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FORUM

Herbicide usage for invasive non-native plant management in wildland areas of North America

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Summary

1. In North America, herbicides are commonly used to control non-native invasive plants on public wildlands. Little is known about the magnitude, efficacy and financial costs of this practice, although this information is crucial for policymakers, researchers, land managers, pesticide producers and the general public.

2. In Canada and Mexico, herbicide usage data have not been tracked by agencies. In the USA, data archiving has been implemented by federal land managing agencies. However, while area sprayed and amounts of herbicides have been documented to varying degrees, efficacy and financial costs have not been recorded in a standardized and consistent manner and data publication has been insufficient.

3. Based on requested data, we estimate that in the USA, half a million hectares of public wildlands were sprayed with herbicides in 2010, representing 201 tonnes. Although non-selective, glyphosate was the most commonly used active ingredient.

4. *Synthesis and applications*. Increasing efforts by land management agencies to collect and share herbicide usage data is a key step towards narrowing the knowledge gap on herbicide usage in invasive non-native plant management on public wildlands. Land managers and policymakers in particular would benefit from an enhanced flow of information on efficacy, costs and effects of herbicides.

Key-words: Canada, ecological restoration, exotic plants, glyphosate, herbicide, invasion, Mexico, non-indigenous, non-native invasive plants, pesticide usage, USA

Introduction

Non-native plants have been identified world-wide as a primary threat to both native biodiversity and ecosystem functioning (Mack *et al*. 2000; Simberloff & Rejmánek 2011). In response to these challenges, many countries have built legal frameworks to prevent, detect, eradicate and control invasive non-native plant species (Miller & Fabian 2004). Although controlling established non-native invasive species should be a last resort in the chain of management actions, as prevention and detection are generally more effective (Leung *et al*. 2002; Olson & Roy 2005), management programmes tend to invest in controlling established populations rather than in prevention strategies (Finnoff *et al*. 2007; Radosevich, Holt & Ghersa 2007).

Land managers have several options for controlling non-native invasive plants, including mechanical (e.g. pulling, mowing, tilling), biological (e.g. using herbivores) and chemical (herbicides) treatments. Choosing an appropriate control method is challenging because managers need to consider key biological and ecological aspects of the target species, predict the efficacy of treatment, anticipate potential adverse effects on non-target organisms and take into account technical and economic feasibility

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(e.g. Derickx & Antunes 2013). In addition, a manager's choice for a control method will be constrained by external factors, such as policy regulations and public opinion (Veitch & Clout 2001; Radosevich, Holt & Ghersa 2007).

Herbicides were initially developed to control unwanted weeds in crop systems but now are widely used in invasive non-native plant management (hereafter invasive plant management) in more natural ecosystems (Radosevich, Holt & Ghersa 2007; Clout & Williams 2009; Fig. 1). Herbicides offer several advantages relative to other management methods: they can control invasive non-native plants quickly, require little human labour, can be relatively inexpensive and do not directly physically disturb soil structure (Clout & Williams 2009). However, there is evidence that at least some herbicides pose risks to non-target organisms (Freemark & Boutin 1995; Wagner & Nelson 2014) and to human health (Alavanja, Hoppin & Kamel 2004). Modern herbicides are less toxic than first-generation herbicides and in most countries, including Canada and the USA, are subject to rigorous evaluation before being brought to market. However, given their complex interactions and fate in the environment, the fact that their effects on ecosystem processes are methodologically difficult to assess, and the large number of active ingredients used, their putative effects on ecosystems and human health remain a continuing concern requiring research (e.g. Pratt *et al.* 1997; Pimentel 2005). Some herbicides, such as 2,4-D, have been relatively well studied, while newer active ingredients (e.g. aminopyralid) have undergone toxicity testing before registration but have received limited attention by scientists (C. R. Nelson, unpublished data). Furthermore, the use of herbicides in invasive plant management has repeatedly led to conflicts between land management agencies and public groups, especially at the local level (Norgaard 2007; Simberloff 2011).

Fig. 1. Herbicide application in invasive non-native plant management (a) with a backpack sprayer and (b) from a vehicle. Photograph courtesy of (a) Ignacio March (The Nature Conservancy) and (b) USDA-ARS. [Colour figure can be viewed at wileyonlinelibrary.com]

Information on the magnitude, efficacy and costs of herbicide usage in invasive plant management can be critical for land management and conservation for the following reasons: (i) it allows land managers and policymakers to consider the risks and evaluate costs and benefits in the process of choosing herbicides, particularly considering specific formulations, and to contrast herbicide usage with putative alternative approaches on the basis of context and cumulative magnitude of their use (Kettenring & Reinhardt Adams 2011; McConnachie *et al.* 2012); (ii) it directs research and monitoring efforts towards assessing efficacy and non-target effects of the most widely used herbicides (Rinella *et al.* 2009); (iii) it provides objective information for conflict resolution between land managers and the public and ensures that opinions will be formed based on evidence rather than personal beliefs (Christie 2008); and (iv) it provides private businesses with information to guide decisions about registering improved herbicides specifically for invasive plant management.

Public land makes up a large proportion of Canada (89%, Neimanis 2011), Mexico (min. 60%, U.S. AID 2011) and the United States (*c.* 30%; United States General Accounting Office 1996) and includes vast wildland areas (i.e. non-agricultural and non-urban areas). For example, forests on public land cover 323 million hectares in Canada (Natural Resources Canada 2016). Herbicides are routinely used to control non-native invasive plants on public land in North America, yet little is known about the extent of the wildland area sprayed, the primary herbicides that are being used, and the efficacy and financial costs of this practice. General pesticide usage and sales data are available through government reports (e.g. Grube *et al.* 2011; Health Canada 2012) and data bases (e.g. California Department of Pesticide Regulation 2015). However, these data focus on usage in crops and horticulture; herbicide usage for invasive plant management in wildlands is not explicitly documented in any of these resources. Similarly, estimates are lacking in the scientific literature. The only exception is an estimate provided by Rinella *et al.* (2009), which was based on a single U.S. Forest Service report and personal communication with the Bureau of Land Management and National Park Service, rather than in-depth analysis of herbicide usage in invasive plant management, including active ingredient usage.

Information on the long-term efficacy, non-target effects and financial costs of invasive plant management actions is key to optimizing control methods and allocating financial resources efficiently (e.g. Maxwell, Lehnhoff & Rew 2009). Unfortunately, the use of herbicides as a management tool for wildlands has not been adequately assessed for North American agencies or countries. Additionally, although there is a large body of scientific literature on the efficacy of herbicides for controlling target weeds (e.g. Kettenring & Reinhardt Adams 2011), most of this research focuses exclusively on the target plant rather than on the desirable natives, monitors outcomes only over a short period of time (but see Crone, Marler & Pearson 2009) and does not consider economic aspects of management actions.

We conducted a survey among major government agencies in Canada, Mexico and the USA and agro-statistical commercial companies to compile current data on herbicide usage in invasive plant management (see Table S1 in Supporting Information for a list of contacted offices and Appendix S1 for details on the survey). We asked whether electronic data were available for the 2007–2011 period and whether offices would be willing to share data with us. Offices that shared herbicide usage data for our study were also asked for data on financial costs and treatment efficacy. We defined wildlands as non-crop-production and non-urban areas that encompass, for example, forests, wetlands, rangelands, but also roadsides and power line corridors. Furthermore, we conducted a literature review of studies that explored non-target effects on native plants to identify whether there is sufficient information about the effects of the most commonly used herbicides in invasive plant management in wildlands. We contrasted the number of publications on non-target effects with estimates of usage for the most commonly used active ingredients (see details in Appendix S1).

Data availability and sharing

According to our survey, herbicide usage data have not been tracked for Canada, at either the provincial or national level. This finding likely reflects the fact that Canada currently lacks a single comprehensive legislative framework on invasive species management (Smith, Bazely & Yan 2014; but see 'Bill 167, Invasive Species Act, 2014', Legislative Assembly of Ontario). Management of public lands ('Crown lands') is a provincial responsibility in Canada. Except in the territories, there is no overarching federal agency overseeing their management. Consequently, there is a lack of data collection at the provincial level and lack of coordination at the national level. Similarly, there was no archived data base of herbicide usage in invasive plant management in Mexico.

By comparison, five out of seven contacted agencies in the USA tracked herbicide usage on public land in an electronic form (Table 1) and four agencies shared data with us: the Bureau of Indian Affairs (BIA), the Bureau of Land Management (BLM), the Fish and Wildlife Service (FWS) and the National Park Service (NPS); the Forest Service (FS) declined to provide data due to data quality concerns (Mike Ielmini, FS, personal communication). However, none of the agencies consistently archive information on efficacy and financial costs and none make usage data publicly available (but see Cota 2004 and United States Forest Service 2014).

Magnitude of herbicide usage

Based on shared data from the BIA, BLM, FWS and NPS, we calculated the first estimate of herbicide usage in invasive plant management on public land in the United States. Our estimate covers 197·1 million hectares. It shows that a total of 1 024 479 ha were sprayed to manage invasive non-native plants in wildlands in 2007–2011. Sixty-five herbicide active ingredients were employed (see Table S2). In terms of area sprayed, glyphosate was the most common active ingredient in 2007–2011 (Fig. 2a, Table S2) and the second most common ingredient in 2010 (Table S3), the year with the most even data coverage among agencies. In terms of amounts used, it was the most widely used active ingredient in 2007–2001 (Fig. 2b, Table S4) and 2010 (Table S5). Data from the National Park Service indicated that grasslands, followed by roadsides and forests, were the most commonly treated sites (Fig. 3).

Our data set did not allow calculating interannual variability in herbicide usage. In 2010, 499 153 ha (Fig. 4a) were sprayed using 201 397 kg of active ingredients (Fig. 4b), corresponding to 0·3% of the public land considered in the estimate.

Our estimate is four times higher than that reported by Rinella *et al.* (2009) but is likely still conservative given that FS usage data were not included. According to its latest pesticide usage reports, the FS sprayed a total of

Table 1. Overview of data sources used to estimate herbicide usage in non-native invasive plant control, in the USA

Governmental agencies	Source	Annual coverage	Area sprayed	Amount used	Data format
Fish and Wildlife Service	PUPS	2007–2011	Yes	Yes	Single applications
National Park Service	PUPS	2007–2011	Yes	Yes	Single applications
Bureau of Indian Affairs	Custom-built reports	2007–2011	Yes	No	Summaries
Bureau of Land Management	Custom-built report	2010	Yes	Yes	Summaries

PUPS, Pesticide Use Proposal System.

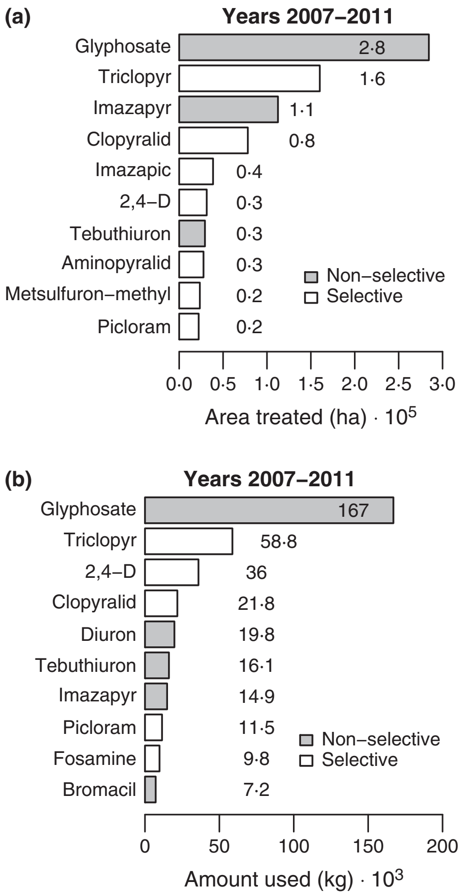

Fig. 2. The ten most commonly used herbicide active ingredients by (a) area sprayed and (b) amount used, in 2007–2011[a, b, c]. See Tables S2 and S4 for 2007–2011 estimates and Tables S3 and S5 for 2010 estimates of all active ingredients. [a]Calculations for area treated were based on data supplied by the U.S. Bureau of Indian Affairs, the U.S. Fish and Wildlife Service, the U.S. National Park Service (all for 2007–2011) and the U.S. Bureau of Land Management (only for 2010). [b]Calculations for amount sprayed were based on data supplied by the U.S. Fish and Wildlife Service, the U.S. National Park Service (both for 2007–2011) and the U.S. Bureau of Land Management (only for 2010). [c]Information on herbicidal selectivity was derived from Tu, Hurd & Randall (2001) and ExToxNet (http://extoxnet.orst.edu, accessed on 20 May 2014).

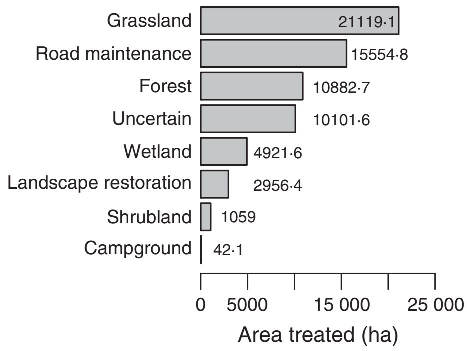

Fig. 3. Area treated with herbicides by site for 2007–2011 (based on National Park Service usage data).

54 253 and 74 495 ha for noxious and aquatic weed control in 2004 (Cota 2004) and 2013 (United States Forest Service 2014), respectively.

According to the U.S. Environmental Protection Agency, 200 488 t of herbicide active ingredients were used in crop-production agriculture, in the USA, in 2007 (Grube *et al.* 2011). Consequently, our estimated herbicide usage in invasive plant management represents only 0·1% of the total used in crop production (Grube *et al.* 2011). In addition, the average herbicide usage per hectare for invasive plant management (0·4 kg ha^{-1}) was lower than that estimated for crop-production systems (1·2 kg ha^{-1}; Appendix S1). However, given their higher biological complexity, wildlands could be disproportionately sensitive to herbicide applications compared to crop-production ecosystems.

Active ingredients

In our estimate, glyphosate was the most common active ingredient, for both the period of 2007–2011 (area sprayed, amount used) and 2010 (amount used). This finding is indeed surprising because glyphosate is non-selective and bears the danger of suppressing non-target native plants. Glyphosate is also the number one active ingredient in the crop sector (Grube *et al.* 2011). The success of glyphosate in agriculture can be explained partly by the increase in transgenic, glyphosate-resistant crops. In contrast, its popularity in invasive plant management is possibly due to its chemical and toxic properties; that is rapid translocation through plant tissue, the low mobility in soil and low toxicity for wildlife (Duke & Powles 2008). In addition, some forms of glyphosate are permitted for aquatic use. In some states, applicators are not required to have a license for spraying glyphosate as long as they are supervised by a license holder. Last but not least, the patent for glyphosate expired in the year of 2000 and its price dropped. This fact may have been an important consideration for land managers (Duke & Powles 2008).

There is relatively little published information on the non-target effects of most active ingredients, including effects on native plants. For instance, our review of the literature published prior to 2012 revealed that there were less than eight published articles for four commonly used active ingredients (aminopyralid, imazapyr, metsulfuron-methyl and triclopyr), respectively (Fig. 5). In contrast, the effects of glyphosate have received more attention; we found 40 articles (33% of all identified articles). Given the paucity of published information and the regular use of non-selective herbicides, there is a critical need for land management agencies to assess non-target effects of the herbicide treatments they are implementing.

Closing the knowledge gap

Herbicide usage data in invasive plant management on public land is an important source of information for land

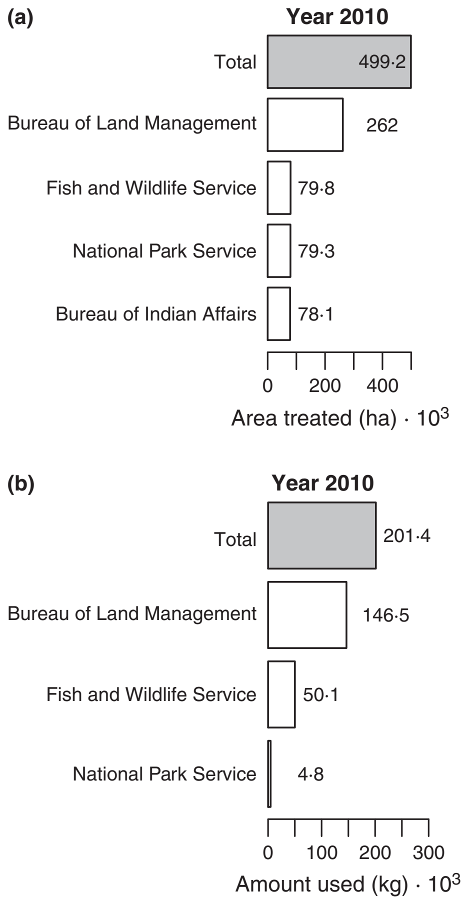

Fig. 4. (a) Area treated with herbicides and (b) amount of active ingredients (acid equivalents) used per federal agency and in total, for 2010.

managers, public groups, scientists and pesticide manufacturers. The case of the surveyed U.S. governmental agencies shows that herbicide usage can be tracked even for large management areas. By archiving and sharing usage, monitoring and financial cost data in a standardized way, agencies would allow scientists, land managers and stakeholders to assess herbicide efficacy and impacts and make inferences about its suitability as a management tool, as well as to share information (Bayliss *et al.* 2013; United States Forest Service 2013). In order to cut costs, scientists could assess general data for every project (e.g. herbicide type, area sprayed, amount used and geographic location) and detailed data for a random subset of projects (e.g. long-term monitoring records, effects on the entire community, financial costs).

Despite the fact that U.S. governmental agencies tracked herbicide usage in invasive plant management, they have been slow at making the data publicly available. However, a positive trend is that both the BLM and the FS are currently working on ways to share their pesticide usage data with the public (Richard Lee, BLM; Mike Ielmini, FS, personal communications). For example, the BLM has recently launched a National Invasive Species Information Management System (NISIMS), which enables managers to submit treatment data to a national archive in a standardized way. This data base can be queried in the future for information on management actions. Furthermore, by collecting and archiving data on the efficacy and costs of invasive plant management actions, agencies could share valuable information among different stakeholders. The U.S. Forest Service has also stated that a standardized data base is key priority of its current strategic framework on invasive species management (United States Forest Service 2013). Other North American agencies should work to make herbicide usage and effects data freely and readily available and not restricted to special requests (e.g. access to data by the U.S. Freedom of Information Act).

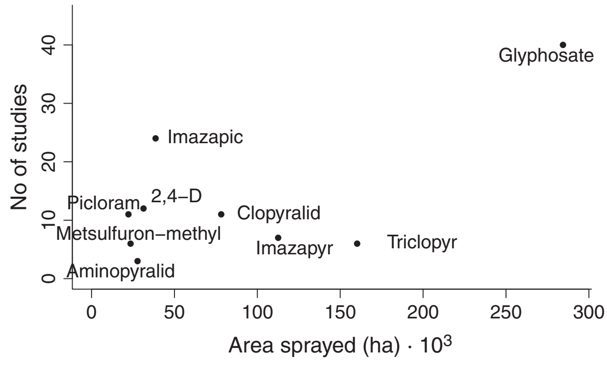

Fig. 5. Number of scientific studies that explored herbicide effects on non-target native plants (*y*-axis) and their area sprayed (*x*-axis) in the framework of invasive non-native plant management in wildlands. To improve visualization, we included only herbicides sprayed on > 20 000 ha.

Conclusions

Data on herbicide usage, efficacy and financial costs are critical for informing stakeholders that develop and implement control programmes for non-native invasive plants in public wildlands. Data tracking and publication by land management agencies are two critical steps towards narrowing our knowledge gap on herbicide usage in invasive non-native plant management.

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Data accessibility

Herbicide usage data (for the BLM, FWS, and NPS) and the R script used in this study have been deposited in the Figshare data repository:

1. R script herbicide usage analysis: – doi: 10.6084/m9.figshare.3386032 (Wagner *et al.* 2016a).

2. BLM herbicide usage data: – doi: 10.6084/m9.figshare.3386062 (Wagner *et al.* 2016b).

3. FWS herbicide usage data and species lists used in data filtering: – doi: 10.6084/m9.figshare.3386083 (Wagner *et al.* 2016c).

4. NPS herbicide usage data: – doi: 10.6084/m9.figshare.3386089 (Wagner *et al.* 2016d).

BIA herbicide usage data can be requested from La Donna Carlisle (LaDonna.Carlisle@bia.gov, Hopi Agency Natural Resources, P.O. Box 158, Keams Canyon, AZ 86034) or from the Bureau of Indian Affairs (MS-4606-MIB, 1849 C Street, N.W., Washington, DC). Results of the herbicide literature review can be obtained from CRN and VW.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Governmental agencies and offices in Canada, Mexico and the USA, and commercial companies that were contacted with a data request.

Table S2. Area sprayed by herbicide active ingredients in 2007–2011.

Table S3. Area sprayed by herbicide active ingredients in 2010.

Table S4. Amount of herbicide active ingredients sprayed in 2007–2011.

Table S5. Amount of herbicide active ingredients sprayed in 2010.

Appendix S1. Survey and data analysis.