weed or related control techniques), and commitment to the problem (Ostrom 1990; Beatley and Manning 1997; Lubell *et al.* 2002).

A third approach to addressing environmental issues is middle-out coordination, which assembles assets "from within both agencies and community-level organizations, to serve local goals" (John *et al.* 2006). Middle-out coordination includes both top-down and bottom-up participants, thus uniting agencies' professional expertise and resources with the enthusiasm and local knowledge of grassroots campaigns (John *et al.* 2006). This may facilitate coordination of invasive species control by encouraging information exchange and increasing both access to funding and the credibility of management agreements (Schneider *et al.* 2003; Higgins *et al.* 2007). Middle-out coordination might best harness potentially positive aspects of complex management mosaics, including a larger pool of skill sets, high densities of individuals to help monitor and conduct weed control (Williams and West 2000; Higgins *et al.* 2007), greater community pressure on managers of lands with uncontrolled invasions, and more experimentation and lobbying for improved control technologies.

County weed programs, weed districts, and cooperative weed management areas (CWMAs) are all examples of organizations in the US that can foster middle-out cooperation. County weed programs generally receive some county funding and have regulatory authority (Hershdorfer *et al.* 2007). Weed districts are most often created through voter-approved legislation and employ taxation to fund regional weed control efforts (Hershdorfer *et al.* 2007). Both county weed programs and weed districts can function primarily as governmental entities, or can actively foster coordination across multiple agencies or groups. In contrast, CWMAs are established under formalized agreements, specifically to facilitate coordination and integrate invasive plant management resources across jurisdictional boundaries (Bean 2006). CWMAs are more common in the western US, where there tends to be more public land, larger land parcels, lower human population densities, and better established legal and personnel infrastructure for weed control (Midwest Invasive Plant Network 2006). These organizations vary in their goals, geographic extent, and types of partnerships; their effects on invasion control can therefore be localized or may extend into the broader management mosaic.

In California, CWMAs are found throughout the state and have primarily been developed under the initiative of the County Agricultural Commissioner's Office or the Department of Conservation's Resource Conservation District agency. We believe CWMAs are the best choice to foster coordination in our system. However, the ranchers in our sample had little familiarity with CWMAs, suggesting that CWMAs must increase their visibility and participation by private land managers in order to generate effective regional control. Our recommendations address this need.

Recommendations for managers and policy makers

Although no single type of management regime works efficiently, fairly, and sustainably for all shared resources (Ostrom *et al.* 1999), layered and diverse institutions that provide redundancy can help address resource issues (Dietz *et al.* 2003). Thus, bottom-up, top-down, and middle-out approaches can all contribute to improved regional control of biological invasions. Furthermore, regional policies and management of invasive species need to explicitly address the social and economic aspects of subdivision and diversity in management mosaics. The following recommendations are tailored to the three levels of management we have discussed.

Bottom-up (ie all resource managers)

This approach depends on the collective action of all public and private land managers in an invaded, or potentially invadable, region. All managers can contribute by talking and coordinating with their neighbors, recognizing the impact of their weed infestations on others, and participating in existing weed control organizations. Individuals can also contribute to regional invasive species control by engaging in civic and political action to contribute to any of the needs described below, including outreach, education, lobbying for legislation, funding, the development of an invasive species control organization, and so on.

Middle-level organization (ie CWMAs, weed districts, or other regional invasive species control organizations)

The primary goals of this approach should be to facilitate communication between all stakeholders in the management mosaic and to focus institutional support, funding, and outreach to reduce the constraints imposed by management mosaics. These middle-level bodies may take many forms and can be created through bottom-up or top-down efforts. Information on how to develop CWMAs is available online (Center for Invasive Plant Management, www.weedcenter.org/cwmas/howCWMA.html). We recommend that these mid-level organizations: (1) Identify all stakeholders and their incentives and encourage engagement by all managers in the mosaic. In our case study, stakeholders included public agencies, private landowners, residential developers, mining companies, vintners, and others. (2) Coordinate control efforts and enhance incentives where they are lacking. Coordination can help diminish sources of reinfestation and increase success of eradication efforts. Coordination can be aided by identifying and collaborating with locally influential institutions, including clubs, churches, unions, and associations. (3) Counter subdivision and diversity effects directly by changing incentives through community appeals and education, organizing for legislation, and directing cost-shares and other incentives to change behaviors. (4) Develop an overarching control strategy that optimizes invasion control at the landscape scale and use this vision to help prioritize eradication and control efforts and resource allocation.

Top-down (ie local, state, or federal government)

Top-down approaches should provide regulatory and financial support for invasive species control. Enforceable regulation and policies such as tax credits can directly influence control incentives. Funding can be funneled through, and used to support, a middle-level body, which may be best situated to connect relevant players, coordinate control actions, and conduct outreach. Governmental support can be critical to their development and success.

Recommendations for researchers

Researchers conducting both empirical and theoretical studies should explicitly include the socioecological effects of management mosaics in their investigations. Empirical questions requiring study include: do the more subdivided and diverse management mosaics experience lower rates of control success and higher rates of reinfestation and spread, as we predict? Can the effects of diversity and subdivision on invasions be countered by policy changes and structured incentives? How effective are education and outreach for increasing individuals' incentives to control? At the theoretical level, how will diverging incentives affect collective action as invasions spread and affect more stakeholders? What combination of factors defines the social tipping point between successful collective action and rampant invasion? What extent of coordination is needed to curtail an invasion, and what factors determine this? How should incentives or control actions be targeted over space and time to reduce damage and pest spread most efficiently at the landscape level?

There are many relevant questions beyond these. Despite the magnitude of negative consequences imposed by biological invasions and the extensive socioecological research on resource management issues, the role of socioecological processes in invasive species management has been understudied and is ripe for more extensive investigation.

Conclusions

We suggest that complex management mosaics pose challenges for regional invasive species control, because (1) managers may disregard the impacts of their management approaches on neighboring lands, (2) a diverse set of incentives apply in complex landscapes, and (3) more and varied stakeholders need to be motivated and educated to coordinate control. Recognizing the mechanisms by which complex social landscapes promote invasion success can lead to improved regional control efforts and to linked social and ecological studies to address questions geared toward regional invasive species management. Rapid globalization, increased trade, human population growth, and alteration of environments contribute to increasing invasions worldwide (Lodge *et al.* 2006), and most invasions occur in complex management mosaics. Invasion biology must place greater importance on the socioecological processes that shape invasive species spread.

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