Invasive Plant Science and Management

www.cambridge.org/inp

Research Article

Cite this article: Hart M, Ritten J, and Mealor BA (2023) A ranching economic analysis of ventenata (*Ventenata dubia*) control in northeast Wyoming. Invasive Plant Sci. Manag **16**: 56–63. doi: 10.1017/inp.2023.8

Received: 8 August 2022
Revised: 24 January 2023
Accepted: 14 February 2023
First published online: 27 February 2023

Associate Editor:
Chelsea Carey, Point Blue Conservation Science

Keywords:
Invasive plant management; invasive species; *Ventenata dubia*

Author for correspondence:
Marshall Hart, University of Wyoming Sheridan Research and Extension Center, 1090 Dome Loop, Sheridan, WY 82801.
(Email: mhart12@uwyo.edu)

A ranching economic analysis of ventenata (*Ventenata dubia*) control in northeast Wyoming

Marshall Hart[1], John Ritten[2] and Brian A. Mealor[3]

[1]Research Assistant, University of Wyoming Sheridan Research and Extension Center, Sheridan, WY, USA; Institute for Managing Annual Grasses Invading Natural Ecosystems; [2]Professor, Department of Agricultural and Resource Economics, Colorado State University, Fort Collins, CO, USA and [3]Associate Professor and Director, University of Wyoming Sheridan Research and Extension Center, Sheridan, WY, USA; Institute for Managing Annual Grasses Invading Natural Ecosystems

Abstract

Invasive species pose a threat to the livelihoods of many people living on rangelands of the western United States. Invasive species impact many ecosystem goods and services of the areas they invade and represent one of the largest causes of habitat degradation. On private ranches, economic analyses often find that conservation practices, such as invasive species control, are not economically viable, in contrast to what is found at the landscape scale. In northeast Wyoming, ventenata [*Ventenata dubia* (Leers) Coss.] is a relatively new invader in the Great Plains ecoregion that threatens forage production on ranches. Our objective was to explore the economic costs of *V. dubia* for two options available to a ranch operation: purchasing extra hay to offset losses in forage and controlling *V. dubia* with herbicide. Using a partial budget analysis, we compare these two options in three invasion scenarios using a range of forage utilization rates and discount rates. Controlling *V. dubia* with herbicide was a cheaper option compared with purchasing additional hay in many cases. In fact, at 50% utilization, it is cheaper to control *V. dubia* in all of our scenarios at all discount rates given our assumptions. For lower grazing utilization rates, it becomes cheaper to purchase hay in some cases other than in our worst-case invasion scenario. In these cases, coordination among ranchers is needed to effectively control *V. dubia*. There are many ranch-specific differences that may make a different option more feasible, and we did not explore options of reducing herd sizes. However, our results suggest that controlling *V. dubia* can be an economically viable option under certain circumstances. Additional assistance in the form of a cost-share program, and facilitation of coordination is needed to overcome the difficulties of private management of invasive species.

Introduction

Many people rely on rangelands for their livelihoods and for ecosystem goods and services (EGS), including cultural and aesthetic needs (DiTomaso et al. 2017; Havstad et al. 2007; York et al. 2019). Invasive species are a major cause of global change and pose a threat to EGS provided by rangelands (DiTomaso et al. 2017; Finnoff et al. 2008; Olson 2006). Invasive plant species are one of the largest causes of biodiversity loss and habitat degradation (Olson 2006; Pimentel et al. 2005; Vitousek et al. 1997).

Introduction and spread of nonnative species is largely the result of human mobility and economic drivers, such as trade (Epanchin-Niell 2017; García-Llorente et al. 2008; Goodenough 2010; Holmes et al. 2009; Olson 2006; Pejchar and Mooney 2009; Sala et al. 2000; Vitousek et al. 1997). Land managers are often faced with multiple target species or populations, multiple control options with different trade-offs, and limited budgets (Carrasco et al. 2010; D'Antonio and Meyerson 2002; Epanchin-Niell 2017; Leung et al. 2002; McIntosh et al. 2010). Therefore, economic considerations of managing invasive species play a central role in determining how best to approach invasive species problems, including preventing introductions, prioritizing different species or populations, slowing spread, weighing control options, and comparing policy options and structures.

Although there is a clear need to prevent and manage invasive plants and their spread, many ranchers may not be able to do so, because prevention and management may be cost-prohibitive. Invasive species management may not be profitable for ranches (Tanaka et al. 2011). This potential lack of profitability seems contradictory with the general finding that invasive species prevention and control is beneficial (De Groot et al. 2013; Taylor et al. 2013). Part of the discrepancy is that invasive species exist on mosaics of public–private ownership, whereas most economic studies of invasion assess the problem at the landscape scale (Epanchin-Niell and Wilen 2015). From the private landowner perspective, each weighs the cost and benefits of management options on their own property (Epanchin-Niell 2017; Epanchin-Niell and Wilen 2015).

Management Implications

Generally, control of invasive species is shown to be economically beneficial at the landscape scale. However, within mosaics of public–private land ownership, control of invasive plants presents challenges that may make economic justification difficult. We calculated the cost of purchasing additional hay needed to maintain a 500-head cattle herd given three *Ventenata dubia* (ventenata) invasion scenarios. We then compared these costs with the cost of controlling *V. dubia* with indaziflam versus purchasing supplemental hay to replace forage lost to *V. dubia* invasion. *Ventenata dubia* management was economically feasible on ranches in northeast Wyoming in many cases. Information on the impacts of *V. dubia*, control options, and the long-term benefits to be had from control are likely persuasive to many landowners, because most landowners are interested in conservation of natural resources and ecosystem goods and services. However, when utilization of available forage or site productivity was low and where higher discount rates were used, purchasing supplemental hay was warranted over *V. dubia* control. In these cases, support and coordination among neighboring landowners is needed to overcome trade-offs between realized and potential losses due to further weed spread and to achieve effective landscape-scale control. Coordination works by aligning individuals' motives with their neighbors, thereby considering the costs and benefits to neighboring properties. In northeast Wyoming, the NRCS has also implemented a cost-share program to relieve much of the cost of control, making control even more realistic for most landowners.

As invasive species spread across the landscape, individual landowners incur only a subset of the total costs to the region. The damages invasive plants cause at larger scales far exceed the damages caused at smaller, parcel-level scales (Cook et al. 2010; Epanchin-Niell and Wilen 2015; Liu and Sims 2016). Some landowners may not be aware of the presence or impacts of invasive species and may tend not to act on invasive species until after they are affected directly by noticeably severe impacts (Johnson et al. 2011; Rajala et al. 2021).

Also important to consider is the long-term nature of prevention and control efforts. Conservation and invasive species control practices generally result in the intended benefits in terms of EGS, and for large entities such as governments and larger ranching operations, invasive species control can be justified at landscape scales (Liu and Sims 2016). However, many EGS are externalities that cannot be accounted for in a profit-driven ranch budget (Roche et al. 2021). Additionally, many control efforts are long-term investments that may not yield net benefits for many years, making them unprofitable for smaller private landowners (Dyer et al. 2021; McDermott et al. 2013). The risk of failure over the long term for individual control efforts is also often high, and ranchers may not be able to justify the repeated treatments necessary to maintain control (Hardegree et al. 2016; Monaco et al. 2017; Sheley et al. 2011).

In northeast Wyoming, ventenata [*Ventenata dubia* (Leers) Coss.] and medusahead [*Taeniatherum caput-medusae* (L.) Nevski] have recently been documented with self-sustaining populations in the Great Plains ecoregion (Garner and Lakes 2019; Hart and Mealor 2021). Ranches affected by invasive annual grasses are more likely to be forced to leave the livestock industry due to the necessity of procuring alternative feeds or decreasing stocking rates to suboptimal levels (Maher et al. 2013). *Ventenata dubia* is associated with reduced perennial forage while being unpalatable, making it a poor forage replacement and a threat to the large livestock industry of Wyoming and neighboring states (Hart and Mealor 2021). Ranchers in northeast Wyoming are therefore faced with a dilemma. Is it more cost-effective to control *V. dubia* with herbicide or purchase additional feed to offset forage losses?

To facilitate the management of *V. dubia* and *T. caput-medusae* in northeast Wyoming, the Northeast Wyoming Invasive Grass Working Group (NEWIGWG) was formed in early 2017. NEWIGWG is composed of agencies and landowners within the region, including the NRCS, country weed and pest offices, and the Nature Conservancy, among others (Sheridan County Weed and Pest 2017). NEWIGWG has been working to curtail the spread of *V. dubia* and *T. caput-medusae* in northeast Wyoming by implementing landscape-scale control efforts, engaging in community outreach and education, and implementing cost-share programs to help with management efforts. We explored the economic efficacy of *V. dubia* control by incorporating field-collected forage and control data for northeast Wyoming into an existing enterprise budget—a cow–calf (*Bos taurus* L.) operation. Our objective was to compare the cost of controlling *V. dubia* with herbicide to the cost of increasing supplemental hay feeding of cattle for a ranch operation in northeast Wyoming. We wanted to learn whether damages caused by *V. dubia* are high enough, and control costs low enough, to justify management on private ranches in the region.

Materials and Methods

The Enterprise Budget

To estimate the economic impacts of *V. dubia* management, we incorporated multiyear forage production data into an enterprise budget developed by University of Wyoming Extension that lists expected expenses and income of specific enterprises for a large (500-head), private land ranch in Major Land Resource Area 58b. This area is described as northern rolling high plains consisting of Campbell, Converse, Johnson, Natrona, Niobrara, Sheridan, and Weston counties of Wyoming, and Big Horn County, Montana (Dyer et al. 2018). We developed partial budgets to assess the economic impacts of *V. dubia* and subsequent control with herbicide compared with the baseline with no *V. dubia* impacts. Partial budgets are decision-making tools used to compare different options in terms of costs and benefits. They are divided into four components: added income, added costs, reduced income, and reduced costs.

Forage Estimates

Because the enterprise budget used here does not specify actual land area of the rangeland portion of the ranch (Dyer et al. 2018), we calculated the acreage based on 3 yr of rangeland biomass collections. The forage estimate was needed to estimate the cost of herbicide spraying, which depends on the spatial extent of land to be sprayed. We sampled rangeland forage production at five sites in Sheridan County, Wyoming, to estimate productivity and forage losses associated with *V. dubia* in the region. These sites were treated aerially with 73 g ai ha^{-1} of indaziflam in the fall of 2018, creating treated and nontreated sites adjacent to one another. These sites account for a wide range of productivity (Table 1) and environmental variability within the region (Table 2). In July of 2019, 2020, and 2021, we sampled four paired, treated and nontreated plots at each site. Each sampling plot was 30 m^2, and all plots at each site were within 100 m of one another. In each plot,

https://doi.org/10.1017/inp.2023.8 Published online by Cambridge University Press

Table 1. Perennial productivity of sites used to estimate available forage on treated (t) and nontreated (n) acres in Major Land Resource Area 58b.

Year	Productivity[a]							
	2019 (127%)		2020 (76%)		2021 (91%)		3-yr average	
	t	n	t	n	t	n	t	n
	kg ha^{-1}							
WC Ranch	1,998	1,169	1,348	554	1,093	818	1,479 (±270)	847 (±178)
LW Ranch	2,093	1,362	1,365	1,055	1,636	1,091	1,698 (±212)	1,169 (±97)
Ma Ranch North	1,061	1,015	537	582	821	399	806 (±151)	665 (±183)
Ma Ranch South	1,437	204	575	119	321	NA	778 (±338)	161 (±43)
CJ Ranch	2,656	1,608	906	545	1,433	833	1,665 (±518)	996 (±317)
Yearly average	1,849 (±276)	1,072 (±239)	946 (±179)	571 (±148)	1,061 (±232)	785 (±143)	1,285 (±164)	811 (±116)

[a]Productivity is kg ha^{-1} of air-dried biomass sampled in July. The 30-yr average annual precipitation in Sheridan county is 359.7 mm (14.2 in.). The percent of the 30-yr average is given in parentheses for each year. Standard error is given for each average in parentheses.

Table 2. Site information for *Ventenata dubia* removal study sites in Sheridan County, Wyoming.

Site	Soil type, slope, and topsoil texture	Aspect	Three most abundant perennial species	Annual precipitation
LW Ranch	Jonpol Platmak complex, 0%–9% slope, loam	Skyward	*Pascopyrum smithii* (Rydb.) Á. Löve *Symphyotrichum ericoides* (L.) G.L. Nesom *Sphaeralcea coccinea* (Nutt.) Rydb.	381–432 mm
Ma Ranch North	Shingle-Worfka-Samday complex, 6%–30% slope, clay-loam	North and northwest facing	*Pascopyrum smithii* *Danthonia unispicata* (Thurb.) Munro ex Macoun *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young	254–356 mm
Ma Ranch South	Samday-Hilight clay loam, 2%–45% slope, clay-loam	South facing	*Pascopyrum smithii* *Artemisia tridentata* ssp. *wyomingensis* *Opuntia polyacantha* Haw.	254–356 mm
CJ Ranch	Platmak loam, 3%–6% slope, loam	East-northeast facing	*Pascopyrum smithii* *Poa pratensis* L. *Symphyotrichum ericoides*	381–482 mm
WC Ranch	Jonpol-Platmak association, 9%–25% slope, loam	North facing	*Pascopyrum smithii* *Tragopogon dubius* Scop. *Pediomelum argophyllum* (Pursh) J. Grimes	381–482 mm

we haphazardly placed two 0.25-m^2 subplots. We collected all herbaceous aboveground biomass and separated it into the following functional groups: perennial grasses, annual grasses, perennial forbs, and annual forbs. We pooled biomass at the plot level for analysis. All biomass was air-dried in a forced-air oven at 60 C for 48 h and then weighed. We calculated total rangeland area for the ranch by estimating the average animal unit months (AUM; defined as 363 kg [800 lb] of air-dried forage) across these sites for a range of forage utilization levels: 25%, 35%, and 50% utilization of total available forage.

Invasion Scenarios

We calculated forage impacts for three invasion scenarios: low invasion, high invasion, and a worst-case scenario. Invasion size in these scenarios (20% of rangeland acres impacted for the low-invasion scenario, 80% for the high-invasion and worst-case scenarios) are somewhat arbitrary. Actual acreage will vary widely depending on suitability for *V. dubia* on any particular ranch. Between 2018 and 2022, NEWIGWG partners treated more than 40,500 ha (100,000 ac) of *V. dubia*– and *T. caput-medusae*–infested rangelands. Initially, several of our sites had extensive, mostly unbroken populations of *V. dubia*, meaning 80% of acres impacted is a reasonable estimate, while 20% allows for a low estimate of population expanse. We based our estimates of impacts on our field production data as well as reports and personal communication from weed and pest offices in the region. Of the impacted acres, ~60% are low population density infestations causing a 20% reduction in forage of those areas, ~10% are medium density causing a 40% reduction of forage on those areas, and the remaining ~30% have a high density of *V. dubia* causing an 80% reduction in forage. Using these estimates, we weighted the impacts based on their expected distribution. For example, in the low-invasion scenario, 12%, 2%, and 6% of rangelands (20% of the total rangeland) are affected by low, medium, and high densities of *V. dubia*, respectively. This invasion scenario causes an estimated 8% reduction (~231 AUM) of forage from the total rangeland AUM (2,890) provided by the baseline of the enterprise budget ($2{,}890*0.12*0.2 + 2{,}890*0.02*0.4 + 2{,}890*0.06*0.8 = 231.2$). In the high-invasion scenario, 80% of the area is impacted, causing an estimated 32% reduction (~925 AUM) of forage from rangelands. For the worst-case scenario, we still assumed that 80% of the area is impacted by *V. dubia*, but with a 50% reduction (1,445 AUM) of total forage; this represents our most extreme observations in the region.

Once we estimated our *V. dubia* impacts, we adjusted available AUM in the rangeland portion of the baseline enterprise budget to simulate a ranch invaded by *V. dubia* in the three scenarios above assuming that (1) perennial grasses on affected lands are still available forage, as we do not know at what point cattle will refuse to

https://doi.org/10.1017/inp.2023.8 Published online by Cambridge University Press

graze *V. dubia*; and (2) *V. dubia* is entirely unpalatable to cattle. For the purposes of illustration, we assume that any loss in AUM is what the ranch has been operating at up to the present. Therefore, the decision being made is whether to treat *V. dubia*, not prevent it. We also assume the rancher wishes to maintain the full size of their 500-cow herd. Other options for the ranch, such as reducing herd size to account for reduced grazing capacity, are not explored for this analysis.

Options for the Ranch

Because the rancher in our scenarios wishes to maintain the size of their herd, the loss of rangeland AUM must be offset by an equivalent amount of supplemental feed, +25% to account for losses associated with hay feeding. These losses can range from 25% to 30% for hay stored outdoors on the ground caused by continued plant respiration and microbial activity after baling, which are affected by moisture content at the time of baling, storage conditions, forage species, and environmental conditions (Lemus 2020). The additional hay needed to feed the herd is split evenly between meadow and alfalfa (*Medicago sativa* L.) hay (sensu Dyer et al. 2018). The price of this hay is US\$249 1,000 kg^{-1} (US\$226 U.S. ton^{-1}) of alfalfa and US\$222 1,000 kg^{-1} (US\$201 U.S. ton^{-1}) of meadow hay. These costs are the 3-yr averages (2019 to 2021) of inflation-adjusted market price for Wyoming (USDA-NASS 2021). One important point is that if excess hay that could be sold were produced on the ranch, we would need to account for the lower quality of *V. dubia*–infested hay. However, excess hay is not produced by this ranch, so accounting for lower-quality hay sold is not necessary.

Because our rangeland forage production estimates were derived from post-treatment data, we calculated that removal of *V. dubia* would return 100% of perennial forage species and lost AUM would completely return the year following herbicide application, bringing the costs and values to the baseline given by the unaffected model. However, results will likely vary across sites and with environmental variability. In other ecoregions with a mix of rhizomatous and bunchgrasses, an additional year to recover from invasion may be required. Cost of control is based on actual costs of applying indaziflam by helicopter for Sheridan County, including labor (US\$144 ha^{-1}; US\$58 ac^{-1}; NRCS and Sheridan County Weed and Pest Office, personal communication). We calculated costs associated with these options at the end of 3 yr, the time frame when the NRCS re-treats sites in northeast Wyoming. Suitability of rangelands for *V. dubia* will also vary widely on different ranches. Depending on how early *V. dubia* is detected, a ranch may see increases in its presence and associated impacts or may have a relatively stable population. For our scenarios, we assume that the *V. dubia* population and its associated costs remain stable, rather than increasing or decreasing from one year to the next.

To calculate the net present value (NPV) of the costs of each option in each scenario, we applied a range of discount rates. A discount rate is applied to take into account the time value of money: the concept that money is worth more now than the same amount of money in the future. We used discount rates of 3%, 5%, 7%, and 10% to account for a range of possibilities. Different discount rates can change the outcome of analyses. For example, a higher discount rate would make the present value of future hay purchases less, but would not change the value of treating *V. dubia* by applying herbicide, as that is an upfront cost. At a high enough discount rate, the cost of hay would be less than the upfront cost of herbicide application for *V. dubia*. Other discount rates may also be appropriate depending on available rates on operational loans and individual risk preference. Agricultural operations can often get a lower interest rate on operational loans, which could justify using a lower rate. However, a risky investment may justify a higher discount rate. For our selected rates, we applied a discount factor to the cost of each year to calculate the present value using the formula $PV = C_t/[(1 + r)^t]$, where PV is present value, r is the discount rate, and C_t is the cost at time t. For example, with a discount rate of 5%, a cost of \$100 in year 3 would be calculated as $100/[(1 + 0.05)^3]$, or 100/1.1576, which is ~US\$86 in present value.

Results and Discussion

Forage and Acreage Estimates

Based on our forage samples, our estimate for average July forage was 1,285 ± 164 kg ha^{-1} (~1,147 lb ac^{-1}) after herbicide treatment (Table 1). We used this estimate as our available forage, post *V. dubia* control. Using this forage estimate, at 50% utilization (1,285 kg ha^{-1} * 0.5 = 643 kg ha^{-1} forage utilized), we found that rangelands at our sites produce ~1.8 AUM ha^{-1} (643 kg ha^{-1}/363 kg AUM^{-1}). Therefore, our biomass production estimates indicate that we would need 1,633 ha (4,033 ac) to provide the 2,890 AUM of usable forage (2,890 AUM/1.8 AUM ha^{-1}) presented in the enterprise budget of Dyer et al. (2018). For 35% utilization, 2,331 ha (5,761 ac) are needed to provide the same AUM. At 25% utilization, 3,264 ha (8,066 ac) are needed.

In nontreated plots, perennial forage for July was 811 ± 116 kg ha^{-1} (~724 lb ac^{-1}). This is a drop in available forage of 37% of the 3-yr average. The lowest drop in forage seen in our study sites was about 4% on Ma Ranch North in 2019. Compare this with the highest drop, which was an 86% drop on Ma Ranch South, also in 2019. These data, along with the reports from weed and pest offices in Wyoming also experiencing *V. dubia* invasion, were used to formulate the three invasion scenarios outlined above.

Hay Costs

In the low-invasion scenario, 8% (231 AUM) of the rangeland AUM are lost due to *V. dubia* invasion. The amount of extra hay needed to supplement the lost grazing would be 104,900 kg (116 U.S. tons) split between alfalfa and meadow hay forages. An extra 52,400 kg (58 U.S. tons) of alfalfa at US\$249 1,000 kg^{-1} and 52,400 kg of meadow hay at US\$222 1,000 kg^{-1} adds an additional US\$24,679 to that spent on hay already in the baseline enterprise budget. This amount, which represents a 5.7% increase in annual operational costs over the baseline enterprise budget, would need to be spent every year the rancher decides not to control *V. dubia* or to explore other options (Table 3). In the high-invasion scenario, with 32% of forage lost (925 AUM), an additional 209,700 kg (231 U.S. tons) of alfalfa and 209,700 kg of meadow hay are needed to maintain the size of the herd each year. This hay amounts to US\$98,715 annually (Table 3), which is 22.9% added to the annual operational costs of the ranch. In the worst-case scenario, with 50% of forage lost (1,445 AUM), 327,700 kg (361 U.S. tons) each of meadow and alfalfa are needed. The cost of this hay would be US\$154,243 spent annually (Table 3), which is a 35.8% increase over the baseline operational costs of the ranch.

Control Costs

Because the cost of controlling *V. dubia* with herbicide is all incurred in Year 0, there are no future costs within the analysis

https://doi.org/10.1017/inp.2023.8 Published online by Cambridge University Press

Table 3. Hay costs under low-invasion, high-invasion, and worst-case scenarios of *Ventenata dubia* impacts for a 500-head, private land ranch in Major Land Resource Area 58b.[a]

Invasion scenario	Nominal annual hay cost	Discount rate	Year 0 present value	Year 1 present value	Year 2 present value	Year 3 present value
	US$	%		US$		
Low invasion	24,679	3	24,679	23,960	23,262	22,585
		5	24,679	23,504	22,384	21,319
		7	24,679	23,064	21,555	20,145
		10	24,679	22,435	20,396	18,542
High invasion	98,715	3	98,715	95,840	93,049	90,339
		5	98,715	94,015	89,538	85,274
		7	98,715	92,257	86,222	80,581
		10	98,715	89,741	81,583	74,166
Worst case	154,243	3	154,243	149,750	145,389	141,154
		5	154,243	146,898	139,903	133,241
		7	154,243	144,152	134,722	125,908
		10	154,243	140,221	127,473	115,885

[a]Nominal hay costs are presented, with various discount rates applied for 3 yr into the future.

Table 4. Herbicide application costs to control *Ventenata dubia* under low-invasion, high-invasion, and worst-case scenarios on a 500-head, private land ranch in Major Land Resource Area 58b.[a]

Utilization rate	Herbicide application cost		
	Low invasion	High invasion	Worst case
%		US$	
25	93,851	375,405	375,405
35	67,037	268,146	268,146
50	46,926	187,702	187,702

[a]Costs are calculated assuming the ranch has a fixed forage availability of 2,890 animal unit months (AUM), making lower utilization rates increase the land area of the grazed rangelands. The cost of applying indaziflam, our herbicide used, is US$143.77 ha $^{-1}$ (US$58.18 ac^{-1}).

time frame. Therefore, discount rates do not affect the cost of control options. Rather, the cost of this option is dependent upon the land area to be sprayed. The enterprise budget tool we used has a fixed quantity of rangeland forage, so different potential forage utilization rates affect the land area needed to provide the same amount of usable forage. At lower utilization rates, a larger land area is needed to provide the 2,890 AUM, while the same AUM can be provided on smaller areas that are utilized more completely. We calculated our lowest utilization rate (25%) to have 3,264 ha (8,066 ac) of rangeland, while the highest utilization rate (50%) had 1,633 ha (4,033 ac). At 35% utilization, we calculated that the ranch would require 2,331 ha (5,761 ac) of rangeland to provide the same amount of forage. Utilization is somewhat analogous to productivity, where lower annual productivity would also need a larger area to provide the same quantity of forage. The area to be sprayed also increases with increasing severity of invasion. In our low-invasion scenario, 20% of the calculated land area is invaded with *V. dubia* and needs to be sprayed. In both the high-invasion and worst-case scenarios, 80% of the land area will need to be sprayed. The cost of herbicide application in our analyses ranges from US $46,926 in our low-invasion scenario at 50% forage utilization to US$375,405 in our high-invasion and worst-case scenarios at 25% forage utilization (Table 4). These additional costs range from 10.9% to 87.2% of the baseline added to the operating costs of the ranch.

We assume that indaziflam is used as the herbicide sprayed to control *V. dubia*. Indaziflam, however, does not yield forage improvement until the year following application. By that time, additional hay would already need to be purchased for Year 0. Therefore, all options where *V. dubia* is controlled in our analyses must also include Year 0 hay costs. Afterward, forage is assumed to return to the baseline scenario, with no loss of forage or additional hay needed. This may not hold true for regions with fewer rhizomatous grasses and dry summers, where additional time may be necessary to fully recover.

Three-Year NPV

We calculated the NPV of each option after a 3-yr period, as that is when reapplication of indaziflam has typically been done in northeast Wyoming (Table 5; NRCS and Sheridan County Weed and Pest Office, personal communication). After the 3-yr period, it is cheaper to treat *V. dubia* with herbicide in the worst-case scenarios with all combinations of discount rates and utilization rates we analyzed (Table 5). However, aside from the worst case, it becomes more expensive to apply herbicide than to buy hay in any scenario with 25% utilization (Table 5). At 35% utilization, the lower discount rates (3% and 5%) result in hay that is more expensive over the 3-yr period than control, while higher discount rates (7% and 10%) result in hay that is cheaper over the 3 yr (Table 5). At 50% utilization, which is more typical of private land management plans, it is cheaper to control *V. dubia* than to purchase hay in all scenarios with our assumptions (Table 5).

We have provided a range of circumstances in our analyses that we believe reasonably captures variation within the northeast Wyoming region. Even so, each ranch is different, and our conclusions should not be applied outside of Major Land Resource Area 58b due to differences in productivity, ranching practices, regional economic differences, and potential differences in the impacts of *V. dubia* and its removal. In addition to regional differences, there are year-to-year variations to consider. We did not take into account yearly variation in cost of hay or herbicide. However, we have provided a reasonably conservative estimate for the amount of hay needed, and have provided a 3-yr average of hay prices that gives an accurate estimate of hay cost for northeast Wyoming. Due to the relatively short time frame of our analyses, we did not account for future costs of herbicide. The cost of control could vary considerably due to changes in herbicide price and area in need of retreatment.

https://doi.org/10.1017/inp.2023.8 Published online by Cambridge University Press

Table 5. A table of the costs of *Ventenata dubia* strategies (buy hay to offset forage losses or apply herbicide) at the end of a 3-yr period on a 500-head, private land ranch in Major Land Resource Area 58b.[a]

		Option cost (NPV over 3-yr chemical control)					
		8% forage loss		32% forage loss		50% forage loss	
Utilization rate	Discount rate	Buy hay	Apply herbicide	Buy hay	Apply herbicide	Buy hay	Apply herbicide
%		US$					
25	3	94,486	118,530	377,943	474,120	**590,536**	**529,648**
	5	91,886	118,530	367,542	474,120	**574,285**	**529,648**
	7	89,444	118,530	357,776	474,120	**559,025**	**529,648**
	10	86,052	118,530	344,206	474,120	**537,822**	**529,648**
35	3	**94,486**	**91,715**	**377,943**	**366,862**	**590,536**	**422,389**
	5	**91,886**	**91,715**	**367,542**	**366,862**	**574,285**	**422,389**
	7	89,444	91,715	357,776	366,862	**559,025**	**422,389**
	10	86,052	91,715	344,206	366,862	**537,822**	**422,389**
50	3	**94,486**	**71,604**	**377,943**	**286,418**	**590,536**	**341,945**
	5	**91,886**	**71,604**	**367,542**	**286,418**	**574,285**	**341,945**
	7	**89,444**	**71,604**	**357,776**	**286,418**	**559,025**	**341,945**
	10	**86,052**	**71,604**	**344,206**	**286,418**	**537,822**	**341,945**

[a]These options are displayed for a range of forage utilization rates, invasion impact severities, and discount rates. Each value represents the cost net present value (NPV) of each option assuming herbicide application costs of US\$143.77 ha $^{-1}$ (US\$58.18 ac^{-1}), productivity of these rangelands is 1,285 kg ha^{-1} (1,147 lb ac^{-1}), and hay costs of US\$221.62 1,000 kg^{-1} (US\$201.05 U.S. ton^{-1}) and US\$249.03 1,000 kg^{-1} (US\$225.92 U.S. ton^{-1}) for meadow and alfalfa hay, respectively. Bolded values represent where annual grass control is the cheaper option.

Another option we did not explore was to reduce the herd size of the ranch. Doing so may have different outcomes and impacts for different ranches. Other analyses examining decisions of whether to liquidate herds or feed extra hay during reductions in forage related to drought have found that there is no single correct decision, and both have merits (Bastian et al. 2009; Ritten et al. 2010). Decreasing herd size may be a long-term option to consider, but comes with other considerations. In other economic analyses exploring the effects of invasive species on ranches, those threatened with cheatgrass (*Bromus tectorum* L.) invasion were more likely to be forced from the industry due to decreased optimal stocking rates and alternative feed costs (Maher et al. 2013). Their study, as well as ours presented here, demonstrates the economic dangers of invasive annual grasses for ranches.

Importantly, none of these options are as ideal as the baseline ranch without any *V. dubia* impacts. We assumed that *V. dubia* would remain stable in the no-control option, but in many cases, ranchers may find that their invasive grass population is increasing, leading to larger economic impacts. In our analyses, comparing low-invasion with high-invasion scenarios shows a greater proportional benefit at low invasion. In other words, the benefits of controlling *V. dubia* are greater when the population is small. This finding is consistent with the literature, which shows that as invasive species spread, their impacts increase exponentially (Epanchin-Niell and Wilen 2015). Other costs analyses have also found that the cost-effectiveness of given actions is highest on healthy rangelands rather than those already degraded (Taylor et al. 2013). It is important to note, however, that in our analyses, the benefits are greater in the worst-case scenario than in the high-invasion scenario, as the impacts are greater, but the affected area to be treated does not change.

Overcoming Challenges

Unfortunately, invasive species prevention and management are inherently complex social issues. The differences between costs and benefits to the individual versus those of their neighbors and broader society make controlling invasive species that exist on mosaics of private properties, public lands, and multiple jurisdictions more complex and difficult (Epanchin-Niell and Wilen 2015; Grimsrud et al. 2008; Perrings 2002; Rich et al. 2005; Siriwardena et al. 2018). Moving from centrally organized invasive plant management to individual management creates misaligned control incentives that favor personal profits over the collective goals of invasive species management (Cook et al. 2010; Liu and Sims 2016). Invasive species management is also characterized as a "weakest link" problem. This means that the effectiveness of management is only as strong as the least effective "link" (Perrings et al. 2002). If one neighbor decides to control an invasive plant, it is linked with their neighbors' actions, affecting both the efficacy of their own control options and the benefits that could be attained (Grimsrud et al. 2008). Because of these factors, invasive species are usually suboptimally controlled on private property, and cooperation and coordination are required to reach maximum benefits (Epanchin-Niell and Wilen 2015; McDermott et al. 2013).

There are a few potential solutions to these problems with invasive species management. One is to provide necessary support for the weakest link (Perrings et al. 2002). The NRCS has implemented a cost-share program for the purpose of controlling *V. dubia* and other invasive annual grasses in Wyoming. The program can greatly reduce the cost to ranchers who elect to control *V. dubia* (Sheridan Country USDA-NRCS Field Office and Sheridan County Weed and Pest, personal communication). These kinds of economic incentives attempt to encourage ranchers to implement conservation practices. In effect, when accounting for this cost-share program in our analysis, it becomes cheaper to control *V. dubia* than to purchase hay in all scenarios.

This study has demonstrated that *V. dubia* control is economically viable under our assumptions in the region of study. However, there are some cases where *V. dubia* control does not fit within the budget of ranchers. To obtain effective control over multiple private lands, the weakest link problem must be addressed. A cost-share program has shown some success for *V. dubia* control in this region by making control a more economically viable option. Programs facilitating organization and cooperation on invasive species control should also be supported. In this way, more effective landscape-scale management can be obtained.

https://doi.org/10.1017/inp.2023.8 Published online by Cambridge University Press

Acknowledgments. We thank the NRCS and the Sustainable Rangelands Roundtable for primary funding of this research. The Nature Conservancy provided partial support for this work through the Nebraska chapter's J.E. Weaver Competitive Grants Program. This research was supported in part by the intramural research program of the U.S. Department of Agriculture–National Institute of Food and Agriculture, Hatch accession no. 1013280 and McIntire-Stennis accession no. 7001691. We also thank the ranching families (names redacted for privacy) for allowing our research to take place on their properties. Finally, we thank Wyoming Game and Fish, Wyoming State Lands, Wyoming Agricultural Experiment Station, John Ritten, Beth Fowers, Jordan Skovgard, Jaycie Arndt, Jodie Crose, Tyler Jones, Shawna LaCoy, Nancy Webb, Heidi Schueler, Steve Paisley, Kelsey Crane, and Kerry White for their contributions to this research in the lab and field. No conflicts of interest have been declared.

References

Bastian CT, Ponnamaneni P, Mooney S, Ritten JP, Frasier WM, Paisley SI, Michael AS, Umberger WJ (2009) Range livestock strategies given extended drought and different price cycles. J Am Soc Farm Manag Rural Appraisers 72:153–163

Carrasco LR, Mumford JD, MacLeod A, Knight JD, and Baker RHA (2010) Comprehensive bioeconomic modelling of multiple harmful non-indigenous species. Ecol Econ 69:1303–1312

Cook DC, Liu S, Murphy B, Lonsdale WM (2010) Adaptive approaches to biosecurity governance. Risk Anal 30:1303–1314

D'Antonio C, Meyerson LA (2002) Exotic plant species as problems and solutions in ecological restoration: a synthesis. Restor Ecol 10:703–713

De Groot RS, Blignaut J, Van Der Ploeg S, Aronson J, Elmqvist T, Farley J (2013) Benefits of investing in ecosystem restoration. Conserv Biol 27:1286–1293

DiTomaso JM, Monaco TA, James JJ, Firn J (2017) Invasive plant species and novel rangeland systems. Pages 429–465 *in* Briske D, ed. Rangeland Systems. Cham, Switzerland: Springer

Dyer H, Kirkpatrick H, Hilken T, Roberts K, Maher A, Ashwell NQ, Feuz B, Tanaka J, Ritten, J, Maczko K (2018) MLRA 58b. University of Wyoming Extension Publication B-1332.35

Dyer H, Maher AT, Ritten JP, Tanaka J, Maczko K (2021) Ranch profitability of improving soil health on rangelands. Rangeland Ecol Manag 77:66–74

Epanchin-Niell RS (2017) Economics of invasive species policy and management. Biol Invasions 19:3333–3354

Epanchin-Niell RS, Wilen JE (2015) Individual and cooperative management of invasive species in human-mediated landscapes. Am J Agric Econ 97: 180–198

Finnoff D, Strong A, Tschirhart J (2008) A bioeconomic model of cattle stocking on rangeland threatened by invasive plants and nitrogen deposition. Am J Agric Econ 90:1074–1090

García-Llorente M, Martín-López B, González JA, Alcorlo P, Montes C (2008) Social perceptions of the impacts and benefits of invasive alien species: implications for management. Biol Conserv 141:2969–2983

Garner L, Lakes S (2019) Early Detection and Rapid Response to New Invasive Grasses in North Central Wyoming. U.S. Fish and Wildlife Service Report for the National Invasive Species Council Secretariat. https://www.doi.gov/sites/doi.gov/files/uploads/wyoming_invasive_grasses_report.pdf. Accessed: March 11, 2021

Goodenough A (2010) Are the ecological impacts of alien species misrepresented? A review of the "native good, alien bad" philosophy. Community Ecol 11:13–21

Grimsrud KM, Chermak JM, Hansen J, Thacher JA, Krause K (2008) A two-agent dynamic model with an invasive weed diffusion externality: an application to yellow starthistle (*Centaurea solstitialis* L.) in New Mexico. J Environ Manag 89:322–335

Hardegree SP, Jones TA, Roundy BA, Shaw NL, Monaco TA (2016) Assessment of range planting as a conservation practice. Rangeland Ecol Manag 69: 237–247

Hart MT, Mealor BA (2021) Effects of *Ventenata dubia* removal on rangelands of northeast Wyoming. Invasive Plant Sci Manag 14:156–163

Havstad KM, Peters DP, Skaggs R, Brown J, Bestelmeyer B, Fredrickson E, Herrick J, Wright J (2007) Ecological services to and from rangelands of the United States. Ecol Econ 64:261–268

Holmes TP, Aukema JE, Von Holle B Liebhold A, Sills E (2009) Economic impacts of invasive species in forests. The Year in Ecology and Conservation Biology. Ann NY Acad Science 1162:18–38

Johnson DD, Davies KW, Schreder PT, Chamberlain AM (2011) Perceptions of ranchers about medusahead (*Taeniatherum caput-medusae* (L.) Nevski) management on sagebrush steppe rangelands. Environ Manag 48:400–417

Lemus R (2020) Hay Storage: Dry Matter Losses and Quality Changes. Mississippi State University Extension Publication 2540. 8 p

Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proc R Soc London B 269:2407–2413

Liu Y, Sims C (2016) Spatial-dynamic externalities and coordination in invasive species control. Resour Energy Econ 44:23–38

Maher AT, Tanaka JA, Rimbey N (2013) Economic risks of cheatgrass invasion on a simulated eastern Oregon ranch. Rangeland Ecol Manag 66:356–363

McDermott SM, Irwin RE, Taylor BW (2013) Using economic instruments to develop effective management of invasive species: insights from a bioeconomic model. Ecol Appl 23:1086–1100

McIntosh CR, Shogren JF, Finnoff DC (2010) Invasive species and delaying the inevitable: valuation evidence from a national survey. Ecol Econ 69:632–640

Monaco TA, Mangold JM, Mealor BA, Mealor RD, Brown CS (2017) Downy brome control and impacts on perennial grass abundance: a systematic review spanning 64 years. Rangeland Ecol Manag 70:396–404

Olson LJ (2006) The economics of terrestrial invasive species: a review of the literature. Agric Resour Econ Rev 35:178–194

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends Ecol Evol 24:497–504

Perrings C, Williamson M, Barbier EB, Delfino D, Dalmazzone S, Shogren J, Simmons P, Watkinson A (2002) Biological invasion risks and the public good: an economic perspective. Conserv Ecol 6:1–7

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52:273–288

Rajala K, Sorice MG, Toledo D (2021) Gatekeepers of transformation: private landowners evaluate invasives based on impacts to ecosystem services. Ecosphere 12:e03652

Rich KM, Winter-Nelson A, Brozović N (2005) Modeling regional externalities with heterogeneous incentives and fixed boundaries: applications to foot and mouth disease control in South America. Rev Agric Econ 27:456–464

Ritten JP, Frasier WM, Bastian CT, Paisley SI, Smith MA, Mooney S (2010) A multi-period analysis of two common livestock management strategies given fluctuating precipitation and variable prices. J Agric Appl Econ 42:177–191

Roche LM, Saitone TL, Tate KW (2021) Rangeland ecosystem service markets: panacea or wicked problem? Front Sustain Food Syst 5:95

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R, Lodge DM, Mooney HA, Oesterheld M, Poff NL, et al. (2000) Global biodiversity scenarios for the year 2100. Science 287:1770–1774

Sheley RL, James JJ, Rinella MJ, Blumenthal D, DiTomaso JM, Briske DD (2011) Invasive plant management on anticipated conservation benefits: a scientific assessment. Pages 291–336 *in* Briske D, ed. Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps. Washington, DC: USDA-NRCS

Sheridan County Weed and Pest (2017) Northeast Wyoming Invasive Grasses Working Group. https://www.scweeds.com/newigwg. Accessed: March 3, 2022

Siriwardena SD, Cobourn KM, Amacher GS, Haight RG (2018) Cooperative bargaining to manage invasive species in jurisdictions with public and private lands. J For Econ 32:72–83

Tanaka JA, Brunson M, Torell LA (2011) A social and economic assessment of rangeland conservation practices. Pages 371–422 *in* Briske D, ed. Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps. Washington, DC: USDA-NRCS

Taylor MH, Rollins K, Kobayashi M, Tausch RJ (2013) The economics of fuel management: wildfire, invasive plants, and the dynamics of sagebrush rangelands in the western United States. J Environ Manag 126:157–173

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service (2021) Home page. https://www.nass.usda.gov/index.php. Accessed: November 29, 2021

Vitousek PM, D'Antonio, CM, Loope LL, Rejmanek M, Westbrooks R (1997) Introduced species: a significant component of human-caused global change. NZ J Ecol 21:1–16

York EC, Brunson MW, Hulvey KB (2019) Influence of ecosystem services on management decisions by public land ranchers in the intermountain west, United States. Rangeland Ecol Manag 72:721–728