CONSERVATION ISSUES

Herbicide Effects on Ground-Layer Vegetation in Southern Pinelands, USA: A Review

Andrea R. Litt[1]
Brenda J. Herring[2]
Louis Provencher[3]

The Nature Conservancy
Longleaf Pine Restoration Project
P.O. Box 875
Niceville, FL 32588-0875 USA

[1] Current address: School of Renewable Natural Resources, University of Arizona, Tucson, AZ 85721 USA

[2] Current address: Florida Natural Areas Inventory, 1018 Thomasville Road, Tallahassee, FL 32303-6237 USA

[3] Corresponding author current address: Disney Wilderness Preserve, The Nature Conservancy, 2700 Scrub Jay Trail, Kissimmee, FL 34759 USA
Lprovencher@tnc.org

Natural Areas Journal 21:177–188

ABSTRACT: Despite the fact that herbicides are widely used across the southeastern United States, their effects on ground-layer vegetation (woody and herbaceous species <1.4 m tall) are not well understood. We conducted a literature review to examine published studies and compile available data. More than 125 studies were examined, based on several criteria (e.g., a sound experimental design, quantitative data, study conducted in southern pinelands). Only 21 studies were retained for our review, and the majority of studies were conducted in pine plantations. Few clear, consistent results were revealed, probably due in large part, to the wide array of herbicides and diverse response variables examined in the studies. Woody plant cover generally declined with herbicide application, an expected result from use of hardwood-specific herbicides in most studies, but results for herbaceous plant cover were mixed. Most studies showed a decrease in total (woody and herbaceous plant) species richness. We also examined the response of plant species of special concern to herbicide application. Most species declined, while wiregrass (*Aristida beyrichiana* Trinius and Ruprecht [syn. *A. stricta* Michx. *s.i.*]) showed mixed responses across studies. Because our findings show that few studies have been conducted under natural conditions, experimental design shortfalls have been common, and study conclusions have been widely divergent, we suggest that research precede extensive herbicide use in pinelands.

Index terms: ground-layer vegetation, herbicides, southern pinelands, threatened and endangered species

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) forests once dominated the landscape of the southeastern United States. In their natural state, these open-structured forests have a high diversity of ground-layer plant species (woody and herbaceous plants <1.4 m tall) and are maintained by periodic fire. These habitats are some of the most species-rich in the world, outside of the tropics (Peet and Allard 1993). Today, only 2% of the longleaf pine landscape remains, much of which is fragmented and fire-suppressed (Myers 1990).

Reduction of hardwood encroachment into the midstory, which has occurred in the absence of fire, is very important for the purpose of maintaining diversity and populations of threatened and endangered species, as well as for pine production. Opening the midstory can be accomplished with prescribed fire; however, due to certain management obstacles (e.g., smoke management, need for rapid hardwood reduction, concern about damage to pines), alternative methods have been explored (e.g., mechanical felling/girdling, herbicide application). Care must be taken when using these methods, because there is a likelihood of loss of nontarget species when using mechanical techniques and herbicide application.

Herbicides were applied to nearly 226,000 ha (552,000 acres) of forest lands in the Southeast in 1992 to control woody and herbaceous plant species (Fallis 1993). While herbicide application is a generally accepted and widely used practice for site preparation in establishment and maintenance of pine plantations, little is known about herbicide effects on nontarget plant species in natural pinelands. Our goal was to compile published data and document the effect of different herbicides on ground-layer vegetation in southeastern pinelands, focused on systems dominated by longleaf pine.

METHODS

We conducted an intensive literature search on the effects of herbicides on ground layer vegetation in southern pinelands. We identified publications through computerized and traditional literature searches and by communicating with experts. Included studies had to have a valid experimental design (i.e., a no-treatment control and replicates); be conducted in sandhills (communities on xeric sand ridges supporting high pine; Myers 1990), flatwoods (communities on poorly drained, acidic sandy soils with open pine forests; Abrahamson and Hartnett 1990), or pine plantations in the Southeast; and include quantitative data for ground-layer plant species groups or particular species of interest (e.g., threatened and endangered plant species). Threatened and endangered plant species were identified using federal, state, and Nature Conservancy Natural Heritage ranks for the region (Mississippi Natural Heritage Program 1997, Marois 1998). Wiregrass (*Aristida beyrichiana* Trinius & Ruprecht, formerly *Aristida stricta* Michx. [Peet 1993]) was added to this group for examination since it is potentially sensitive to soil disturbance (Clewell 1989) and is a focal species in fire management and conservation of longleaf pine systems. We also eliminated from consideration wildlife food plot and pure weed control studies.

We examined over 125 studies, from which 21 were retained for analysis. Data were extracted from text, figures, and/or tables in each study, and some grouping of data was performed to facilitate analysis. (A detailed appendix of data is available by contacting Lprovencher@tnc.org). Plant species/life forms were grouped into five categories: (1) total species; (2) herbaceous species (includes forbs, legumes, non-legumes, ferns, and other herbaceous plants); (3) woody species (includes arborescent, non-arborescent, woody, and semi-woody plants); (4) graminoid species (includes grasses, sedges, and grasslike plants); and (5) woody vines. Response variables were grouped into species richness, Shannon diversity, Simpson diversity, importance value, cover, density, frequency, or biomass. Some response variables were not included due to infrequent use in the studies examined (e.g., Hill's index). No data were included regarding pines or oaks (*Quercus* L. spp.) (e.g., height, mortality), as we were only interested in the impacts on the ground-layer plant community. We only included data corresponding to no-treatment control and herbicide treatment plots (i.e., no combination treatments such as herbicide + fertilization). If multiple years of data were provided, we only included data from immediate post-treatment and the last year of the study, and these values were averaged to reduce complexity.

Some studies reported means adjusted for pre-treatment condition, but most did not. The pre-treatment effect for control and treated areas was accounted for by calculating:

$(X_{post\text{-}treatment} - X_{pre\text{-}treatment}) / X_{pre\text{-}treatment}$.

We then calculated the percent change in value compared to the control (impact of the herbicide),

$100 * [(X_{treatment} - X_{control}) / X_{control}]$,

to obtain a relative measure. All data were grouped by two natural habitats (flatwoods and sandhills) and one artificial habitat (pine plantation), herbicide, response variable, and category. For studies using the same herbicide, we compiled data by calculating the weighted average (weighted by the number of replicates, n_i) of the percent change in value, $[(X_1 * n_1) + (X_2 * n_2) + ... + (X_i * n_i)] / (n_1 + n_2 + ... + n_i)]$.

RESULTS

Overview

A striking result of this literature survey is the small number of studies that document herbicide effects on ground-layer plants in southern pinelands. Paucity of data is especially evident in natural flatwoods and sandhills, where we found, respectively, three and seven studies (Table 1). Moreover, at least six different herbicides were used among these studies. A greater number of studies occurred in pine plantations where weed control was the main objective for herbicide application (Table 1). Despite the greater number of studies involved, a greater number of herbicides and unique herbicide combinations were also employed in pine plantations, sometimes repeatedly. This great heterogeneity hindered generalizations across studies.

Flatwoods

All herbicides used in flatwoods reduced species richness and cover of herbaceous and woody ground-layer plants (Table 1). The weakest effect was a 5.1% decrease in herbaceous species richness compared to the control due to Pronone® (Wilkins et al. 1993a). The strongest effect was a decline of 71.8% in total species richness using a mixture of sulfometuron, glyphosate, and triclopyr (Neary et al. 1991). In the one study that documented effects on cover, both herbaceous (27.2%) and woody vegetation (58.6%) declined after Pronone® application (Wilkins et al. 1993a).

Sandhills

Herbicide effects on ground-layer plants were more heterogeneous in sandhills. As expected, ground-layer woody cover and density decreased following hexazinone application (10.3% to 55.9% depending on herbicides) (Boyer 1990; Wilkins et al. 1993a, b; Brockway et al. 1998; Provencher et al. 2001; Provencher et al., unpubl. data), whereas woody biomass increased by 105.3% with 2,4 D (Kush et al. 1999) (Table 1). Graminoid density and cover increased with ULW® and Velpar-L® application (Wilkins et al. 1993b; Brockway et al. 1998; Provencher et al. 2001; Provencher et al., unpubl. data). Herbaceous plant cover experienced mixed effects: 49.8% increase with ULW® (Brockway et al. 1998; Provencher et al., unpublished data) as compared to 33% and 21.5% decreases with Pronone® and Velpar-L®, respectively (Wilkins et al. 1993a, b; Brockway et al. 1998).

The effect on ground-layer species richness depended on the herbicide used (type and application rate) in the different studies. Pronone® and ULW® decreased species richness by 55.2% (herbaceous species; Wilkins et al. 1993a) and 81% (total species; Brockway et al. 1998, Provencher at al. 2001), respectively, whereas 2,4 D and Velpar-L® resulted in moderate increases by 6.4% and 12% (total species; Brockway et al. 1998, Kush et al. 1999).

Pine Plantations

Due to the large number of herbicides, unique combinations used, and the heterogeneity of response variables, it was difficult to find commonality in results of the studies we examined (Table 1). Most herbicides increased herbaceous species richness, with values ranging from 10.5% (dicamba + 2,4 D) to 84.7% (picloram) (Miller et al. 1999). Not surprisingly, woody species richness was negatively affected by

Table 1. The number of studies, total number of replicates (N), average percent change (averaged by habitat and herbicide), and the respective study reference for each response variable, categorized by habitat and herbicide.

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
FLATWOODS					
Hexazinone (Pronone)	**Species richness**				
	Herbaceous	1	9	-5.1	Wilkins et al. 1993a
	Woody	1	9	-35.6	Wilkins et al. 1993a
	Cover				
	Herbaceous	1	9	-27.2	Wilkins et al. 1993a
	Woody	1	9	-58.6	Wilkins et al. 1993a
Sulfometuron methyl + sulfometuron methyl + glyphosate + glyphosate + [glyphosate + triclopyr] (repeated)	**Species richness**				
	Total	1	108	-71.8	Neary et al. 1991
Sulfometuron methyl + triclopyr	**Species richness**				
	Total	1	150	-30.2	Neary et al. 1991
SANDHILLS					
2,4 D	**Species richness**				
	Total	1	3	6.4	Kush et al. 1999
	Herbaceous	1	3	3.3	Kush et al. 1999
	Woody	1	3	6.5	Kush et al. 1999
	Graminoids	1	3	6.7	Kush et al. 1999
	Woody vines	1	3	30.0	Kush et al. 1999
	Density				
	Woody	1	3	67.1	Boyer 1990
	Biomass				
	Total	1	3	82.7	Kush et al. 1999
	Herbaceous	1	3	14.2	Kush et al. 1999
	Woody	1	3	105.4	Kush et al. 1999
	Woody vines	1	3	12.3	Kush et al. 1999
Hexazinone (Pronone)	**Species richness**				
	Herbaceous	1	9	-55.2	Wilkins et al. 1993a
	Woody	1	9	-42.9	Wilkins et al. 1993a
	Cover				
	Total	1	4	111.7	Berish 1996
	Herbaceous	1	9	-33.0	Wilkins et al. 1993a
	Woody	1	9	-55.9	Wilkins et al. 1993a
Hexazinone (ULW)	**Species richness**				
	Total	2	11	-80.9	Brockway et al. 1998, Provencher et al. 2001
	Shannon diversity				
	Total	1	5	125.4	Brockway et al. 1998
	Cover				
	Total	1	4	333.9	Berish 1996
	Herbaceous	2	11	49.8	Brockway et al. 1998, Provencher et al., unpublished data

Table 1, *continued*

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
	Woody	2	11	-36.2	Brockway et al. 1998, Provencher et al., unpublished data
	Graminoids	2	11	96.3	Brockway et al. 1998, Provencher et al., unpublished data
	Density				
	Herbaceous	1	6	15.5	Provencher et al. 2001
	Woody	1	6	-23.1	Provencher et al. 2001
	Graminoids	1	6	26.1	Provencher et al. 2001
	Woody vines	1	6	-14.0	Provencher et al. 2001
Hexazinone (Velpar L)	**Species richness**				
	Total	1	10	11.9	Brockway et al. 1998
	Shannon diversity				
	Total	1	5	18.6	Brockway et al. 1998
	Cover				
	Total	1	4	136.4	Berish 1996
	Herbaceous	2	19	-21.5	Brockway et al. 1998, Wilkins et al. 1993b
	Woody	2	19	-10.3	Brockway et al. 1998, Wilkins et al. 1993b
	Graminoids	2	19	698.3	Brockway et al. 1998, Wilkins et al. 1993b
PINE PLANTATIONS					
Dicamba + 2,4 D	**Species richness**				
	Total	1	4	-3.6	Miller et al. 1999
	Herbaceous	1	4	10.5	Miller et al. 1999
	Woody	1	4	-4.4	Miller et al. 1999
	Graminoids	1	4	-3.1	Miller et al. 1999
	Woody vines	1	4	-12.5	Miller et al. 1999
	Simpson diversity				
	Total	1	4	-2.2	Miller et al. 1999
	Shannon diversity				
	Total	1	4	-7.1	Miller et al. 1999
	Importance value				
	Herbaceous	1	4	-27.4	Miller et al. 1999
	Woody	1	4	8.4	Miller et al. 1999
	Graminoids	1	4	14.3	Miller et al. 1999
	Woody vines	1	4	-7.3	Miller et al. 1999
	Density				
	Woody	1	4	-50.0	Miller et al. 1999
Glyphosate (Roundup)	**Species richness**				
	Total	2	7	8.7	Boyd et al. 1995, Miller et al. 1999
	Herbaceous	2	7	43.8	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-6.6	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	12.9	Boyd et al. 1995, Miller et al. 1999
	Woody vines	2	7	8.6	Boyd et al. 1995, Miller et al. 1999
	Simpson diversity				
	Total	2	7	-0.3	Boyd et al. 1995, Miller et al. 1999
	Shannon diversity				
	Total	2	7	3.2	Boyd et al. 1995, Miller et al. 1999

Table 1, *continued*

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
Importance value					
	Herbaceous	2	7	16.0	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-2.3	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	33.3	Boyd et al. 1995, Miller et al. 1999
	Woody vines	2	7	-0.6	Boyd et al. 1995, Miller et al. 1999
	Density				
	Woody	2	7	-62.3	Boyd et al. 1995, Miller et al. 1999
Glyphosate + sulfometuron + sulfometuron + glyphosate (repeated as needed)	**Simpson diversity**				
	Total	1	4	74.9	Zutter et al. 1987
	Shannon diversity				
	Total	1	4	-28.7	Zutter et al. 1987
	Cover				
	Herbaceous	1	4	-84.3	Zutter et al. 1987
	Biomass				
	Herbaceous	1	4	-95.3	Zutter et al. 1987
Hexazinone (Pronone)	**Species richness**				
	Total	4	17	-11.2	Boyd et al. 1995, Blake 1986, Hurst and Blake 1987, Miller et al. 1999
	Herbaceous	2	7	38.4	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-3.3	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	6.0	Boyd et al. 1995, Miller et al. 1999
	Woody vines	2	7	-6.4	Boyd et al. 1995, Miller et al. 1999
	Simpson diversity				
	Total	2	7	-1.7	Boyd et al. 1995, Miller et al. 1999
	Shannon diversity				
	Total	2	7	1.2	Boyd et al. 1995, Miller et al. 1999
	Importance value				
	Herbaceous	2	7	19.4	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-8.8	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	8.5	Boyd et al. 1995, Miller et al. 1999
	Woody vines	2	7	9.9	Boyd et al. 1995, Miller et al. 1999
	Density				
	Woody	2	7	0.8	Boyd et al. 1995, Miller et al. 1999
	Biomass				
	Total	1	5	-26.4	Blake 1986
Hexazinone (ULW) + sulfometuron + glyphosate + glyphosate + sulfometuron	**Density**				
	Woody	1	3	-82.7	Haywood et al. 1997
	Woody vines	1	3	35.8	Haywood et al. 1997
	Biomass				
	Herbaceous	1	3	-95.3	Haywood et al. 1997
Hexazinone (Velpar L)	**Species richness**				
	Total	4	17	-7.3	Boyd et al. 1995, Blake 1986, Hurst and Blake 1987, Miller et al. 1999
	Herbaceous	2	7	24.3	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-12.2	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	-16.7	Boyd et al. 1995, Miller et al. 1999

Table 1, *continued*

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
	Woody vines	2	7	0.7	Boyd et al. 1995, Miller et al. 1999
	Simpson diversity				
	Total	2	7	-5.6	Boyd et al. 1995, Miller et al. 1999
	Shannon diversity				
	Total	2	7	-8.4	Boyd et al. 1995, Miller et al. 1999
	Importance value				
	Herbaceous	2	7	57.7	Boyd et al. 1995, Miller et al. 1999
	Woody	2	7	-15.9	Boyd et al. 1995, Miller et al. 1999
	Graminoids	2	7	38.1	Boyd et al. 1995, Miller et al. 1999
	Woody vines	2	7	25.0	Boyd et al. 1995, Miller et al. 1999
	Density				
	Woody	2	7	47.0	Boyd et al. 1995, Miller et al. 1999
	Biomass				
	Total	1	5	-21.9	Blake 1986
Hexazinone (Velpar L) + triclopyr ester + imazapyr + glyphosate	**Species richness**				
	Herbaceous	1	6	20.0	Harrington and Edwards 1999
	Cover				
	Herbaceous	1	6	1.9	Harrington and Edwards 1999
	Woody	1	6	-81.3	Harrington and Edwards 1999
	Graminoids	1	6	-113.2	Harrington and Edwards 1999
	Woody vines	1	6	129.0	Harrington and Edwards 1999
	Density				
	Total	1	6	110.6	Harrington and Edwards 1999
Imazapyr (Arsenal)	**Species richness**				
	Total	1	3	-2.7	Boyd et al. 1995
	Herbaceous	1	3	13.5	Boyd et al. 1995
	Woody	1	3	-17.3	Boyd et al. 1995
	Graminoids	1	3	-3.3	Boyd et al. 1995
	Woody vines	1	3	33.33	Boyd et al. 1995
	Simpson diversity				
	Total	1	3	-9.8	Boyd et al. 1995
	Shannon diversity				
	Total	1	3	-7.5	Boyd et al. 1995
	Importance value				
	Herbaceous	1	3	45.4	Boyd et al. 1995
	Woody	1	3	52.5	Boyd et al. 1995
	Graminoids	1	3	30.2	Boyd et al. 1995
	Woody vines	1	3	-3.6	Boyd et al. 1995
	Density				
	Woody	1	3	-60.6	Boyd et al. 1995
Picloram	**Species richness**				
	Total	1	4	-3.6	Miller et al. 1999
	Herbaceous	1	4	84.7	Miller et al. 1999
	Woody	1	4	-0.5	Miller et al. 1999
	Graminoids	1	4	-10.8	Miller et al. 1999
	Woody vines	1	4	-6.3	Miller et al. 1999

Table 1, *continued*

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
	Simpson diversity				
	Total	1	4	-2.2	Miller et al. 1999
	Shannon diversity				
	Total	1	4	-7.1	Miller et al. 1999
	Importance value				
	Herbaceous	1	4	133.3	Miller et al. 1999
	Woody	1	4	9.7	Miller et al. 1999
	Graminoids	1	4	0.0	Miller et al. 1999
	Woody vines	1	4	-12.7	Miller et al. 1999
	Density				
	Woody	1	4	-65.0	Miller et al. 1999
Sulfometuron + glyphosate	**Cover**				
	Herbaceous	1	10	-11.5	Lauer and Glover 1998
	Woody	1	10	-7.7	Lauer and Glover 1998
Sulfometuron (annually for 11 years) + glyphosate (annually for 3 years)	**Cover**				
	Herbaceous	1	5	-86.7	Zutter and Miller 1998
	Woody	1	5	-27.7	Zutter and Miller 1998
Sulfometuron + sulfometuron + glyphosate + glyphosate + glyphosate	**Cover**				
	Herbaceous	1	4	-97.5	Zutter et al. 1986
	Woody	1	4	-66.7	Zutter et al. 1986
	Biomass				
	Herbaceous	1	4	-99.1	Zutter et al. 1986
	Woody	1	4	-47.3	Zutter et al. 1986
Triclopyr	**Species richness**				
	Total	1	4	10.9	Miller et al. 1999
	Herbaceous	1	4	68.8	Miller et al. 1999
	Woody	1	4	-2.3	Miller et al. 1999
	Graminoids	1	4	30.8	Miller et al. 1999
	Woody vines	1	4	-8.8	Miller et al. 1999
	Simpson diversity				
	Total	1	4	-1.1	Miller et al. 1999
	Shannon diversity				
	Total	1	4	0.0	Miller et al. 1999
	Importance value				
	Herbaceous	1	4	67.1	Miller et al. 1999
	Woody	1	4	-19.8	Miller et al. 1999
	Graminoids	1	4	57.1	Miller et al. 1999
	Woody vines	1	4	-10.9	Miller et al. 1999
	Cover				
	Herbaceous	1	10	43.8	Lauer and Glover 1998
	Woody	1	10	-67.4	Lauer and Glover 1998
	Density				
	Woody	1	4	-55.0	Miller et al. 1999
	Frequency				
	Herbaceous	2	6	-76.3	Clewell and Lasley 1998 (Trial 1, 3)
	Woody	2	6	787.9	Clewell and Lasley 1998 (Trial 1, 3)

Table 1, *continued*

Habitat/Herbicide	Response variable	# of studies	Total N	Average % change	Studies
	Graminoids	2	6	517.9	Clewell and Lasley 1998 (Trial 1, 3)
Triclopyr + triclopyr	**Cover**				
	Herbaceous	1	5	-60.0	Zutter and Miller 1998
	Woody	1	5	-59.0	Zutter and Miller 1998
Triclopyr ester + sulfometuron	**Simpson diversity**				
	Total	1	4	25.2	Zutter et al. 1987
	Shannon diversity				
	Total	1	4	-8.4	Zutter et al. 1987
	Cover				
	Herbaceous	2	8	-32.4	Zutter et al. 1987, Zutter et al. 1986
	Woody	1	4	-16.7	Zutter et al. 1986
	Biomass				
	Herbaceous	2	8	-32.1	Zutter et al. 1987, Zutter et al. 1986
	Woody	1	4	-12.7	Zutter et al. 1986
Triclopyr + triclopyr + sulfometuron (annually for 11 years) + glyphosate (annually for 3 years)	**Cover**				
	Herbaceous	1	5	-86.7	Zutter and Miller 1998
	Woody	1	5	-92.8	Zutter and Miller 1998
Triclopyr + sulfometuron + glyphosate	**Cover**				
	Herbaceous	1	10	15.7	Lauer and Glover 1998
	Woody	1	10	-70.6	Lauer and Glover 1998
Triclopyr + glyphosate (for 5 years)	**Cover**				
	Total	1	53	-5.0	Miller et al. 1995
	Herbaceous	1	53	7.7	Miller et al. 1995
	Woody	1	53	150.0	Miller et al. 1995
	Graminoids	1	53	2.1	Miller et al. 1995
	Woody vines	1	53	26.2	Miller et al. 1995
Triclopyr + triclopyr + [triclopyr + glyphosate]	**Cover**				
	Herbaceous	1	10	70.9	Lauer and Glover 1998
	Woody	1	10	-76.5	Lauer and Glover 1998
Triclopyr + triclopyr + [triclopyr + glyphosate] + sulfometuron + glyphosate	**Cover**				
	Herbaceous	1	10	31.4	Lauer and Glover 1998
	Woody	1	10	-69.9	Lauer and Glover 1998

all herbicides, but declines never exceeded 17.2% (imazapyr) (Boyd et al. 1995). Graminoid species richness decreased by 16.7% with Velpar-L® (Boyd et al. 1995, Miller et al. 1999) but increased by 30.8% with triclopyr (Miller et al. 1999); other herbicides yielded intermediate values (Table 1). Herbicides generally decreased total species richness, with the largest reduction produced by Pronone® (11.2%) (Blake 1986, Hurst and Blake 1987, Boyd et al. 1995, Miller et al. 1999). Triclopyr (Miller et al. 1999) and glyphosate (Boyd et al. 1995, Miller et al. 1999) increased total richness by 10.9% and 8.7%, respectively.

Importance values (IVs) were reported for many different plant species in herbicide studies (Boyd et al. 1995, Miller et al. 1999) (IVs in the two studies were calculated slightly differently, but used the same component variables) (Table 1). The importance value of graminoids was unchanged by picloram, but increased with other herbicides by as much as 56.1% (triclopyr) (Miller et al. 1999). Herbaceous plant IVs only decreased by 27.4% with the combination of dicamba and 2,4 D, but increased by as much as 133.3% under picloram application (Miller et al. 1999). This latter value was at least twice the increase reported for other herbicides (e.g., Velpar-L®) and their combinations. The effect of different herbicides on the IVs of woody plant species was very heterogeneous: a maximum 52.5% increase was found with imazapyr (Boyd et al. 1995), whereas the greatest decrease was detected for triclopyr (19.8%) (Miller et al. 1999). A little more than half the herbicides examined demonstrated reductions in this parameter.

Percent ground-layer cover was the other most commonly reported response variable, but it was most closely associated with studies using unique combinations of herbicides. As expected, woody plant cover generally declined after herbicide application. The largest decrease, 92.8%, was found for a combination of triclopyr, glyphosate, and sulfometuron applied repeatedly for 11 years (Zutter and Miller 1998). A combination of triclopyr and glyphosate applied annually for 5 years generated the only increase (150%) in woody plant cover (Miller et al. 1995). Herbaceous cover varied greatly among studies even when using combinations of the same herbicides, a variation which may be due to differences in application sequences and rates. A combination of sulfometuron applied twice and glyphosate applied three times decreased herbaceous plant cover by 97.5%, the greatest decline noted (Zutter et al. 1986). A sequence of triclopyr applied twice followed by a mixture of triclopyr and glyphosate produced a maximum 70.9% increase in herbaceous plant cover (Lauer and Glover 1998). However, triclopyr alone resulted in a 43.8% increase in herbaceous cover when applied once (Lauer and Glover 1998) and a 60% decrease when applied twice (Zutter and Miller 1998). Only two studies reported cover values for graminoids: a combination treatment of Velpar-L®, triclopyr, imazapyr, and glyphosate reduced graminoid cover by 113.2% (Harrington and Edwards 1999); triclopyr and glyphosate, applied annually for 5 years, barely increased cover by 2% (Miller et al. 1995).

Few studies reported density, frequency, or biomass of ground-layer plants as response variables (Table 1). Herbaceous plant biomass closely tracked cover in three cases (Zutter et al. 1986, 1987). Little can be said about density and frequency due to the paucity of studies.

Species of Special Concern

Results for species of concern come from six studies conducted over several years (Table 2). Pronone® decreased wiregrass (all *A. stricta* data refer to *A. beyrichiana*) by as much as 142% at intermediate or higher rates of application (Wilkins et al. 1993a). Other studies, however, reported increases of 7480% with Velpar-L® (Wilkins et al. 1993b), although the same herbicide applied elsewhere at approximately the same rates yielded more moderate increases of 22.3% (Brockway et al. 1998). Triclopyr initially increased *A. beyrichiana* frequency by 204.8% in south Mississippi flatwoods, but 5 months later frequency of this species decreased by 329.8% compared to controls (Clewell and Lasley 1998, Trial 1). Three years after ULW® application, hairy wild indigo (*Baptisia calycosa* var. *villosa* Canby) and pineland hoary pea (*Tephrosia mohrii* [Rydb.] Godfrey) densities were reduced by 100% and 59.7%, respectively (Provencher et al. 2001). The 100% decrease reported for *B. calycosa* var. *villosa* may be an artifact of low abundance and small sample sizes. In south Mississippi flatwoods, beardgrass (*Andropogon capillipes* Nash) decreased by 162.5% with triclopyr, but frequencies were generally too low to calculate a percent change compared to the control (Clewell and Lasley 1998). Low numbers also prevented us from measuring herbicide effects on myrtle holly (*Ilex myrtifolia* Walt.), huckleberry (*Gaylussacia frondosa* [L.] T. & G.), and coastal plain beak sedge (*Rhyncospora stenophylla* Carey ex. Chapm.) (Clewell and Lasley 1998).

DISCUSSION

Our most notable finding was that the effects of herbicides on ground-layer vegetation in natural flatwoods and sandhills have rarely been measured. In addition, we found a dearth of data on specific plant species because authors preferred grouping them as weeds, grasses, herbs, etc. Therefore, it was generally not possible to distinguish between the responses of desirable and undesirable plant species. This is troublesome because herbicide effects on species of management concern cannot generally be evaluated. For instance, when numbers were sufficient to calculate percent change, three threatened species in Mississippi, namely *B. calycosa* var. *villosa*, *T. mohrii*, and *A. capillipes*, all showed negative responses to herbicide treatments. Wiregrass was either stimulated or decreased by herbicide treatment, sometimes by the same chemical, in different studies.

It is unclear whether results from pine plantations, which included the bulk of studies examined, apply to natural forests because of the preponderance of early successional species associated with disturbed plantation soils (Grelen 1962, Campbell 1983, Conde et al. 1983, Provencher et al. 2000). In many plantation studies, weed control was the reason for herbicide application, suggesting presence of undesirable, competitive ruderal plant species. This fact

Table 2. Herbicide, application rate, time since treatment, number of replicates (N), treatment value, control (untreated) value, and percent change for response variables for species of special concern or of interest (e.g., wiregrass), categorized by habitat and herbicide. All *Aristida stricta* refer to *A. beyrichiana* (Peet 1993).

HABITAT/ Species	Herbicide	Rate	Time post-treatment	Response variable	N	Treat-ment	Control	% change	Studies
FLATWOODS									
Aristida stricta	Sulfometuron methyl	0.50 lb/acre	months	cover	108	0.90	2.50	-64.00	Neary et al. 1984
SANDHILLS									
Aristida stricta	Hexazinone (Pronone)	1.70 kg/ha	1 year	cover	3	1.00	1.76	-43.18	Wilkins et al 1993a
Aristida stricta	Hexazinone (Pronone)	1.70 kg/ha	2 years	cover	3	3.07	3.44	-10.76	Wilkins et al 1993a
Aristida stricta	Hexazinone (Pronone)	3.40 kg/ha	1 year	cover	3	-0.74	1.76	-142.05	Wilkins et al 1993a
Aristida stricta	Hexazinone (Pronone)	3.40 kg/ha	2 years	cover	3	1.09	3.44	-68.31	Wilkins et al 1993a
Aristida stricta	Hexazinone (Pronone)	6.80 kg/ha	1 year	cover	3	-0.74	1.76	-142.05	Wilkins et al 1993a
Aristida stricta	Hexazinone (Pronone)	6.80 kg/ha	2 years	cover	3	-0.89	3.44	-125.87	Wilkins et al 1993a
Aristida beyrichiana	Hexazinone (ULW)	2.44 kg/ha	1 year	density	6	0.12	0.10	20.00	Provencher et al. 2001
Aristida beyrichiana	Hexazinone (ULW)	2.44 kg/ha	3 years	density	6	0.11	0.10	10.00	Provencher et al. 2001
Aristida stricta	Hexazinone (ULW)	1.10 kg/ha	nd[a]	cover	5	61.70	57.80	6.75	Brockway et al. 1998
Baptisia calycosa var. *villosa*	Hexazinone (ULW)	2.44 kg/ha	1 year	density	6	0.00	0.01	-100.00	Provencher et al. 2001
Baptisia calycosa var. *villosa*	Hexazinone (ULW)	2.44 kg/ha	3 years	density	6	0.00	0.01	-100.00	Provencher et al. 2001
Tephrosia mohrii	Hexazinone (ULW)	2.44 kg/ha	1 year	density	6	0.40	0.92	-56.52	Provencher et al. 2001
Tephrosia mohrii	Hexazinone (ULW)	2.44 kg/ha	3 years	density	6	0.29	0.72	-59.72	Provencher et al. 2001
Aristida stricta	Hexazinone (Velpar L)	0.42 kg/ha	1 year	cover	3	0.90	0.05	1700.00	Wilkins et al. 1993b
Aristida stricta	Hexazinone (Velpar L)	0.84 kg/ha	1 year	cover	3	0.65	0.05	1200.00	Wilkins et al. 1993b
Aristida stricta	Hexazinone (Velpar L)	1.68 kg/ha	1 year	cover	3	3.79	0.05	7480.00	Wilkins et al. 1993b
Aristida stricta	Hexazinone (Velpar L)	1.10 kg/ha	nd[a]	cover	5	61.20	57.80	5.88	Brockway et al. 1998
Aristida stricta	Hexazinone (Velpar L)	2.20 kg/ha	nd[a]	cover	5	70.70	57.80	22.32	Brockway et al. 1998
PINE PLANTATIONS[b]									
Andropogon capillipes	Triclopyr	0.40%	7 months	frequency	3	-1.00	-1.00	0.00	Clewell and Lasley 1998 (Trial 1)
Andropogon capillipes	Triclopyr	0.40%	7 months	frequency	3	-1.00	-1.00	0.00	Clewell and Lasley 1998 (Trial 3)
Andropogon capillipes	Triclopyr	0.40%	12 months	frequency	3	0.50	-0.80	-162.50	Clewell and Lasley 1998 (Trial 3)
Aristida stricta	Triclopyr	0.40%	7 months	frequency	3	-0.27	-0.09	204.78	Clewell and Lasley 1998 (Trial 1)
Aristida stricta	Triclopyr	0.40%	12 months	frequency	3	-0.16	0.07	-329.79	Clewell and Lasley 1998 (Trial 1)

[a] The values presented are based on the adjusted mean taken from this paper. We could not determine if this value was based on an average of all three seasons of data or solely the last year (2.5 years post-treatment).

[b] Clewell and Lasley (1998) also examined the effects of herbicides on several other species (Trial 1—*Andropogon capillipes* [12 months post-treatment], *Ilex myrtifolia*, and *Rhyncospora stenophylla*; Trial 3—*Aristida stricta* and *Gaylussacia frondosa*); however, because the species was either not present at pre-treatment or was not present at all during the study in the control plot, values for % change could not be calculated and are not presented in this table.

would also explain the elaborate combinations and repeated applications of herbicides more commonly reported in pine plantations than in natural forests. Therefore, plantation studies may report more conservative values for herbaceous plant and graminoid control because herbaceous weeds may show a greater resistance to herbicides than do herbaceous nonweedy species.

Although herbicide use in flatwoods vegetation uniformly reduced plant species richness and herbaceous and woody plant cover, the same cannot be said about sandhill vegetation. The general pattern for sandhills was a decrease in woody plant species cover and increase in graminoid species cover after herbicide application. The responses of species richness and herbaceous cover or density were mixed and rarely exceeded 100%. Because so few studies occurred in sandhills, it was not possible to determine if specific herbicides or the diverse study designs or goals were the source of variation.

A troubling aspect of the herbicide literature we examined was the lack of experimental rigor and inconsistent reporting standards among studies. Many studies lacked discrete experimental designs, lacked clear descriptions of methods, were poorly, if at all replicated, lacked control or reference plots, performed no pre-treatment sampling, performed incorrect statistical analyses or none at all, reported no measure of variability (thus we could not perform meta-analysis [Gurevitch and Hedges 1999]), or only presented response variables as percent control without supplying numbers that led to this derivation. Studies we used were among the better ones, but many included some of these problems, and only two studies reported variance measures for means. Finally, the diverse array of response variables and varied herbicide choices among studies was perhaps our greatest challenge in reaching general conclusions.

Our findings suggest that widespread use of herbicides to control unwanted vegetation in public and private southern pinelands (Fallis 1993) may have undesirable effects on nontarget plant species. Additional studies of herbicide impact are needed before treating large, diverse landscapes. Furthermore, should agencies and private landowners decide to pay for the greater cost of herbicide application relative to prescribed burning (Provencher et al. 2001), implementation of rigorous experimental designs free of the problems listed above, and a deliberate effort to track species of special concern, should be the norm. This is especially true of public lands, which are generally extensive and more likely to be subject to large aerial herbicide applications.

ACKNOWLEDGMENTS

The Longleaf Pine Restoration Project acknowledges the Natural Resources Division of Eglin Air Force Base for its assistance and funding for this project. We are also grateful for additional funding from The Nature Conservancy's Florida Regional Office (TNC/FLRO). We thank the Public Lands Program of TNC/FLRO and TNC/FLRO for their administrative help. This literature review would not have been possible without help from many scientists and librarians; we thank them all. Thanks also to Drs. Doria Gordon, George Tanner, and the *Natural Areas Journal* Editorial Board for comments on earlier drafts, greatly improving this work.

This effort was sponsored by the U.S. Army Medical Research Acquisition Activity (USAMRAA), U.S. Army Medical Research and Materiel Command, Department of the Army under Cooperative Agreement number DAMD17-98-2-8006. The U.S. Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Air Force, or of the USAMRAA, U.S. Army, or the U.S. Government.

Andrea Litt is a Science Assistant for The Nature Conservancy at Eglin Air Force Base, Florida. She is primarily interested in investigating community-level ecological change due to restoration.

Brenda Herring has worked as a Botanist/Field Ecologist with The Nature Conservancy since 1994. Her main research interest is the study of Gulf Coastal Plain flora.

Louis Provencher joined The Nature Conservancy in 1994 as Research Ecologist at Eglin Air Force Base, Florida. He and staff have tested hardwood reduction effects on multiple taxa and variables.

LITERATURE CITED

Abrahamson, W.G. and D.C. Hartnett. 1990. Pine flatwoods and dry prairies. Pp. 103-149 *in* R.L. Myers and J.J. Ewel, eds., Ecosystems of Florida. University of Central Florida Press, Orlando.

Berish, S.J. 1996. Efficacy of three formulations of the forest herbicide hexazinone as an aid to restoration of longleaf pine (*Pinus palustris*) sandhills at Eglin Air Force Base, Florida. M.S. thesis, University of Florida, Gainesville. 51 pp.

Blake, P.M. 1986. Diversity, biomass, and deer forage in banded vs. broadcast hexazinone in a pine plantation. Proceedings of the Southern Weed Science Society 39:404.

Boyd, R.S., J.D. Freeman, J.H. Miller, and M.B. Edwards. 1995. Forest herbicide influences on floristic diversity seven years after broadcast pine release treatments in central Georgia, USA. New Forests 10:17-37.

Boyer, W.D. 1990. Effects of a single chemical treatment on long-term hardwood development in a young pine stand. Pp. 599-606 *in* S.S. Coleman and D.G. Neary, eds., Proceedings of the Sixth Biennial Southern Silvicultural Research Conference. General Technical Report 70, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Memphis, Tenn.

Brockway, D.G., K.W. Outcalt, and R.N. Wilkins. 1998. Restoring longleaf pine wiregrass ecosystems: plant cover, diversity and biomass following low-rate hexazinone application on Florida sandhills. Forest Ecology and Management 103:159-175.

Campbell, C.S. 1983. Systematics of the *Andropogon virginicus* complex (Gramineae). Journal of the Arnold Arboretum 64:171-254.

Clewell, A.F. 1989. Natural history of wiregrass (*Aristida stricta* Michx., Gramineae). Natural Areas Journal 9:223-244.

Clewell, A.F. and M.E. Lasley. 1998. Triclopyr for gallberry reduction at Mississippi Sandhill Crane National Wildlife Refuge. Final Report to Mississippi Sandhill Crane Wildlife Refuge. A.F. Clewell, Inc., Quincy, Fla. 16 pp.

Conde, L.F., B.F. Swindel, and J.E. Smith. 1983. Plant species cover, frequency, and biomass: early responses to clearcutting, burning, windrowing, discing, and bedding in *Pinus elliottii* flatwoods. Forest Ecology and Management 6:319-331.

Fallis, F.G. 1993. Forest vegetation and management—current practices and future needs: perspective from forest industry. Proceedings of the Southern Weed Science Society 46:124.

Grelen, H.E. 1962. Plant succession on cleared sandhills in northwest Florida. American Midland Naturalist 67:36-44.

Gurevitch, J. and L.V. Hedges. 1999. Statistical issues in ecological meta-analyses. Ecology 80:1142-1149.

Harrington, T.B. and M.B. Edwards. 1999. Understory vegetation, resource availability, and litterfall responses to pine thinning and woody vegetation control in longleaf pine plantations. Canadian Journal of Forest Research 29:1055-1064.

Haywood, J.D., A.E. Tiarks, and M.A. Sword. 1997. Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development. New Forests 14:233-249.

Hurst, G.A. and P.M. Blake. 1987. Plant species composition following hexazinone treatment-site preparation. Proceedings of the Southern Weed Science Society 40:194.

Kush, J.S., R.S. Meldahl, and W.D. Boyer. 1999. Understory plant community response after 23 years of hardwood control treatments in natural longleaf pine (*Pinus palustris*) forests. Canadian Journal of Forest Research 29:1047-1054.

Lauer, D.K. and G.R. Glover. 1998. Early pine response to control of herbaceous and shrub vegetation in the flatwoods. Southern Journal of Applied Forestry 15:201-208.

Marois, K.C. 1998. Plants and lichens, vertebrates, invertebrates, and natural communities tracked by Florida Natural Areas Inventory. Florida Natural Areas Inventory, Tallahassee. 68 pp.

Miller, J.H., R.S. Boyd, and M.B. Edwards. 1999. Floristic diversity, stand structure, and composition 11 years after herbicide site preparation. Canadian Journal of Forest Research 29:1073-1083.

Miller, J.H., B.R. Zutter, S.M. Zedaker, M.B. Edwards, and R.A. Newbold. 1995. Early plant succession in loblolly pine plantations as affected by vegetation management. Southern Journal of Applied Forestry 19:109-126.

Mississippi Natural Heritage Program. 1997. Special plant list. Mississippi Department of Wildlife, Fisheries and Parks, Museum of Natural Science, Jackson. 12 pp.

Myers, R.L. 1990. Scrub and high pine. Pp. 150-193 *in* R.L. Myers and J.J. Ewel, eds., Ecosystems of Florida. University of Central Florida Press, Orlando.

Neary, D.G., L.F. Conde, and J.E. Smith. 1984. Effects of sulfometuron methyl on six important competing species in coastal plain flatwoods. Proceedings of the Southern Weed Science Society 37:193-199.

Neary, D.G., J.E. Smith, B.F. Swindel, and K.V. Miller. 1991. Effects of forestry herbicides on plant species diversity. Proceedings of the Southern Weed Science Society 44:266-272.

Peet, R.K. 1993. A taxonomic study of *Aristida stricta* and *A. beyrichiana*. Rhodora 95:25-37.

Peet, R.K. and D.J. Allard. 1993. Longleaf pine-dominated vegetation of the southern Atlantic and eastern Gulf Coast region, USA. Pp. 45-91 *in* S.M. Hermann, ed., Proceedings of the Tall Timbers Fire Ecology Conference. Tall Timbers Research Station, Tallahassee, Fla.

Provencher, L., B.J. Herring, D.R. Gordon, H.L. Rodgers, K.E.M. Galley, G.W. Tanner, J.L. Hardesty, and L.A. Brennan. 2001. Effects of hardwood reduction techniques on longleaf pine sandhill vegetation in northwest Florida. Restoration Ecology: in press.

Provencher, L., B.J. Herring, D.R. Gordon, H.L. Rodgers, G.W. Tanner, L.A. Brennan, and J.L. Hardesty. 2000. Restoration of northwest Florida sandhills through harvest of invasive *Pinus clausa*. Restoration Ecology 8:175-185.

Wilkins, R.N., W.R. Marion, D.G. Neary, and G.W. Tanner. 1993a. Vascular plant community dynamics following hexazinone site preparation in the lower Coastal Plain. Canadian Journal of Forest Research 23:2216-2229.

Wilkins, R.N., G.W. Tanner, R. Mulholland, and D.G. Neary. 1993b. Use of hexazinone for understory restoration of a successionally-advanced xeric sandhill in Florida. Ecological Engineering 2:31-48.

Zutter, B.R. and J.H. Miller. 1998. Eleventh-year response of loblolly pine and competing vegetation to woody and herbaceous plant control on a Georgia flatwoods site. Southern Journal of Applied Forestry 22:88-95.

Zutter, B.R., G.R. Glover, and D.H. Gjerstad. 1986. Effects of herbaceous weed control using herbicides on a young loblolly pine plantation. Forest Science 32:882-899.

Zutter, B.R., G.R. Glover, and D.H. Gjerstad. 1987. Vegetation response to intensity of herbaceous weed control in a newly planted loblolly pine plantation. New Forests 4:257-27.