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ABSTRACT—Vehicle training, a common disturbance of military lands, is part of a suite of land uses that also includes cattle grazing. Yet, no studies have examined their interaction. Our objective was to review the effects of vehicle training and grazing on grassland soils and vegetation and develop a state-and-transition model that incorporates grazing and training for Fort Hood, TX. Both grazing and training can cause soil compaction and vegetation disturbance, altering hydrology and increasing erosion. While the effects of grazing largely depend on stocking rate, vehicle training causes greater disturbance when wet soils are driven on, when vehicles are turned sharply, and as the number of vehicle passes increases. Grazing and training are expected to maintain grasslands in secondary succession, though eroded sites dominated by annuals also could develop under frequent training. The state-and-transition model may guide decision making for military land managers faced with training and grazing effects.

Key Words: cattle grazing, disturbance, grasslands, Great Plains ecosystems, military impacts, state-and-transition models

INTRODUCTION

Public land managers face pressure to maintain ecosystems, often in an idealized natural state, while supporting multiple and sometimes conflicting land uses (National Research Council 1994). Lack of reliable and accurate scientific information about the impacts of various possible land uses makes ecosystem maintenance more difficult. Military land managers increasingly face similar concerns because of the importance of large, contiguous tracts of land to conservation (Goodman 1996). Tracked vehicle training, a common disturbance of military lands, is part of a suite of land uses that includes grazing by domestic livestock and wildlife, crop production, forestry, recreation, and habitat protection for threatened and endangered species.

Knowledge of the interactive effects of military vehicle training and other land uses is presently unavailable to military land managers (Anderson et al. 2005). Cattle grazing is one use that occurs at Fort Hood, TX, and possibly could constitute part of management strategies on other military lands throughout the Great Plains. Military land managers' informal reasons for either allowing or not allowing grazing seem to have little empirical basis. They could allow grazing to maintain savanna and grassland and reduce the risk of fire, thus benefiting military training. The use of grazing animals to maintain vegetative structure is often preferred over the use of more intensive means such as herbicides, mowing, or burning. Grazing also brings in funds to support management, creates a stronger tie with the local community, and allows local residents to benefit from the land, all of which add support for grazing as a management tool. Research has not examined the training and grazing interaction.

State-and-transition models, where states represent alternative vegetation communities and transitions represent the processes that replace one community with another, may be effective tools for military land managers to evaluate the main and potential interactive effects of grazing and training. State-and-transition models provide a framework for organizing current understanding of ecosystem dynamics based on the concept that sites may support multiple stable vegetation states and that transitions between states occur when ecological thresholds are surpassed (Briske et al. 2003, 2005; Stringham et al. 2003). These models accommodate both continuous and reversible vegetation dynamics that prevail within stable vegetation states and discontinuous and nonreversible dynamics that occur when one stable state replaces another (Briske et al. 2003, 2005; Stringham et al. 2003). Through their respective influences on species interactions, grazing and training, when combined, may facilitate transitions to alternative states not readily anticipated by their effects alone.

In an effort to add some relevant facts to the assessment of grazing and training effects and to aid military land managers, we reviewed the scientific literature on cattle grazing and tracked-vehicle-training effects on grassland soils and vegetation. Then we developed a state-and-transition model that incorporates grazing and training for Fort Hood, TX. Compiling and generalizing information about the main and interactive effects of land uses may allow military installations to manage land in a way that supports the widest array of public interests.

METHODS

The literature on the effects of cattle grazing (hereafter grazing) and military vehicle training (hereafter training) consisted of published results of studies conducted in the northern and southern plains of the United States. In general, the literature documented effects of grazing and training on the Chihuahuan Desert in southern New Mexico, shortgrass steppe in eastern Colorado, mixed-grass prairies in central Oklahoma and Texas, and tallgrass prairie in eastern Kansas. These grasslands represented native vegetation on the military installations of Fort Bliss in southwest Texas, Fort Carson in Colorado, Fort Hood in central Texas, and Fort Riley in eastern Kansas (Goran et al. 1983). Studies conducted elsewhere were reviewed if applicable.

As a group, the studies lacked similar response variables, measurement scales, and environmental conditions, which made comparisons of the effects of grazing and training problematic. Grazing and training effects on soil compaction, plant cover, soil erosion, and vegetation change were evaluated because most of the military impact studies focused on these variables. Given that our interest was to provide information for better management of military training lands, we assumed that the impacts from the tracked vehicles will occur and that the effects of grazing will be superimposed on the training impacts.

We developed the state-and-transition model to depict the main and potential interactive effects of grazing and training on grasslands at Fort Hood, TX. We based the model structure on recent reviews of the application of these models to rangelands (Bestelmeyer et al. 2003; Briske et al. 2003, 2005; Stringham et al. 2003). We developed definitions of vegetation states and transitions through conversations with personnel at Fort Hood, literature on grazing and training effects on Texas rangelands (Goran et al. 1983; Thurow et al. 1986; Thurow et al. 1993), soil surveys for Bell and Coryell counties (USDA-SCS 1977; USDA-SCS 1985), description of Cross-Timbers Prairie communities (Smeins 1994), and personal experience with grasslands throughout the Great Plains.

LITERATURE REVIEW

Soil Compaction

Training produced soil bulk densities and penetration resistances that were 8% and 58% greater, respectively, within vehicle tracks than outside the tracks (Table 1). The severity of compaction often was positively correlated with the number of vehicle passes and with moist rather than relatively dry soil (Thurow et al. 1993; Halvorson et al. 2001). Halvorson et al. (2001) found that training on moist soil created soil ruts 15 cm deep and compacted soils to a depth of 30 cm. Soils are more susceptible to compaction when soil moisture is at or near field capacity because of the ease at which soil particles, lubricated by water in micropores, are repositioned into available air spaces upon compression (Geeves et al. 2000).

Grazing increased soil bulk density 11% and penetration resistance 30% relative to ungrazed areas (Table 1). The results ranged widely, but the severity of compaction was largely correlated with stocking rate or estimates of grazing intensity and did not exceed soil layers below 5 to 6 cm (Chanasyk and Naeth 1995; Dormaar and Willms 1998; Greenwood and McKenzie 2001; Daniel et al. 2002). Dormaar and Willms (1998) showed that grazing

TABLE 1
CATTLE GRAZING AND TRACKED VEHICLE TRAINING EFFECTS ON SOIL BULK DENSITY AND PENETRATION RESISTANCE, INDICATORS OF SOIL COMPACTION

			Bulk density		Penetration resistance		
Disturbance	Location	Soil depth	Range of means	Increase from controls	Range of means	Increase from controls	Source
		— (cm) —	— (g cm^{-3}) —	(%)	— (MPa) —	(%)	
Cattle grazing[1]	Wyoming	0–5	1.19–1.28	0			Abdel-Magid et al. 1987
	Alberta	0–7.5	0.74–0.91	10			Chanasyk and Naeth 1995
		0–10.5			1.02–2.59	47	
		0–30			2.29–4.04	21	
	Oklahoma	0–5	1.04–.27	13	1.20–1.99	58	Daniel et al. 2002
		5–10	1.27–1.45	4	1.64–1.97	23	
		10–15	1.36–1.47	1	1.67–1.77	2	
	Alberta	0–3	0.44–0.81	43			Dormaar and Willms 1998
		3–6	0.60–0.88	25			
	North Dakota	0–15[2]	1.28–1.34	1			Hofman and Ries 1991
		0–15[3]	1.02–1.08	6			
	Alberta	0–7.5	0.79–1.11	2			Naeth et al. 1990
	Average			11		30	
Vehicle training[4]	Kansas	0–7.6	0.95–1.22	5			Althoff and Thien 2005
		0–10			1.5–3.8	35	
		10–20			1.5–3.8	10	
	Washington	0–10	0.95–1.60	12	0.2–4.0	100	Halvorson et al. 2001
		10–20	1.00–1.68	10	1.6–4.0	94	
		20–30	0.90 –1.58	5	1.2–2.8	50	
	Texas	0–5	1.13–1.33	17			Thurow et al. 1993
		5–10	1.16–1.16	0			
	Average			8		58	

[1] Data represent averages across stocking rates and grazing systems
[2] Reclaimed mineland
[3] Native prairie
[4] Data represent averages of dry-soil and moist-soil tracking

increased bulk density by 43% at 0 to 3 cm soil depths and 25% at the 3 to 6 cm range. Daniel et al. (2002) reported 58% increases of penetration resistance and 13% increases of bulk density at 0 to 5 cm depths, but few grazing effects at 5 to 10 cm, 10 to 15 cm, and presumably, below 15 cm. Overall, the evidence from these studies points toward grazing having little additional impact on military lands due to the distribution of the impacts. The impact of grazing appears in the surface soil, while training impacts soil in the deeper layers.

Plant Cover

Both training and grazing reduce living and dead plant cover, often exposing bare soil (Table 2). Training had a greater impact on soil cover as the number of vehicle passes increased (Braunack and Williams 1993; Grantham et al. 2001) and when sharp turns were made (Ayers 1994; Watts 1998). Vehicle passage detaches and crushes plant tissues, but the dead material that remains on the ground minimizes erosion of bare soil. When vehicles are turned sharply, shear forces disturb the ground, generating piles of scraped soil and vegetation alongside the tracks (Ayers 1994). Frequent disturbance and soil compaction caused by repeated vehicle passage likely reduce net primary production (the vegetative biomass produced per unit ground area annually) both above and below ground. Thus, repeated vehicle passage reduces over time the supply of organic materials that cover soil and maintain soil structure.

Grazing results in diminishing vegetative cover as stocking rate increases (Table 2). At heavy stocking rates, between 75% and 90% of the standing biomass may be utilized as forage or detached through animal tracking, compared with 25% to 50% at light to moderate stocking rates. Whether grazing reduces net primary production depends on site productivity, disturbance history, and precipitation (Archer and Smeins 1991). Nonetheless, grazing does reduce the accumulation of dead plant material, and therefore may further reduce soil cover on military lands. Some research (McNaughton 1985) also has shown that many kinds of grazing animals prefer fresh regrowth to undisturbed original growth, raising the concern that more grazing will occur in areas recovering from training damage rather than in areas undisturbed from vehicles.

Soil Erosion

Rainfall simulation experiments have shown that both training and grazing may reduce infiltration rates and enhance the potential for soil erosion (Table 3). Fuchs et al. (2003) reported that training did not significantly affect sediment production on tracked compared to untracked areas at Fort Bliss, NM. They nonetheless expressed concern about soil losses between 6 to 8 Mg ha^{-1} y^{-1} on these lands. At Fort Hood, TX, training had minimal effects on infiltration and sediment production of dry-tracked soil, but it increased sediment production on wet-tracked soil from ~75 to 325 kg ha^{-1} relative to untracked areas (Thurow et al. 1993). Though training effects on infiltration rates and other soil properties may persist for more than 50 years in desert environments (Prose and Wilshire 2000), infiltration and sediment production rates similar to untracked areas were recovered within two years after training at Fort Hood (Thurow et al. 1993).

Overall effects of grazing on hydrology and erosion depend on the spatial and temporal patterns of both grazing and vegetation (Blackburn 1992; Thurow 1991; Pierson et al. 2002). Daniel et al. (2002) reported that grazing reduced infiltration rates by 75% to 83% in mixed-grass range in Oklahoma. Thurow et al. (1986) found that increased sediment production in response to grazing was greater from sodgrass than bunchgrass and oak motte vegetation in Texas. Spatial and temporal variation of soil erosion often is attributed to interactions of slope, soil cover, and soil type rather than specific effects of vegetation (Blackburn 1992; Pierson et al. 2002). We expect that on military lands the potential for a grazing and training interaction is likely to be terrain specific. On areas prone to erosion, especially overland flow and gully formation, grazing may increase the amount of soil transported off site, and therefore would not be recommended on slopes with training damage.

Vegetation Change

Both training and grazing have altered the composition of grasslands in the Great Plains. Training decreased basal cover of perennial warm-season grasses and increased cover of perennial cool-season grasses and annual warm-season forbs in shrub-grassland communities at Pinon Canyon Maneuver Site in Colorado (Shaw and Diersing 1990; Milchunas et al. 1999). At Fort Carson, CO, training increased cover of non-native species, weeds, and annuals (Milchunas et al. 2000). At Fort Riley, KS, training reduced cover of native perennial grasses and forbs in favor of annuals and non-native species (Quist et al. 2003). Goran et al. (1983) described the general sequence of vegetation change that results from increased vehicle training. A one-time occurrence of vehicle traffic has marginal effects. Occasional disturbance displaces species sensitive to soil compaction and defoliation. Frequent, repeated use displaces most native perennial vegetation with annual grasses and weedy forbs. Intense, constant use results in an eroded state supportive of only the most disturbance-tolerant vegetation (Goran et al. 1983).

Grazing has been shown to reduce cover of tall perennial warm-season grasses, while increasing cover of short and mid-height warm- and cool-season grasses, annuals, and forbs in tallgrass prairie (Hartnett et al. 1996; Gillen et al. 1998). In southern mixed-grass range, grazing

TABLE 2
CATTLE GRAZING AND TRACKED VEHICLE TRAINING EFFECTS ON GROUND COVER OF GREAT PLAINS GRASSLANDS

Disturbance	Plant community	Treatment conditions	Percentage cover: Bare soil	Percentage cover: Litter	Percentage cover: Vegetation	Source
Cattle grazing	Arid grassland, NM	Ungrazed	80	1	19[1]	Nash et al. 2004
		Heavy, short duration	91	2	8	
	Temperate pasture, ND	Ungrazed	3	87	10[2]	Hofman and Ries 1991
		Light	6	82	12	
		Moderate	28	66	6	
		Heavy	46	48	6	
	Native prairie, ND	Ungrazed	5	72	23	
		Moderate	6	76	16	
	Rolling plains, TX	Moderate, continuous	9	28	64[3]	Pluhar et al. 1987
		Heavy, rotational	25	25	51	
	Mixed-grass prairie, ND	Ungrazed		67	29[2]	Biondini and Manske 1996
		Rotational		65	24	
		Season-long		64	25	
	Mixed-grass prairie, OK	Ungrazed	5	22	55[1]	Fuhlendorf et al. 2002
		Moderate	21	13	46	
		Heavy	27	13	41	
	Rolling plains, TX	Heavy, continuous	19		4[2]	Teague and Dowhower 2003
		Heavy, rotational	16		5	
	Shortgrass steppe, CO	Ungrazed	16	60	24[2]	Hart and Ashby 1998
		Light	22	55	24	
		Moderate	22	50	28	
		Heavy	23	44	33	
Vehicle training	Sagebrush steppe, ID	Untracked	6	16	50[3]	Watts 1998
		Straight track	10	32	34	
		Sharp turn	27	30	20	
	Chihuahuan Desert, NM	Dry soil, unpassed	35	31	16[2]	Fuchs et al. 2003
		Dry soil, 3 passes	57	21	4	
		Wet soil, unpassed	34	31	15	
		Wet soil, passed	47	35	7	
	Tallgrass prairie, KS	Low training	0		220[1]	Quist et al. 2003
		High training	27		190	
	Shortgrass steppe, CO	Before tracking	54	13	22[2]	Shaw and Diersing 1990
		Tracked, 2 years	45	38	9	
	Shortgrass steppe, CO	Before tracking	64	14	20[2]	Milchunas et al. 1999
		Tracked, 10 years	54	38	4	
	Bluegrass field, ND	Untracked	2	84	14[2]	Prosser et al. 2000
		Moderate	17	70	10	
		Heavy	22	65	10	

[1] Aerial canopy cover
[2] Basal cover
[3] Cover not specified

TABLE 3
CATTLE GRAZING AND TRACKED VEHICLE TRAINING EFFECTS ON INFILTRATION AND SEDIMENT PRODUCTION OF GREAT PLAINS GRASSLANDS

Disturbance	Plant community	Treatment conditions	Infiltration (mm h^{-1})	Sediment production (kg ha^{-1})	Source
Cattle grazing	Temperate pasture, ND	Ungrazed	46	0	Hofmann and Ries 1991
		Light	37	40	
		Moderate	28	150	
		Heavy	21	810	
	Oak motte, TX	Ungrazed	200	5	Thurow et al. 1986
		Moderate, continuous	200	3	
		Heavy, continuous	200	75	
		Heavy, short duration	190	14	
	Bunchgrass, TX	Ungrazed	160	200	
		Moderate, continuous	190	190	
		Heavy, short duration	135	1600	
	Sodgrass, TX	Ungrazed	150	1000	
		Moderate, continuous	160	1400	
		Heavy, continuous	70	5600	
		Heavy, short duration	100	2400	
	Bare soil, TX	No trampling	160	976	Warren et al. 1986
		Moderate trampling	140	2827	
		Double	121	3438	
		Triple	117	4788	
Vehicle training	Mixed-grass prairie, TX	0 passes, dry soil	68	22	Thurow et al. 1993
		10 passes, dry soil	62	67	
		0 passes, wet soil	66	28	
		10 passes, wet soil	42	155	
	Chihuahuan Desert, NM	Untracked		11,347[1]	Fuchs et al. 2003
		1 pass, dry season		10,681	
		3 passes, dry season		12,970	
		Untracked		10,392	
		1 pass, wet season		10,661	
		3 passes, wet season		16,624	
	Mojave Desert, CA	Untracked	272[2]		Prose and Wilshire 2000
		Tracked	179		

[1] Cumulative sediment loss after two-year period
[2] Measured 50 years after initial track establishment from World War II-era training exercises

increased short grasses at the expense of mid-height grass species (Taylor et at. 1997). Grazing has produced few significant compositional changes in shortgrass steppe (Hart and Ashby 1998) and its effects are secondary to precipitation in northern mixed-grass prairie (Biondini and Manske 1996).

Traditional succession models for rangelands depict sites as having a single "climax" or stable vegetative community and assume changes in response to grazing, drought, or other disturbances are reversible given sufficient recovery periods (Briske et al. 2003, 2005). Recent studies have shown that rangeland vegetation dynamics are not always continuous, reversible, and consistent, and that alternative stable vegetation states such as woodlands and shrublands may expand under grazing (Archer and Smeins 1991). Briske et al. (2003, 2005) and Stringham et al. (2003) have recently reviewed the development of state-and-transition models as a means to depict both continuous and reversible and discontinuous and irreversible vegetation dynamics. These models may provide a constructive framework that illustrates the main and interactive effects of grazing and training on military lands.

STATE-AND-TRANSITION MODEL FOR FORT HOOD

At Fort Hood, TX, vegetation varies in structure from grassland with a few scattered trees to nearly closed canopy woodlands with a sparse herbaceous layer. Before Euro-American settlement, grasslands were mid-grass associations dominated by little bluestem [*Schizachyrium scoparium* (Michx.) Nash]. There were inclusions of taller grasses such as indiangrass [*Sorghastrum nutans* (L.) Nash], switchgrass (*Panicum virgatum* L.), and big bluestem (*Andropogon gerardii* Vitman). Common mid-grass species included hairy grama (*Bouteloua hirsuta* Lag.), sideoats grama [*B. curtipendula* (Michx.) Torr.], Texas grama [*B. rigidiseta* (Steud.) A.S. Hitch.], and Texas wintergrass [*Nassela leucotricha* (Trin. & Rupr.) Pohl]. Regionally, a continuum of tall to short grasses dominated along the range from the wettest to driest grassland sites, and frequent fires generally confined woody vegetation to riparian areas, rocky slopes, hillsides, and mesas (Smeins 1994).

Training favors the transition of late-succession, little-bluestem-dominated communities to earlier-succession grassland communities (Fig. 1). Secondary-succession species adapted to occasional training include sideoats grama, Texas wintergrass, silver bluestem [*Bothriochloa saccharoides* (Sw.) Rydb.], and buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.]. When training becomes frequent, early-succession species such as broomweeds [*Amphiachyris* spp. (A. DC.) Nutt.], western ragweed (*Ambrosia psilostachya* DC.), and threeawn grasses (*Aristida* spp. L.), favored by increased recruitment and colonization opportunities, become widespread (Goran et al. 1983; Wilson 1988). Trees and shrubs typically do not persist under training (Johnson 1982).

Grazing also favors the transition of late- to secondary-succession grassland communities (Fig. 1). While little bluestem, big bluestem, and other late-succession grasses have physiological and morphological mechanisms to recover and retain their dominance under deferred grazing regimes, heavy continuous grazing reduces their vigor and abundance (Smeins 1994; Anderson and Briske 1995). Late-succession-dominated states may not reemerge without reseeding of late-succession species and restoration of the ecological processes responsible for maintaining equilibrium of a mid- to tallgrass state (Briske et al. 2005). The increased occurrence of shorter, secondary-succession grasses and reduced dead plant material under grazing also limits range fire intensities and may facilitate invasion by woody species and transition of grasslands and savannas to woodlands (Fig. 1). Typical woody invaders include mesquite (*Prosopis glandulosa* Torr.) and Ashe's juniper (*Juniperus ashei* Buchh.). Once in a woodland state, restoration of a grassland state is difficult without tree and brush removal, prescribed burning, and reseeding of desired species.

Interactions of grazing and training are likely to retain vegetative communities in a grassland or savanna state consisting largely of secondary-succession species and reduce the risk of fire, both desired outcomes from a military management perspective (Fig. 1). In concert with frequent training, however, grazing may increase the occurrence of annual grasses, weedy forbs, and introduced species tolerant of both disturbances, and land rehabilitation and maintenance procedures may be required to limit erosion and restore perennial vegetative cover (Goran et al. 1983). Species commonly seeded for erosion control efforts have included the naturalized grasses bermudagrass [*Cynodon dactylon* (L.) Pers.] and King Ranch bluestem [*Bothriochloa ischaemum* (L.) Keng]. Under infrequent training, prescribed burning may be necessary to limit woody plant invasion into grasslands and the expansion of woodlands outside riparian areas and steep slopes.

Researchers who would refine the state-and-transition model for Fort Hood should consider site-dependent responses to multiple disturbances such as natural events (e.g., climate change, floods, wildfire) and/or management actions (grazing, training, prescribed burning). Our

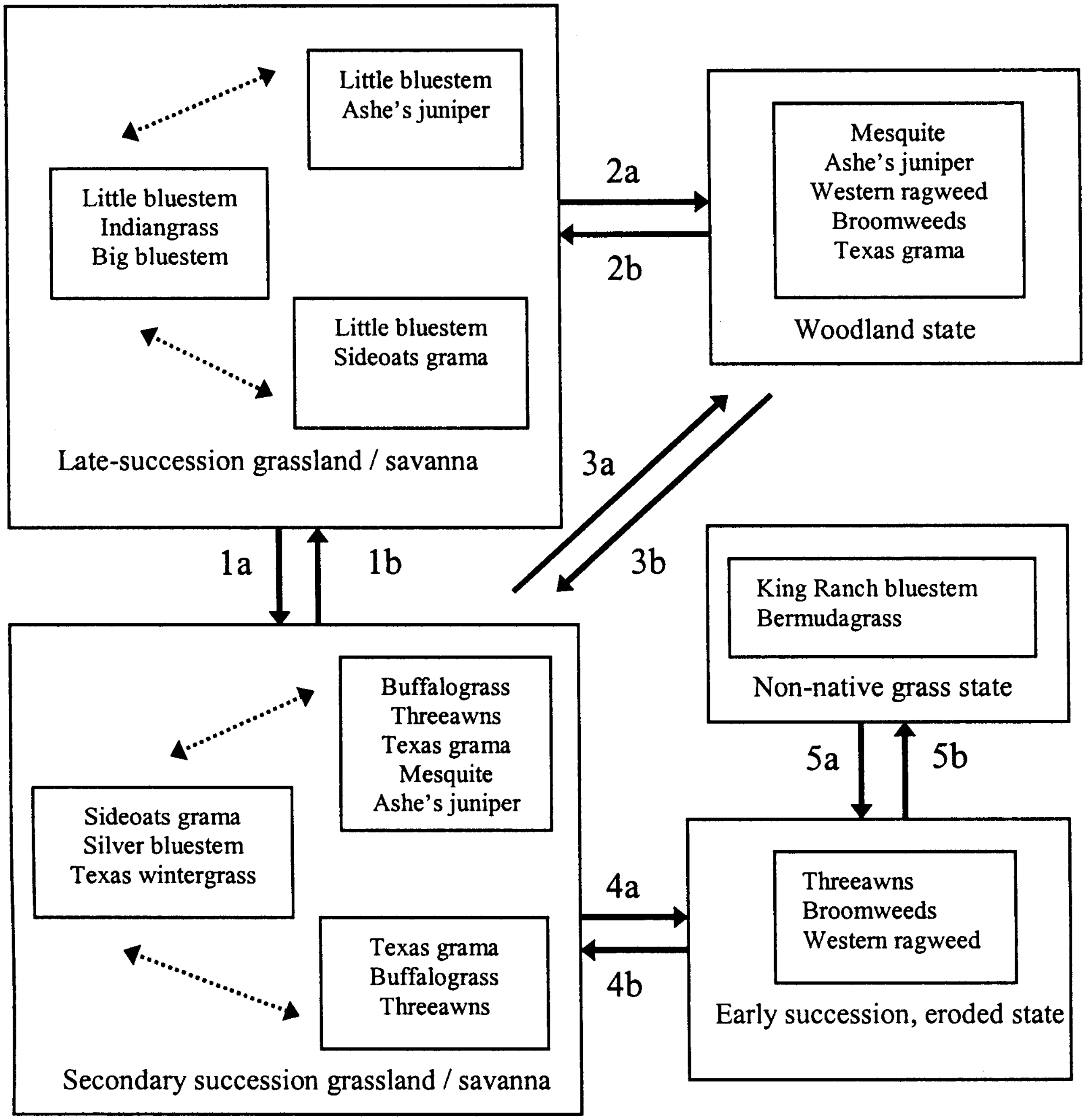

Figure 1. State-and-transition model of grassland dynamics at Fort Hood, TX. Smaller boxes are communities identified by dominant species and larger boxes are vegetative states. Dashed arrows represent reversible vegetation change within communities caused by variation in grazing, precipitation, and burning regimes. Solid arrows are transitions between alternative vegetation states. 1a = Grazing and training encourages transition of late-succession grasslands and savanna to secondary-succession grasslands and savanna. 2a, 3a = A reduction of rangeland fire enables invasion and dominance by woodland species. 1b, 2b = Brush and tree removal, prescribed burning, and reseeding of mid- to tallgrass dominants are necessary for restoration of late-succession grassland and savanna. 3b = Training reduces establishment and persistence of trees and shrubs. 4a = Constant training combined with grazing may favor early-succession grassland largely supportive of annual grasses and weedy forbs. 4b, 5b = Land rehabilitation may be necessary to restore perennial vegetation and limit erosion. 5a = Return of continuous disturbance likely will revert improved sites back to an early-succession eroded state.

model focused on grazing and training effects on grasslands. Drought and fire are common disturbances of the Great Plains that are likely to contribute to both grassland and woodland vegetation dynamics (Archer and Smeins 1991; Briske et al. 2005). Vegetation responses to grazing and training also are likely to be site-dependent, a fact that may require researchers to develop state-and-transition models for specific climatic, soil, and hydrologic units (Bestelmeyer et al. 2003).

SUMMARY

The combination of cattle grazing and tracked vehicle training on military lands has the potential to accelerate soil compaction and erosion on military lands. Alternatively, it may be the key to an effective vegetation management strategy. The literature showed that grassland compositional changes in response to grazing and training were common and may or may not be reversible on practical time scales. A state-and-transition model we developed for Fort Hood, TX, illustrated that grazing and training were likely to maintain grasslands in secondary succession, consisting of shortgrass to mid-grass species. Landscapes dominated by woody vegetation or eroded sites, where annual grasses and weedy forbs persist, could develop depending on soil and climatic conditions, rangeland fire frequencies, and the frequency and pattern of use by both cattle and troops. State-and-transition models are useful tools for military land managers to evaluate the effects of different land uses on ecosystems and should be developed for military lands in other grassland formations throughout the Great Plains.

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