An Invasive Cool-Season Grass Complicates Prescribed Fire Management in a Native Warm-Season Grassland

Authors: McGranahan, Devan Allen, Engle, David M., Fuhlendorf, Samuel D., Miller, James R., and Debinski, Diane M.

Source: Natural Areas Journal, 32(2) : 208-214

Published By: Natural Areas Association

URL: https://doi.org/10.3375/043.032.0214

CONSERVATION ISSUE

•

An Invasive Cool-season Grass Complicates Prescribed Fire Management in a Native Warm-season Grassland

Devan Allen McGranahan[1,5]

[1]Rangeland Ecology Lab
Department of Natural Resource Ecology and Management
Iowa State University
Ames, Iowa

David M. Engle [2]
Samuel D. Fuhlendorf [2]
James R. Miller [3]
Diane M. Debinski [4]

[2]Department of Natural Resource Ecology and Management
Oklahoma State University
Stillwater, Oklahoma

[3]Department of Natural Resources and Environmental Science
University of Illinois
Urbana, Illinois

[4]Department of Ecology, Evolution and Organismal Biology
Iowa State University
Ames, Iowa

•

[5] Corresponding author:
mcgranah@alumni.grinnell.edu

Natural Areas Journal 32:208–214

ABSTRACT: Invasive species challenge managers of natural areas. In many ecosystems, restoring and maintaining pre-historic disturbance regimes promotes native biodiversity and controls invasive plant species. We report challenges in applying patch-burn grazing to restore the ecological interaction between fire and herbivores in eastern North American tallgrass prairie. We use United States Forest Service fire behavior software and fuel models to simulate the effect of a cool-season grass invasion into tallgrass prairie. By introducing a high-moisture fuel type into the native fuelbed, tall fescue (*Lolium arundinaceum* Schreb. S.J. Darbyshire) creates a heterogeneous fuelbed that limits fire spread rate. Our results indicate that a high-moisture fuel type invading a high proportion of a fuelbed requires up to four times the wind speed to achieve a rate of spread similar to that in an uninvaded fuelbed. Reduced fire spread undermines restoring the natural fire regime, putting invaded grassland systems at a higher risk of succession to a woodland state. To mitigate against negative effects of high-moisture invaders on prescribed burning and ensure that fires maintain the intensity required for management goals, managers should consider the following when planning burns: Accumulate higher fuel loads by reducing herbivory or reducing fire frequency; burn earlier in the spring or later in the fall, during the dormant season of the invader; and consider alternative fire weather such as lower relative humidity, perhaps with lower wind speeds to maintain an acceptable level of complexity.

Index terms: BehavePlus, fire behavior, fire regime, *Lolium arundinaceum*, tall fescue

INTRODUCTION

Invasive, non-native species pose one of the greatest challenges to the management of natural areas worldwide (Pimentel et al. 2005). Behind habitat loss, invasive species are the second most important threat to native biodiversity (Wilcove et al. 1998). Invasive plant species can disrupt important ecosystem processes in natural areas (Vitousek et al. 1997; Ehrenfeld 2003; Levine et al. 2003), but the control of invasive species often comes at extraordinary cost (Babbit 1998; Mack et al. 2000).

Restoration of natural disturbance regimes is an important element in the maintenance of native biodiversity (Stohlgren et al. 1999). Natural processes, such as fire and grazing, can economically and effectively control invasive species (Ortmann et al. 1998; Bidwell et al. 2002; DiTomaso et al. 2006; Rinella and Hileman 2009). Many grassland systems evolved under an interactive fire and grazing disturbance regime in which herds of herbivores follow spatially-discrete fires and concentrate grazing on the succulent regrowth without discriminating between individual forage species, an effect distinct from fire or grazing alone (McNaughton 1984; Fuhlendorf and Engle 2001; Archibald et al. 2005; Fuhlendorf et al. 2009). Patch burn-grazing is the operationalization of the fire-grazing interaction as a management tool, replicating pre-settlement disturbance patterns in modern grasslands (Fuhlendorf and Engle 2001, 2004; Toombs et al. 2010).

By shifting forage selection from the plant scale to the landscape scale within the burned area, managers can target otherwise unpalatable invasive species with patch burn-grazing. Some invasive species – like sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don), a serious invasive species in North American grasslands – are promoted by fire (Munger 2004) and avoided by grazers (Dwyer et al. 1964). By following fire with concentrated herbivory, patch burn-grazing limits the annual spread of sericea lespedeza (Cummings et al. 2007).

We attempted to implement patch burn-grazing in tallgrass prairie to increase native plant species abundance, reduce exotic plant invaders, and improve wildlife habitat. While research on the effects of patch burn-grazing on plant and wildlife communities is ongoing, we discuss here our prescribed burning experience in heavily-invaded tallgrass prairie. We have found that the invasive plant species of greatest management concern – tall fescue (*Lolium arundinaceum* Schreb. S.J. Darbyshire, syn. *Festuca arundinacea* Schreb.) – appears to have a negative impact on fire, rather than vice-versa. This effect seems to be attributable to differences in growing seasons between the cool-season invasive grass and the warm-season native prairie community. In this paper, we present the results of fire behavior models that show

how tall fescue affects the spread of fire across a gradient of invasion and wind speeds, and discuss the implications of altered fire behavior in terms of fire regime and the management of natural areas.

AN INVASIVE SPECIES COMPLICATES PRESCRIBED FIRE

We identified nine remnant prairie tracts identified as moderate to high conservation value (The Nature Conservancy, unpubl. data) within the Grand River Grasslands of northern Harrison County, Missouri, and southern Ringgold County, Iowa. Pre-treatment surveys confirmed that each tract had a respectable list of native species, although it was clear that several tracts had been degraded by a recent history of severe cattle (*Bos taurus*) grazing and invasion by exotic species (McGranahan 2008).

In the first season, we struggled to complete our prescribed fire treatment, especially on those sites that were historically severely grazed and invaded by exotic species. We observed low fire intensity and patchy fire spread: forb stems and ground litter remained unconsumed by fire, and low-intensity fire spread was limited to 60% – 70% of burn patches, despite tightly-spaced, strip-fire ignition patterns.

Continuity of spread and fire intensity have increased because of greater fuel load following moderate stocking rates under the patch-burn grazing scheme. However, from 2007 through 2010, we have observed that several fire effects – including the patchiness of fire spread, amount of surface fuels consumed, and response to the burned area by grazers in the patch burn-grazing experiment – depend on growth of tall fescue at the time of the fire.

While research has shown that fire alone is a poor control measure for tall fescue (Washburn et al. 1999; Madison et al. 2001; Rhoades et al. 2002; Barnes 2004), to our knowledge no studies have addressed the effect of tall fescue on fire behavior within an invaded fuelbed. Although the dormant season for native prairie extends through the spring (Briggs and Knapp 1995) when fine, dead fuel moisture in a native-dominated fuelbed averages about 30% (Bidwell and Engle 1992), we have frequently observed green, photosynthetically-active tall fescue in our burn units. Furthermore, we have observed a negative relationship between the amount of live, green material and the intensity and spread of our fires.

Our observations suggest that the asynchrony in growing season between the cool-season invader and the native, warm-season prairie introduces a substantially different fuel type into the tallgrass prairie fuelbed. Introducing a different fuel type into the native fuelbed is a common denominator of exotic species invasions that result in altered fire regimes (D'Antonio 2000).

Although the ecological literature contains numerous examples of invasive grasses that alter native fire regimes (D'Antonio and Vitousek 1992; D'Antonio 2000; Grace et al. 2001; Brooks et al. 2004), establishing that a particular invasive species has such an effect is a complex process that begins with demonstrating that the invader alters the native fuelbed (Brooks 2008).

MODELING INVADER EFFECT ON THE FUELBED

We hypothesize that tall fescue alters the tallgrass prairie fuelbed by introducing live plant tissue with high foliar moisture into an otherwise dry and dormant stand during the fire season. As such, we expect that fire spreads more slowly through the fuelbed as the amount of tall fescue in the fuelbed increases. We test this prediction by modeling the effect of tall fescue invasion into native tallgrass prairie with the BehavePlus fire modeling software (Andrews et al. 2008) using fuelbed parameters measured from our study tracts in the Grand River Grasslands. BehavePlus operates standard United States Forest Service fuel models (Rothermel 1983; Scott and Burgan 2005) that have been used to predict the effects of invasive species on fire behavior (van Wilgren and Richardson 1985).

To better inform the fire spread simulation, we assessed the following aspects of the fuelbed: live foliar moisture content of tall fescue over the course of a growing season, dead fuel moisture of the fuelbed during the prescribed fire season, and the range of tall fescue invasion across our remnant tracts. We measured the moisture content of living tall fescue tillers from April to November 2008 at four sites in Ringgold County, Iowa, by clipping approximately 40 g of live leaf material and drying to constant weight at 60 ºC at approximately 10-day intervals. Expressed on a dry-weight basis, tall fescue foliar moisture was above 100% for most of the growing season, and averaged about 250% during the spring prescribed fire season (Figure 1). Water content of live, tall fescue and dead, native grass fuel samples collected in early April, 2010 averaged 250% and 10%, respectively.

We determined the range of tall fescue invasion within our study tracts by measuring tall fescue canopy cover from 2007 – 2009 within 90, 0.5-m^2 quadrats per tract (Daubenmire 1959), spaced evenly along transects located to cover the maximal area of each tract. Across all years and all tracts, these data indicated that tall fescue canopy cover ranged between 0 and 70%.

To simulate invasion of tall fescue into a tallgrass prairie fuelbed, we used the two fuel model option in the SURFACE module of BehavePlus to predict the maximum rate of spread (ROS) of a flame front moving with the wind (headfire) across a fuelbed made up of patches of slow-burning and fast-burning fuel types (Finney 2003; Andrews et al. 2008). The two fuel types are input to BehavePlus as a relative proportion of the total fuelbed – in this case, 0 – 70% tall fescue canopy cover, in 10% increments. To determine how prescribed fire managers might mitigate the effects of tall fescue invasion, we simultaneously modeled the effect of increasing wind speed on fire spread rates through tall fescue-invaded prairie, assuming fire will likely bridge fuel gaps via heat transfer. We used grass fuel model GR4 to represent patches of tall fescue invasion, and modified the GR7 model to represent a tallgrass prairie fuelbed typical of our study area (Scott and Burgan 2005; see Figure 2 legend for fuel model parameters).

When calculating a single fuel model, BehavePlus returns several correlated

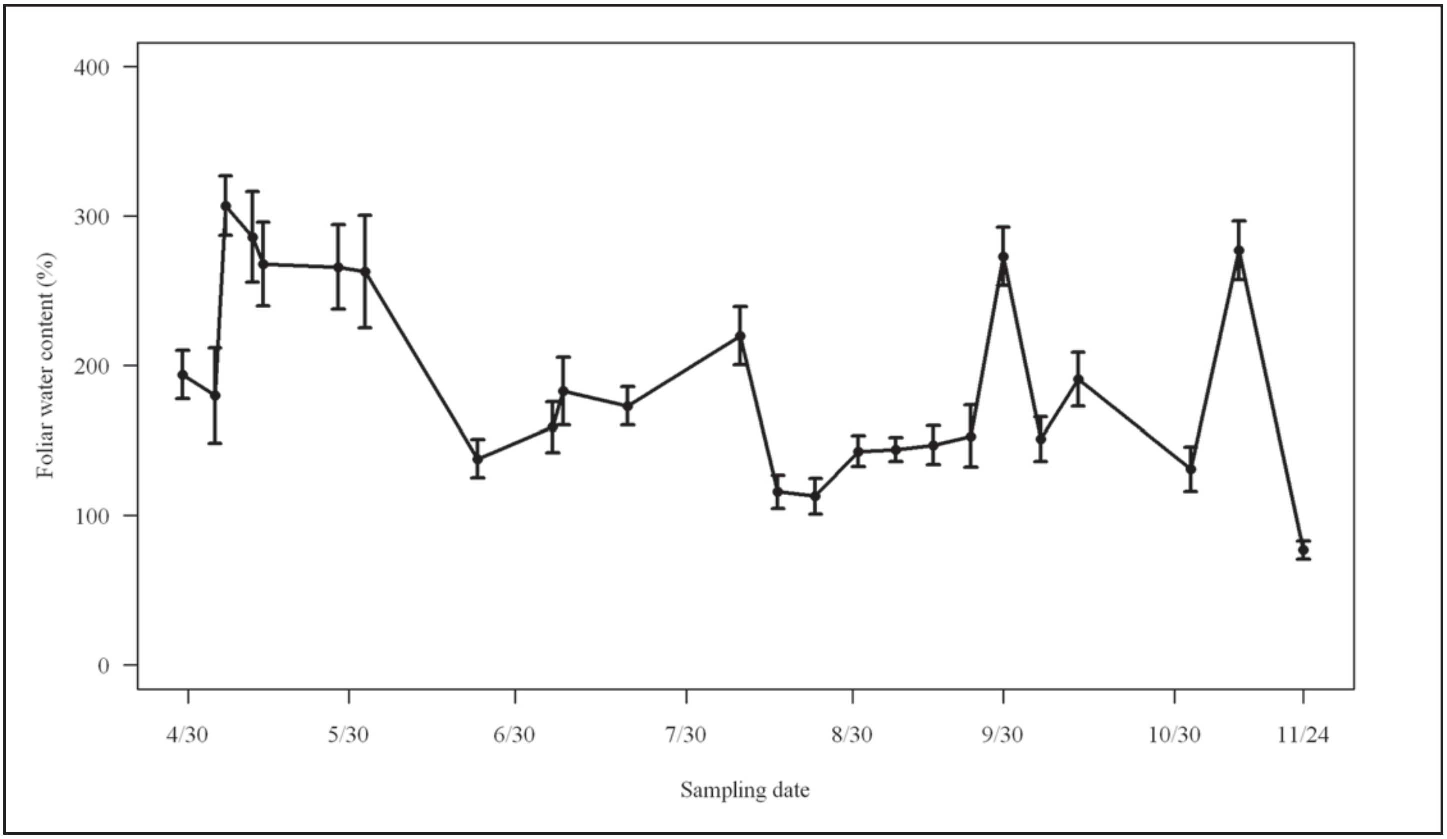

Figure 1. Tall fescue live foliar water content from Apr. 29 – Nov. 24, 2008, expressed on a dry-weight basis. Data are mean (± standard error) foliar water content, on a dry-weight basis, from tillers collected at four sampling points located in south-central Iowa.

measures of fire behavior, including fireline intensity (heat released meter^{-1} second^{-1} by the flame front of the fire), flame length (a visual measure derived from fireline intensity; the distance between the combustion zone and average flame tip), and rate of spread (the speed at which the fire travels through surface fuels) (Andrews et al. 2008). Because this simulation involves an average between the two constituent fuel models, BehavePlus only returns an average rate of spread for the fuelbed as a fire behavior output. However, since the two-model concept is based on a slow-burning fuel type constituting a certain proportion of the simulated fuelbed (Finney 2003), one can attribute slower rates of spread to the reduced intensity of the slow-burning fuel type. When applying model results to a realistic prescribed fire scenario, one can interpret reduced rate of spread to indicate a lower-intensity fire producing shorter flames and less severe fire effects.

Fire behavior differed greatly between the tall fescue (GR4) and uninvaded tallgrass prairie (modified GR7) fuel models as single fuel model runs in BehavePlus. The tall fescue model (GR4) spread at a rate of 0.1 m/min and produced 1.0 kW/m of energy and flames 0.1 m in length at all wind speeds. The tallgrass prairie fuel model (GR7) responded to increases in wind speed (8-24 km/hr), with rate of spread ranging from 23 – 118 m/min, fireline intensity ranging from 3245 – 16,638 kW/m, and flame length ranging from 3.2 – 6.8 m.

As expected, increasing the proportion of tall fescue in the tallgrass prairie fuelbed decreased ROS across the fuelbed (Figure 2). With no tall fescue, increasing the wind speed by a factor of four increased ROS by a factor of 5.1, while at 70% tall fescue cover, this same increase in wind speed increased ROS by a factor of 4.3. At the highest wind speed modeled here (24 km/h), increasing tall fescue's proportion of the fuelbed from zero to 70% reduced ROS by a factor of five. Although ROS increases with wind speed across the range of tall fescue cover – counteracting the effects of the slow-burning fuel type – increases in the proportion of tall fescue in the fuelbed clearly affect fire behavior by substantially decreasing ROS at a given wind speed. Moreover, as tall fescue cover increases, wind speed has less influence on ROS.

IMPLICATIONS FOR PRESCRIBED FIRE MANAGEMENT

These results indicate that when a high-moisture fuel type invades a high proportion of a fuelbed, up to four times the wind speed is required in a prescribed fire to achieve a rate of spread similar to that in an uninvaded fuelbed. However, managers should be reticent to conduct prescribed fires under such conditions, given the increased complexity of containing and perhaps suppressing a fire under high winds. Such high winds likely exceed the maxima set out in burn plans, especially those approved at higher levels of management, as in many agencies.

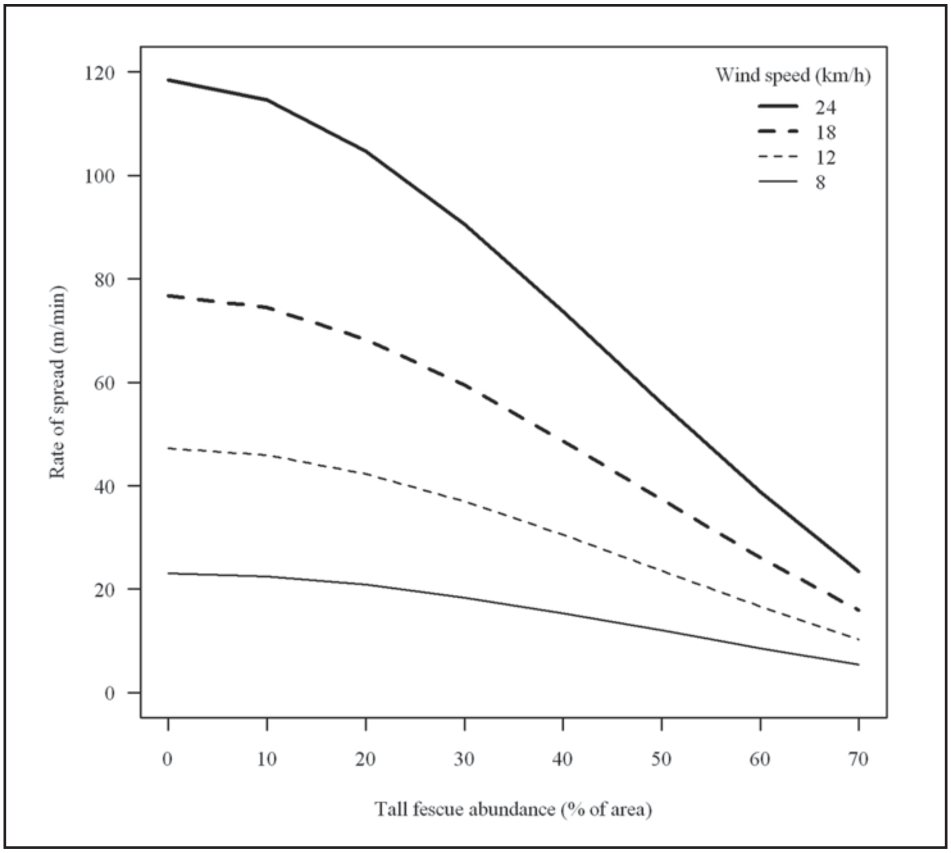

Figure 2. Rate of fire spread, predicted by BehavePlus, at four wind speeds across a gradient of tall fescue invasion of tallgrass prairie. Tall fescue invasion is represented by the GR4 fuel model, and the tallgrass prairie fuelbed is represented by a modified GR7 fuel model (Scott and Burgan 2005). Parameters modified from the standard GR7 fuel model include fine dead fuel load = 8649 kg/ha (3.5 tons/acre) and live herbaceous fuel load = 1236 kg/ha (0.5 tons/acre). All other fuel model parameters unmodified from Scott and Burgan (2005). Parameters set for this simulation (BehavePlus v.4.0; Andrews et al. 2008) include live herbaceous fuel moisture = 250%; dead fine fuel moisture = 10%; slope = 0%.

Factors other than wind speed might also increase fire behavior in high invasion situations. In our experience, three factors can be used to mitigate the effects of high-moisture tall fescue in the fuelbed during the prescribed fire: (1) total fuel load, (2) relative humidity, and (3) burning date.

Total fuel load

Grazing, by nature, reduces the total fuel load by removing biomass that could otherwise be burned. In fact, in natural areas where invasive species have contributed to increased fire frequency and intensity, such as cheatgrass (*Bromus tectorum* L.) in western North American rangelands, grazing has been prescribed for fuel reduction (Davidson 1996). On several of our tallgrass prairie tracts that had been historically severely grazed, the plant community has begun to recover from the severe herbivory and increase annual productivity. Many of these tracts have carried fire better in recent years because of increased fuel load, but setting appropriate stocking rates so as to ensure sufficient fuel for the next season's fire remains a key management consideration. Because grazers focus on the most recently burned patch in areas managed with patch burn-grazing, and generally ignore patches with longer time since fire, patch burn-grazing might increase total fuel load in future burn patches when stocking rate is managed appropriately.

Relative humidity

We have observed substantial increases in fire behavior, including increased rate of spread, in tall fescue-invaded fuelbeds when relative humidity falls below about 30% – 32%. We have burned with relative humidity as low as 27% using typical control tactics, including narrow strip ignition patterns to create wide (at least four times expected flame length) areas of consumed fuel around the perimeter of the burn unit. When burning with relative humidity around or below 30%, these control lines are usually about 50 m wide – often > 10 times the expected flame length in light, invaded fuelbeds – and are intended mostly to keep airborne firebrands within the unit to reduce the potential for spot fires beyond the perimeter. The strip ignition pattern, versus a single backing fire, allows for both rapidity and safety when establishing wide control lines.

Unfortunately, relative humidity is not directly user-manipulated in BehavePlus, although dead fuel moisture content (DFMC) is a user-defined variable that is influenced by relative humidity. Reducing DFMC from 10% to 5% in the present simulation increased ROS by about 25% at all wind speeds and all levels of invasion (data not shown). Thus, despite the physical relationship between DFMC and relative humidity, manipulating DFMC in BehavePlus does not seem to be an accurate way to model change in relative humidity. Relative humidity is influenced by air temperature, which is not considered in the SURFACE module of BehavePlus (Andrews et al. 2008).

It is apparent that more research into the effect of relative humidity on fire behavior in high-moisture fuel types is necessary. We do not yet have a physical or physiological explanation for how relative humidity, more than other elements of the fire environment such as air temperature or wind speed, might affect the combustion of photosynthetically-active plant tissue. In the meantime, prescribed fire managers might find it more favorable to burn at a lower relative humidity than at a higher wind speed, especially if they can mitigate the increased complexity with a lower-than-normal wind speed and still achieve management objectives.

Season of burn

Our most effective mitigation of high-moisture tall fescue within our burn units has been to burn before tall fescue becomes photosynthetically active in the spring. In our experience, tall fescue greens up rapidly before both the tallgrass prairie community's native plants and most other exotic cool-season grasses. Thus, we seek to begin fire operations within a couple of weeks of snowmelt, as early as the first week of March in a region in which spring burning peaks about the first week of April. This early date presents additional challenges to prescribed fire crews, including the necessity for warmer clothes and the risk of water tanks and pumps freezing. Fall fires are possible, but as Figure 1 indicates, the same challenges from cold would confront fire crews attempting to burn after tall fescue's growing season, which extends into late November. Conducting burns during tall fescue's dormant season might require fire managers to overcome logistical challenges and perhaps cultural perceptions about the use and timing of prescribed fire. However, evidence indicates that the window of acceptable burning conditions in tallgrass prairie might be wider than conventional wisdom suggests (Weir 2011).

IMPLICATIONS FOR FIRE-DEPENDENT ECOSYSTEMS

Generally, research has shown that fire frequency and intensity increase as a result of exotic grass species invading native fuelbeds (Mack and D'Antonio 1998; D'Antonio 2000; Grace et al. 2001), which D'Antonio and Vitousek (1992) generalize as the 'grass-fire cycle.' Numerous examples from natural areas around the world support this model, including African grasses in Australia (Rossiter et al. 2003) and Hawai'i (Hughes et al. 1991) and cheatgrass in western North America (Brooks 2008). The invasive grass in each of these settings promotes fire by increasing fuelbed homogeneity in such a way that reduces fuel gaps that normally interrupt fire spread in the natural fire regime (Whisenant 1990; Levine et al. 2003).

This rule fails to cover the contrasting effect of invasive species on fire behavior. We suggest that asynchrony in growing seasons between tall fescue (with its maximum growth period in the cool season) and native tallgrass prairie (with maximum growth in the warm season) intersperses high-moisture, living tissue that slows fire spread within an otherwise dry, dormant fuelbed. The 250% live tissue moisture content of tall fescue reported here during the spring burning season far exceeds 120%, the level of live moisture at which fire behavior is severely altered (Jolly 2007).

The effects of an invasive species that restricts the spread of fire in a fire-dependent ecosystem could be profound. Although evidence that an invasive species modifies the native fuelbed is but the first step in establishing that an invasive species alters the natural fire regime (Brooks 2008), the potential ecological ramifications of reduced fire spread following the invasion of high-moisture exotic species are clear. The eastern tallgrass prairie has maintained a grassland state because of an evolutionary history of fire that has been essential for both plant and wildlife communities (Transeau 1935; Reinking 2005), but without fire of sufficient frequency and intensity, these grasslands are replaced by woodlands dominated by species such as eastern redcedar (*Juniperus virginiana* L.) (Engle et al. 1987; Briggs et al. 2002). Without the herbaceous fuel required to carry fire, managers must resort to much more expensive mechanical or chemical means to restore and maintain the native grassland state once woodland has established (Bidwell et al. 2002).

CONCLUSIONS

Invasive species present a major challenge to the management of natural areas, but the restoration and maintenance of pre-historic disturbance regimes is often a cost-effective means to combat invasive species and promote native biodiversity. As climate change affects the distribution of species and composition of communities (Walther et al. 2002), managers of natural areas are increasingly confronted by the challenge of invasive species with fire-related traits that differ from native systems.

In the tallgrass prairie of eastern North America, we suggest that tall fescue limits restoration of the fire-grazing interaction by introducing a high-moisture fuel type into the native fuelbed. By creating a heterogeneous fuelbed through which fire spreads more slowly, up to four times the wind speed is required to achieve a rate of spread similar to that in an uninvaded fuelbed. Conventional, cost-effective tools, like prescribed fire and prescribed grazing, might be ineffective or even counter-productive when an invasive species modifies the native fuelbed to the point that fire behavior is altered. Managers of natural areas might need to adjust their strategies to mitigate negative effects on the native fuelbed. We suggest that managers consider increasing the total fuel load, altering the season of burn, and re-evaluating fire weather conditions under which prescribed fire can both achieve management objectives as well as meet standards for safety and control. Fire prescriptions and burn plans for areas with high levels of invasion by high-moisture species should also account for fuel moisture and fuel load parameters to ensure that fires maintain the intensity required to achieve management goals.

ACKNOWLEDGEMENTS

This work is made possible by support from: the National Research Initiative of the U.S. Department of Agriculture Cooperative State Research, Education and Extension Service, grant number 2006-35320-17476; Iowa Department of Natural Resources and U.S. Fish and Wildlife Service through the State Wildlife Grants Program; Iowa State University; Oklahoma State University; and The Nature Conservancy Nebraska's Weaver competitive grants program. We thank R. Harr and S. Rusk for collecting samples of tall fescue.

Devan Allen McGranahan earned his PhD in Ecology and Evolutionary Biology at Iowa State University in 2011 and is a post-doctoral fellow at The University of the South in Sewanee, TN.

David M. Engle is a rangeland ecologist and Director of the Water Research and Extension Center at Oklahoma State University, Stillwater, OK. Dr. Engle is involved with fire-grazing interaction work in Iowa and Oklahoma.

Samuel D. Fuhlendorf is a rangeland ecologist and Sarkeys Distinguished Professor of *Rangeland Ecology and Management in the Department of Natural Resource Ecology and Management at Oklahoma State University, Stillwater, OK. His work includes research on the fire-grazing interaction in a number of ecosystems.*

James R. Miller is a landscape ecologist and professor in the Department of Natural Resources and Environmental Sciences at the University of Illinois, Urbana, IL. His work focuses on reconciling human land use with the conservation of biodiversity.

Diane M. Debinski is a conservation biologist and professor in the Department of Ecology, Evolution and Organismal Biology at Iowa State University, Ames, IA. Her research includes the restoration of prairie habitats and the study of montane meadows and climate change.

LITERATURE CITED

Andrews, P.L., C. Bevins, and R. Seli. 2008. BehavePlus fire modeling system. United States Department of Agriculture, Forest Service, Ogden, Utah. Available online <http://www.firemodels.org>.

Archibald, S., W.J. Bond, W.D. Stock, and D.H.K. Fairbanks. 2005. Shaping the landscape: fire-grazer interactions on an African savanna. Ecological Applications 15:96-109.

Babbit, B. 1998. Statement by Secretary of the Interior on invasive alien species. Proceedings, National Weed Symposium, BLM Weed Page, April 8-10, Denver, Colo.

Barnes, T.G. 2004. Strategies to convert exotic grass pastures to tall grass prairie communities. Weed Technology 18:1364-1370.

Bidwell, T.G., and D.M. Engle. 1992. Relationship of fire behavior to tallgrass prairie herbage production. Journal of Range Management 45:579-584.

Bidwell, T.G., J.R. Weir, and D.M. Engle. 2002. Eastern redcedar control and management – best management practices to restore Oklahoma's ecosystems. Oklahoma Cooperative Extension Service, Stillwater.

Briggs, J.M., G.A. Hoch, and L.C. Johnson. 2002. Assessing the rate, mechanisms, and consequences of the conversion of tallgrass prairie to Juniperus virginiana forest. Ecosystems 5:578-586.

Briggs, J.M., and A.K. Knapp. 1995. Interannual variability in primary production in tallgrass prairie: climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. American Journal of Botany 82:1024-1030.

Brooks, M.L. 2008. Plant invasions and fire regimes. General Technical Report RMRS-GTR-42-vol. 6, U.S. Department of Agriculture, Forest Service, Ogden, Utah.

Brooks, M.L., C.M.D. Antonio, D.M. Richardson, J.B. Grace, J. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. BioScience 54:677-688.

Cummings, D.C., S.D. Fuhlendorf, and D.M. Engle. 2007. Is altering grazing selectivity of invasive forage species with patch burning more effective than herbicide treatments? Rangeland Ecology and Management 60:253-260.

D'Antonio, C.M. 2000. Fire, plant invasions, and global changes. Pp. 65-93 *in* H.A. Mooney and R. J. Hobbs, eds., Invasive Species in a Changing World. Island Press, Washington, D.C.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63-87.

Daubenmire, R. 1959. A canopy-coverage method of vegetational analysis. Northwest Science 33:43-64.

Davidson, J. 1996. Livestock grazing in wildland fuel management programs. Rangelands 18:242-245.

DiTomaso, J.M., M.L. Brooks, E.B. Allen, R. Minnich, P.M. Rice, and G.B. Kyser. 2006. Control of invasive weeds with prescribed burning. Weed Technology 20:535-548.

Dwyer, D.D., P.L. Sims, and L.S. Pope. 1964. Preferences of steers for certain native and introduced forage plants. Journal of Range Management 17:83-85.

Ehrenfeld, J.C. 2003. Effects of exotic plant invasions on soil nutrient cycling processes. Ecosystems 6:503-523.

Engle, D.M., J.F. Stritzke, and P.L. Claypool. 1987. Herbage standing crop around eastern redcedar trees. Journal of Range Management 40:237-239.

Finney, M.A. 2003. Calculation of fire spread rates across random landscapes. International Journal of Wildland Fire 12:167-174.

Fuhlendorf, S.D., and D.M. Engle. 2001. Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns. BioScience 51:625-632.

Fuhlendorf, S.D., and D.M. Engle. 2004. Application of the fire-grazing interaction to restore a shifting mosaic on tallgrass prairie. Journal of Applied Ecology 41:604-614.

Fuhlendorf, S.D., D.M. Engle, J. Kerby, and R. Hamilton. 2009. Pyric herbivory: rewilding landscapes through the recoupling of fire and grazing. Conservation Biology 23:588-598.

Grace, J.B., M.D. Smith, S.L. Grace, S.L. Collins, and T.J. Stohlgren. 2001. Interactions between fire and invasive plants in temperate grasslands of North America. Pp. 40-65 *in* Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Tall Timbers Research Station, Tallahassee, Fla.

Hughes, F., P.M. Vitousek, and T. Tunison. 1991. Alien grass invasion and fire in the seasonal submontane zone of Hawai'i. Ecology 72:743-747.

Jolly, W.M. 2007. Sensitivity of a surface fire spread model and associated fire behaviour fuel models to changes in live fuel moisture. International Journal of Wildland Fire 16:503-509.

Levine, J.M., M. Vilà, C.M. D'Antonio, J.S. Dukes, K. Grigulis, and S. Lavorel. 2003. Mechanisms underlying the impacts of exotic plant invasions. Proceedings of the Royal Society of London Series B 270:775-781.

Mack, M.C., and C.M. D'Antonio. 1998. Impacts of biological invasions on disturbance regimes. Trends in Ecology and Evolution 13:195-198.

Mack, R.N., D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout, and F.A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecological Applications 10:689-710.

Madison, L.A., T.G. Barnes, and J.D. Sole. 2001. Effectiveness of fire, disking, and herbicide to renovate tall fescue fields to Northern Bobwhite habitat. Wildlife Society Bulletin 29:706-712.

McGranahan, D.A. 2008. Degradation and restoration in remnant tallgrass prairie: grazing history, soil carbon, and invasive species affect community composition and response to the fire-grazing interaction. M.S. thesis, Iowa State University, Ames.

McNaughton, S.J. 1984. Grazing lawns: animals in herds, plant form, and coevolution. The American Naturalist 124:863-886.

Munger, G.T. 2004. Lespedeza cuneata. *In* Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah. Available online <http://www.fs.fed.us/database/feis/>.

Ortmann, J., J. Stubbendieck, R.A. Masters, G.H. Pfeiffer, and T.B. Bragg. 1998. Efficacy and costs of controlling Eastern redcedar. Journal of Range Management 51:158-163.

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

Reinking, D.L. 2005. Fire regimes and avian responses in the central tallgrass prairie. Studies in Avian Biology 30:116-126.

Rhoades, C., T. Barnes, and B. Washburn. 2002. Prescribed fire and herbicide effects on soil processes during barrens restoration. Restoration Ecology 10:656-664.

Rinella, M.J., and B.J. Hileman. 2009. Efficacy of prescribed grazing depends on timing intensity and frequency. Journal of Applied Ecology 46:796-803.

Rossiter, N.A., S.A. Setterfield, M.M. Douglas, and L.B. Hutley. 2003. Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. Diversity and Distributions 9:169-176.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. General Technical Report, U.S. Department of Agriculture, Forest Service, Ogden, Utah. Available online <http://www.fs.fed.us/rm/pubs_int/int_gtr143.pdf>.

Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. General Technical Report, U.S. Department of Agriculture, Forest Service, Fort Collins, Colo.

Stohlgren, T.J., D. Binkley, G.W. Chong, M.A. Kalkhan, L.D. Schell, K.A. Bull, Y. Otsuki, G. Newman, M. Bashkin, and Y. Son. 1999. Exotic plant species invade hot spots of native plant diversity. Ecological Monographs 69:25-46.

Toombs, T.P., J.D. Derner, D.J. Augustine, B. Krueger, and S. Gallagher. 2010. Managing for biodiversity and livestock. Rangelands 32:10-15.

Transeau, E.N. 1935. The prairie peninsula. Ecology 16:423-437.

van Wilgren, B.W., and D.M. Richardson. 1985. The effects of alien shrub invasions on vegetation structure and fire behaviour in South African fynbos shrublands: a simulation study. Journal of Applied Ecology 22:955-966.

Vitousek, P.M., C.M. D'Antonio, L.L. Loope, M. Rejmanek, and R. Westbrooks. 1997. Introduced species: a significant component of human-caused global change. New Zealand Journal of Ecology 21:1-16.

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesank, T.J.C. Beebee, J.-M. Fromentin, O. Hoegh-Guildberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature 416:389-395.

Washburn, B.E., T.G. Barnes, and J.D. Sole. 1999. No-till establishment of native warm-season grasses in tall fescue fields. Ecological Restoration 17:144-149.

Weir, J.R. 2011. Are weather and tradition reducing our ability to conduct prescribed burns? Rangelands 33:25-30.

Whisenant, S.G. 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. General Technical Report INT-276, U.S. Department of Agriculture, Frest Service, Logan, Utah.

Wilcove, D.S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience 48:607-615.