MANAGEMENT OF WOODY PLANT ENCROACHMENT:

DECISION THEORY, ECOLOGICAL THEORY, & EVALUATION

A Dissertation

by

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ABSTRACT

Woody plant encroachment (WPE) reduces ecosystem services and economic benefits obtained from rangelands. Prescribed fire disturbance regimes have been identified as an ecologically and economically viable management options. Practitioners have tools for individual treatments but lack process for integrating individual events into successful management regimes. Practitioners lack ecological theory for the interaction between disturbance and WPE in a language and format accessible by the majority of practitioners. Disturbance regime theory (DRT) was developed as ecological theory for practitioners seeking to utilize disturbance, specifically fire to control WPE. DRT utilizes thresholds between population resistance to disturbance intensity and species resilience to disturbance frequency to estimate effects of disturbance regimes to WPE. Disturbance Regime Management (DRM) is the development and application of disturbance regimes for managing WPE. Successful implementation of DRM requires adaptive management. Integrated Rangeland Management System (IRMS) was designed as a structured process for facilitating the implementation of adaptive management on rangelands. It is a wholistic[1] process for visioning, planning, implementing, and monitoring of rangelands. IRMS serves as a common framework for implementing DRM within adaptive rangeland management.

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[1] *Concerning the whole of a system*

Adaptive management and DTR was evaluated through an applied management case study on the Duncan Spade Ranch. McCartney Rose (*Rosa bracteata*) encroachment was adaptively managed with a prescribed fire disturbance regime. Woody cover was monitored with National Agriculture Imagery Program airborne digital images, permanent line transects, and plot photographs. DRM worksheets were used to make qualitative predictions of impact or no impact on McCartney Rose for resistance to fire intensity and resilience to fire frequency. Classified imagery measured 24% woody cover in 2010 decreasing to 6% in 2018. A paired t-test for line transect McCartney Rose cover measured a significant (P= 0.02, 14 df) decrease in woody cover from 16% in 2012 to 8% in 2018. These data support the use of adaptively managed disturbance regimes to control WPE.

This research developed an explicit process for adaptive management. It developed an explicit process for integrating disturbance events into a disturbance management regime to control WPE. Finally, these processes were validated with an adaptive management case study on WPE.

Keywords: adaptive management; rangeland management; disturbance; disturbance regimes; woody plant encroachment; prescribed fire; resistance; resilience.

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Contributors

This work was supervised by a dissertation committee consisting of Professors Mort Kothmann [advisor] and Dr. Douglas Tolleson of the Department of Rangeland Wildlife and Fisheries Management and Professors Dr. William Grant and Sorin Popescu of the Department of Ecology and Conservation Biology.

Josh Britt, Heather Baldi, and Mike Bartmess assisted in data collection for line intercept and photo point monitoring. Ranch manager Robert Spitzmiller implemented management.

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NOMENCLATURE

DRT	Disturbance Regime Theory
DRM	Disturbance Regime Management
IBMS	Integrated Brush Management System
IPT	Individual Plant Treatment
IRMS	Integrated Rangeland Management System
MU	Management Unit
NAIP	National Agriculture Imagery Program
RCM	Range Condition Model
STM	State & Transition Model
VRG	Vegetation Response Group
WPE	Woody Plant Encroachment

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1. INTRODUCTION

Management of Woody Plant Encroachment (WPE) is a challenge faced by rangeland managers across North America. WPE reduces ecosystem services and decreased economic benefits from rangelands (Sala and Maestre 2014). The impact of WPE is heightened by a disconnect between WPE knowledge (control/cause) and widespread application by practitioners. Leading practitioners have successfully utilized fire as a targeted disturbance within adaptive management regimes to control WPE. Adaptive management has been identified as the critical element for successful management regimes utilized by top practitioners (Allen et al. 2017; Briske 2011; Derner and Augustine 2016; Teague and Barnes 2017). However, the decision processes used by successful adaptive managers are not explicit and most producers are not able to successfully apply adaptive management to their management units. Simply saying ‘do adaptive management’ is not sufficient. Novice practitioners need an explicit conceptual framework to guide the implementation of adaptive management and structure the decision processes.

Rangelands are dynamic and leading managers apply dynamic management i.e. adaptive management. To facilitate a transition from static practices and individual treatments to dynamic adaptive regimes practitioners require a framework that supports dynamic management. Integrated Rangeland Management System (IRMS) was developed to provide a structured process managers seeking to apply adaptive management. Disturbance regime theory (DRT) is decision aid developed for application with the IRMS process. It facilitates the development of managed prescribed fire disturbance regimes for controlling WPE. Adaptive management and DRT were evaluated with an adaptive management case study on the Duncan Spade Ranch from 2012 to 2018.

For the field of rangeland management to overcome WPE it must foster the application of dynamic regime management. This research develops an adaptive management process and a prescribed fire disturbance regime decision aid to meet the calls to implement adaptive management by Allen et al. (2017) and reintroduce prescribed fire by Twidwell et al. (2013) to rangeland systems . Successful reintroduction of fire to rangeland requires management transitioning from individual events to regimes. Planning and implementing ‘a prescribed fire’ does not involve adaptive management. It is the management process over many years to create management regimes that involves adaptive management.

1.1.1. Integrated Rangeland Management System: A Process Model for Adaptive Management of Rangelands

WPE reduces ecosystem services and economic benefits provided by rangelands. Adaptive management has been identified as a critical component for successful management of WPE. However, an explicit process for adaptive management of rangelands for use by rangeland mangers has not been designed.

This paper creates an explicit model for the process of rangeland adaptive management. IRMS is a wholistic[2] process for visioning, planning, implementing, and monitoring of rangelands. IRMS development followed management science principles from Scarnecchia (2003), and Forester (1961). IRMS serves as a common framework for implementing adaptive rangeland management. Such a framework is necessary for the implementation of DRT.

1.1.2. 21st Century Management of Woody Plant Encroachment Using Disturbance Regime Theory

WPE on rangelands decreases ecosystem services and economic viability. Practitioners lack ecological theory for the interaction between disturbance and WPE in a language and format accessible by the majority of practitioners. DRT was developed as ecological theory for practitioners seeking to utilize disturbance, specifically fire to control WPE. DRT utilizes thresholds between population resistance to disturbance intensity and species resilience to disturbance frequency to estimate effects of disturbance regimes to WPE. Disturbance regime management worksheets were developed to assist practitioners in the application of DRT to prescribed fire management. Although the concepts of DRT are applicable to mechanical, chemical, or biological control treatments, this paper is focused on prescribed fire as a primary disturbance utilized to control WPE. Prescribed fire regimes are

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[2] *Concerning the whole of a system*

ecologically effective and economically viable for WPE on rangelands, but the planning and implementation of prescribed fire events within a management regime is complex and not easy for managers to apply. Knowledge for the planning and implementation of a fire event is common but the rangeland field lacks a process for integrating a disturbance event into a disturbance regime. This paper reviews and presents theory and tools to support practitioners in application of managed prescribed fire disturbance regimes to manage WPE.

1.1.3. Disturbance Regime Theory and Woody Plant Encroachment: An Adaptively managed Prescribed Fire-Grazing Regime Case Study

This paper is a case study of WPE control on a working ranch on the Texas coastal prairie. A disturbance regime was applied with adaptive management to control McCartney Rose (*Rosa bracteata*) on the Duncan Spade Ranch Wharton County, Texas. The woody cover of the ranch was monitored with National Agriculture Imagery Program airborne digital images, permanent line transects, and plot photographs. Monitoring data were utilized to evaluate the effects of the disturbance regime, consisting of one herbicide treatment and prescribed grazing and fire, on McCartney Rose cover. The monitoring data were used to modify the grazing and fire prescriptions following adaptive management procedures, and to DRT. Disturbance regime management worksheets were utilized to apply DRT to make qualitative predictions of impact or no impact for resistance to fire intensity and resilience to fire frequency for McCartney Rose. McCartney Rose was rated as low-moderate resistance to fire intensity. Resilience to fire frequency was rated high. Estimated prescribed fire intensities varied between low-moderate to moderate. Classified aerial photography measured 24% woody cover in 2010 which decreased to 6% in 2018. A paired t-test for mean cover measured by line transect measured a significant (P= 0.02, 14 df) 50% decrease in woody cover from 16% in 2012 to 8% in 2018. These data support the use of adaptively managed disturbance regimes to control WPE.

1.2. Literature Review

1.2.1. Woody Plant Encroachment

Why are woody plants encroaching on rangelands? Hypotheses include changes in climate, fire, herbivory, atmospheric CO2, and N deposition (Archer 1994). Of the identified causes of WPE, only fire and herbivory regimes can be managed at the ranch level. Current research indicates that WPE was primarily driven by reduction of fine fuel by domestic animals (heavy grazing) reducing frequency and intensity of fires (Archer et al. 2017).

Woody plant abundance has increased over the past 100 years. Rates of encroachment vary dramatically based on environmental factors, disturbance regimes, and land use. Increases in WPE cover for North American ecoregions vary between 0.1 to 2.3 % per year. (Barger et al. 2011). WPE rates for Africa, Australia, and South America were similar but a lower magnitude with rates varying between 0.1 to 1.1% cover (Stevens et al. 2017). Woody cover encroachment rate of change is determined by the kinds and intensities of disturbances. Also, the rate of encroachment is directly related to the amount of precipitation the area receives. Changes in the plant community associated with WPE affect many grassland animals, birds, and insects, principally by changing the habitat and altering a suite of fundamental ecological processes. Archer et al. (2017) argues “Unless subsidized, brush management is rarely economically feasible based solely on increases in forage production and livestock performance.”

1.2.2. Vegetation History

Rangelands are disturbance ecosystems with disturbance frequency and intensity controlling the state of the ecosystem (Anderson 2005). Prior to European settlement, American rangeland vegetation was predominantly grasses, grass-like plants, and forbs, with few woody plants. Explorers recorded the Great Plains as “tremendous areas of luxuriant grass” (Frémont 1842) and “not a tree, shrub, or any other object, either animate or inanimate, relieved... the dreaded 'Llano Estacado'” Randolph Marcy (1850). These open areas were counter balanced by wooded areas along ridges, bottoms, etc. creating a mosaic of vegetation types driven by the interaction of disturbance with climate, soils, and topography. The disturbance regimes of these rangelands have undergone drastic changes since these early explorers reported their findings.

The patterns and scale of land use have changed drastically since those early explorers. Herbivory shifted from a shifting grazing mosaic composed of migratory and sedentary grazers to primarily enclosed continuous grazing. Fire patterns shifted with removal of anthropogenic fire and reduction of fuel loads from over grazing, resulting in passive fire suppression which transitioned to active fire suppression with advent of mechanization. The historic regime of grazing and fire acted as a repeated disturbance creating a feedback loop that suppressed WPE across rangelands (Hart and Hart 1997). The historic plant communities of the majority of North American rangelands were the result of the disturbance regimes of fire and grazing selecting for disturbance adapted species (Brown et al. 2005). As these disturbance regimes were altered by the settlement of the rangelands, WPE increased from the lack of fire as a controlling disturbance to suppress their growth.

1.2.3. . Range Condition Model History

The rangeland science profession in the United States has its roots in the vegetation degradation resulting from widespread overgrazing and recurring severe droughts of the late19th century and early 20th century. Ecological theory to explain vegetation dynamics was critical for the establishment of rangeland science. Key authors include Clements, Gleason, Sampson, Tansley, and Weaver. Clements (1916, 1936) described a regional mono-climax based on climate with the community likened to an organism. Gleason (1917) described "the Individualistic concept of ecology," in which "the phenomena of vegetation depend completely upon the phenomena of the individual". Sampson (1917, 1919) described the relationship of grazing to vegetation/plant community response based on grazing intensity, which serves as the basis for disturbance theory. Tansley (1939) described a poly-climax. Weaver (1929) described poly-climax, based on soils and disturbance (e.g., grazing ‘disclimax’, post-climax from sandy soils in arid region, pre-climax based on heavy clay soils in arid climates). Dyksterhuis (1949) developed the work of Sampson and Weaver into a management tool for assessment of rangelands based on management scale sites (range sites) and application of ecological theory for disturbance (grazing intensity) and secondary succession. He measured the degree of disturbance as the degree of departure from the historical climax vegetation (range condition).

The first widespread applications of ecological theory on rangeland for vegetation management were the range site concept, range condition, and the range condition model (RCM) (Dyksterhuis 1949; Sampson 1919). The range site concept is a management tool. It is based on soils and topography within a climatic zone (precipitation). Range site is an area with similar potential with respect to the kinds and amounts of vegetation it can produce and its response to management. Range condition is a measure of the degree of disturbance/departure of current vegetation of a range site from the climax (natural potential) plant community for that site (SRM 1974). The range condition classes (poor, fair, good, and excellent) reflect the extent of overgrazing disturbance on the plant community. The RCM assesses retrogression of vegetation under prolonged overgrazing. Recovery of disturbed rangelands through secondary succession towards a climax type community generally will follow different pathways than the retrogression. The RCM did not include frequency of disturbance since it was regarded as an unnecessary complication since most managers used continuous stocking, not rotational grazing. Modern rangeland management that incorporates many types of deferred and rotational grazing has shown that frequency is a necessary disturbance factor that must be included within management theories.

The failure of range site and condition to predict WPE can be attributed to incorrect assumptions about the relationship between soils, vegetation, grazing, and fire. Dyksterhuis assumed that there were rangeland soils (range sites) and forest soils (forest sites) (Kothmann 2019). Succession on rangeland sites would produce grasslands and succession on forest sites would produce forests. In his paper, The Savannah Concept and its use in Ecology (1957), Dyksterhuis recognized the importance of fire in creating the transitions between rangelands and forest. However, grazing was the only disturbance factor he included in the RCM. He assumed that on rangeland soils removal of the overgrazing disturbance would result in secondary succession producing climax rangeland (Dyksterhuis 1957). He recognized the need for mechanical or chemical treatments to remove long-lived perennial woody invaders, but did not recognize the need for a continuing fire regime to develop and maintain the climax plant community. The removal of fire as a driving disturbance for WPE explains why the RCM did not account for woody plant dynamics.

The RCM methodology has been effective for perennial herbaceous rangelands with a long term history of grazing and mature soils, but the omission of fire as a critical disturbance factor in forming the climax plant community caused the RCM not to function adequately with respect to woody plant dynamics. The failure of the Dyksterhuis' RCM to predict WPE was a primary cause of the range management profession shifting from the RCM to the State and Transition model (STM) for vegetation dynamics as an alternative model for rangeland vegetation dynamics that incorporated observed WPE (Briske et al. 2017; Westoby et al. 1989). The STM is similar to the range condition classes described by Sampson (1919) and Humphrey (1947).The STM is a descriptive model. It describes possible ecosystem states and the disturbances that cause transitions between states (Rodriguez Iglesias and Kothmann 1997; Westoby et al. 1989). STM does not provide prediction through ecological theory but explains observed dynamics. STM is not a dynamic model of vegetation changes in that it does not include time for transitions between possible states.

1.2.4. Ecology Theory

The concept of plant succession arose in North America during the early 20th century with Clements offering a comprehensive theory(Glenn-Lewin et al. 1992). Clementsian theory predicts that with stability of the historical disturbance regimes and given an adequate period of time (thousands of years), that a vegetation will reach a stable equilibrium with the climate and soil. "Modern successional theory has emphasized the importance of repeated, relatively frequent disturbances and accepts continuous change in vegetation as the norm"(Glenn-Lewin et al. 1992).

Equilibrium ecology is founded on the assumption that ecosystems are self-regulated by internal biotic processes that result in a single stable state that will return after disturbances cease (Briske et al. 2017). Non-equilibrium theory is founded on the assumption that ecosystems have a finite capacity for internal regulation resulting in the potential for multiple stable states (Briske et al. 2017). Examination of the STM reveals that the multiple states are a product of different disturbance regimes, indicating that vegetation will establish different stable states in the presence of different disturbance regimes. The key to understanding STM is understanding the multiple disturbance regimes incorporated as causes of transitions.

The RCM was based on resilience of the vegetation to an equilibrium state; whereas, STM is descriptive and loosely based on non-equilibrium/resilience theory. STM does not use general properties or attributes of the components (e.g., plant species assemblages, individual species) or processes (e.g., growth, reproduction, and mineralization) of the system to generate prediction rules of wider than local relevance (Rodriguez Iglesias and Kothmann 1997). Rodriguez Iglesias and Kothmann (1997) showed that every published STM proceed though secondary plant succession to a woody state in the absence of human caused disturbance and in the absence of fire. Disturbance (fire and grazing) controls the balance of resource allocation between herbaceous and woody species through removal of photosynthetic structures. Succession theory predicts that higher successional species (woodies) will out compete lower successional species (grasses) in the absence of disturbance (Clements 1936). Following removal of above ground biomass woody plants take longer to restore photosynthetic structures than grasses (Jarvis and Jarvis 1964). Fire and grazing by large ungulates are considered integral to the persistence of grassland ecosystems (Teague et al. 2008). The ecological cost of **not** burning is not understood by many ranchers.

1.2.5. Adaptive Management in Rangelands

Successful rangeland management requires the integration and synthesis of knowledge and skills from multiple disciplines (ecology, animal science, economics….). Successful managers balance competing economic, social, and ecological needs to create a sustainable operation in a stochastic environment. The process of adaptive management is characterized by explicit structure, careful description of the management vision, objectives, hypotheses of problem causation, alternative management approaches, predicted consequences of management alternatives, procedures for collection and analysis of monitoring data, and a mechanism for updating management as learning occurs (Allen et al. 2017).

Rangeland management is inherently uncertain because of external variables that are not controlled by the manager. The process of handling uncertainty is critical for successful rangeland management. Adaptive management is a systematic approach for improving management under uncertainty by learning from management outcomes; i.e., monitoring (Johnson et al. 1999; Williams et al. 2007). The adaptive management process is designed to improve how managers handle uncertainty through structured learning and iterative decision feedbacks (Allen et al. 2017). “Adaptive management is not really much more than common sense, but common sense is not always in common use” (Holling 1978).

Adaptive management is a process for managing dynamic systems over time and is required for the design and application of effective disturbance regimes. It involves consideration of multiple variables in dynamic systems (Holling 1978). It is difficult to apply because successful adaptive managers follow an intuitive or mental model that is not explicit. The individual analyses are not complex, but the need to evaluate the interaction of many factors and multiple steps over time makes the process complex. This suggests that a guided structure is necessary since human ability to accurately and quickly process multiple variables decreases significantly between three-way to four-way interactions (Halford et al. 2005).

1.2.6. Management Regime History: Transition from Dynamic to Static Regimes

The disturbance regimes for North American rangelands can be separated into two types based on disturbance patterns, static and dynamic. Historical (pre 1880s) rangeland disturbance regimes were dynamic with frequent fire and non-continuous grazing shifting across the landscape. Traditional (post 1880s) rangeland disturbance regimes tend towards static inputs with continuous grazing and fire exclusion. Rangeland management arose during the period of transition from dynamic to static disturbance regimes. The prior dynamic regimes were characterized by migratory grazing, uncontrolled fire, and drought coupled animal populations. The current static regimes are characterized by integrated fencing, water development, supplemental feeding, and fixed stocking rates. These changes altered the grazing regime, which altered the fire regime due to decreases in fine fuel and active fire suppression. Management has attempted mitigation of these altered fire regimes with mechanical and chemical treatments of woody plants without changing the static grazing and fire management regimes.

Rangeland management in the United States originated in the late 1880s. By the 1920s rangeland science was flowering with the first textbook on rangeland management by Arthur Sampson in 1923. The research of these early periods was focused on the effects of stocking rates on the rangeland. The modern roots of rangeland management can be traced to the 1940’s with the development of 2,4-D herbicide, E.J. Dyksterhuis (1949) publishing *Condition and Management of Rangeland Based on Quantitative Ecology* and the founding of the Society for Range Management. (Holechek 1981) The 1950’s saw the development of treatment approaches to rangeland management and WPE. Treatments included brush control, reseeding, stocking rate adjustments and grazing period adjustments (Hamilton 2004). Most rangelands are still managed with a treatment approach that was developed during the 50s-60s. Rangeland managers select a treatment to achieve a specific result. Non-consumptive uses of rangelands began increasing by the 1970s with a decrease in livestock stocking rates. As livestock stocking rates decreased, especially small ruminants (sheep and goats), WPE accelerated in the absence of fire (Archer et al. 2017). Control of WPE by treatments of herbicide or mechanical clearing incurs high economic and ecological costs that are unstainable for most practitioners (Conner 2004). Fire has been recognized as integral for “solving” WPE, but application of fire requires integration with the grazing to create an effective disturbance regime (Archer 1994; Archer et al. 2017).

Twentieth century management primarily focused on treatments to solve range condition problems without the development of an integrated management system. Grazing management was treated as a stocking rate problem with limited feedbacks between varying treatments. The concept of Integrated Brush Management Systems successfully increased the effectiveness of treatments by integrating multiple treatment methods to increase effectiveness or the lifespan of an initial treatment through maintenance treatments (Scifres et al. 1985).

1.2.7. Management Science

Rangeland management is a translational science of multiple disciplines (ecology, animal science, soil science, economics…). As a translational science rangeland management practitioners utilize art and science. Forester (1961) the founder of system dynamics discussed the interaction of the art and the science of management.

> The art develops through empirical experience but in time ceases to grow because of the disorganized state of its knowledge. Management science develops to explain, organize, and distill experience into a more compact and usable form… As the science grows, it provides a new basis for further extension of the art of management... Management is in transition from an art based only on experience, to a profession, based on an underlying structure of principles and science.

Leading managers master the art; however, they may not have an explicit understanding of the process that is easily extended to novice managers. Management science distills their application of principles and knowledge into a form (wisdom) that other practitioners of the art of rangeland management (Scarnecchia 2003) can use to improve their management.

The development of management science is necessary for effective adaptive management. The Data-Information-Knowledge-Wisdom-Decision hierarchy (Figure 1) illustrates the various levels from which management can be implemented with the process used to move up or down the hierarchy. Additionally, the boundaries of traditional science and management science are made explicit, as each deals with a unique set of levels within the hierarchy, overlapping with knowledge. All managers apply some form of management science. Innovators and early adopters draw heavily from the application of science-generated knowledge. Late adopters learn from the management wisdom generated by the early adopters. Management science can facilitate both the generation of wisdom and the application of that wisdom by the larger community of managers.

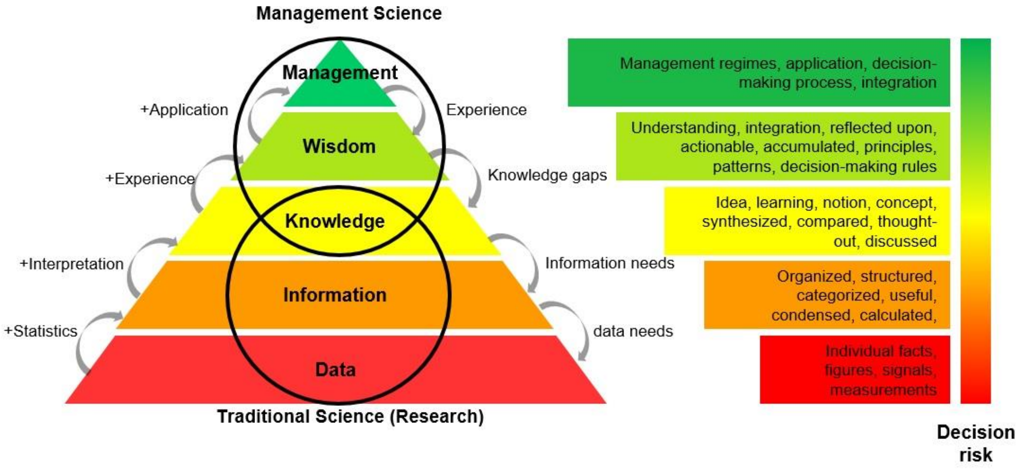

Figure 1.1 A modified data–information–knowledge–wisdom [management] (DIKW) hierarchy as applied to adaptive management. Modified from (Atzori et al. 2019). The modifications were the addition of management as the application of wisdom and the delineation of Management Science and Traditional Research.

The traditional role of science is to formulate hypotheses, gather data, analyze and interpret it, and create knowledge. Management science translates scientific knowledge into a language with which the manager is familiar (Forrester 1961).The traditional role of extension services is to transfer this knowledge to managers; i.e. Texas A&M Agrilife, Natural Resource Conservation Service technical assistance. The development of management science will facilitate the integration of treatments (e.g. herbicides, mechanical brush control, animal health, etc.) into a management regime. Management science will thus enhance the transfer of knowledge from traditional science into applied management.

1.3. Study Area

The Duncan Spade Ranch is a historic ranch near Egypt, Texas in the Gulf Coast Prairies and Marshes ecoregion. The ranch enterprises include livestock grazing, hay production, rice, and crop production. The Spanish Camp Unit consists of 400 ha of unplowed coastal prairie rangeland. The traditional management of the Spanish Camp Unit was continuous grazing and yearly herbicide spraying application for McCartney Rose control. The stocking rate began at 2.5 HA/AUY and rose to 2.1 HA/AUY at the beginning of 2015, at which time a management decision was made to reduce to the original stocking of 2.5 HA/AUY. In 2012, the unit was cross-fenced into five pastures (Figure 1). A severe drought during 2010-11 resulted in extreme overgrazing of grasses in 2011 and a dense stand of weeds in the spring of 2012. To reduce the herbaceous weed density, all pasture except the northwest pasture were sprayed during the spring of 2012. The Northwest Pasture was not sprayed because it was adjacent to a cotton field. It was dominated by herbaceous weeds in 2012 but was sprayed during the spring of 2013.

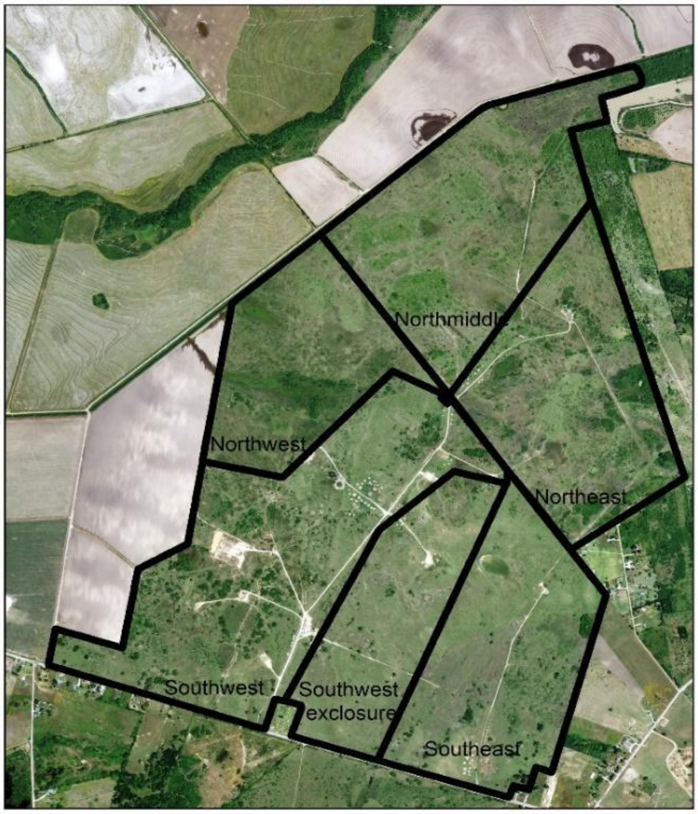

Figure 1.2 Duncan Spade ranch pasture map National Agriculture Imagery Program 2016

The climate is humid subtropical with mild winters and an average rainfall of 11 cm per year. Standing water is common for low-lying areas for multiple weeks following heavy rains. The pastures are dominated by Bahiagrass (Paspalum notatum) and Brownseed paspalum (Paspalum plicatulum) with remnants of tall grasses little bluestem (Schizachyrium scoparium), Indian grass (Surgastrum nutuns), and Switchgrass (Panicum virgatum) remaining primarily in areas protected by McCartney Rose cover. McCartney Rose is the primary encroaching woody species, a vigorous re-sprouting evergreen shrub that can dominate the landscape by forming large hedges. Small amounts of Chinese tallow (Triadica sebifera) and Honey mesquite (Prosopis glandulosa) are present, although neither are vigorous encroaching species on this location and they have relatively stable cover. Honey mesquite is present primarily in the Southwest pasture, which was the original watering location before cross-fencing. Chinese tallow is limited to low areas where standing water is common after rains.

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2. INTEGRATED RANGELAND MANAGEMENT SYSTEM (IRMS): A PROCESS MODEL FOR ADAPTIVE MANAGEMENT OF RANGELANDS

2.1. Overview

Woody plant encroachment (WPE) reduces ecosystem services and economics welfare provided by rangelands. Adaptive management has been identified as critical component for successful management of WPE by leading practitioners. However, the processes used by successful adaptive managers are not explicit and most producers are not able to successfully apply adaptive management to their operations. This paper creates an explicit model for the process of adaptive rangeland management. Integrated Rangeland Management System (IRMS) is a wholistic[3] process for visioning, planning, implementing, and monitoring of rangelands. IRMS development followed management science principles from Kothmann[4], Scarnecchia (2003), and Forester (1961). IRMS serves as a common framework for implementing adaptive rangeland management.

Keywords: woody plant encroachment; adaptive management; rangeland management; management decision theory.

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[3] *Concerning the whole of a system*

[4] *See Appendix A Rationale for a New Model*

2.2. Introduction

Woody plant encroachment (WPE) on rangelands across North America and throughout the world has caused undesired ecosystem transitions that reduce ecosystem services and decrease economic welfare (Sala and Maestre 2014). The impact of WPE is heightened by a disconnect between WPE knowledge (control/cause) and widespread application by practitioners. Top practitioners have successfully utilized fire as a targeted disturbance within adaptive management regimes to control WPE. Adaptive management has been identified as the critical element of successful management by top practitioners (Allen et al. 2017; Briske 2011; Derner and Augustine 2016; Teague and Barnes 2017). However, the processes used by successful adaptive managers are not explicit and most producers are not able to successfully apply adaptive management to their management units. Simply saying ‘do adaptive management’ is insufficient for most rangeland managers. Teachers and structured processes can facilitate managers in learning and applying adaptive management. Widespread adoption of adaptive management can benefit from an explicit conceptual framework to guide practitioners in the implementation of adaptive management.

This paper creates an explicit model for the process of rangeland adaptive management. We developed the Integrated Rangeland Management System (IRMS) model as a wholistic process for visioning, planning, implementing, and monitoring of rangelands. IRMS draws from experience facilitating application of apply adaptive management to control McCartney Rose (*Rosa bractata*) with a prescribed fire disturbance regime on the Duncan Spade Ranch 4.5.2. It can function as a common framework for applying adaptive management to rangelands.

IRMS guides adaptive management of the whole rangeland system instead of treating individual parts of the system, e.g., Integrated Brush Management Systems (IBMS) and Individual Plant Treatment (IPT) (Scifres et al. 1985). IRMS arose from the requirement of adaptive management within the Disturbance Regime Theory (Steigerwald in preparation) for managing WPE and the lack of an explicit process for adaptive management of rangelands. Simply saying “do adaptive management” is not sufficient. Successful adoption of adaptive management requires a framework and supporting science. Science can advance adaptive management through management research on the decision making process and the creation of knowledge ready for application within adaptive management; however, a structured framework is essential for widespread application of that research by managers.

2.3. Literature Review

2.3.1. Woody Plant Encroachment

Why are woody plants encroaching on rangelands? Hypotheses include changes in climate, fire, herbivory, atmospheric CO2, and N deposition (Archer 1994). Of the identified causes of WPE, only fire and herbivory regimes can be managed at the ranch level. Current research indicates that WPE was primarily driven by reduction of fine fuel by domestic animals (heavy grazing) reducing frequency and intensity of fires (Archer et al. 2017).

Woody plant abundance has increased over the past 100 years. Rates of encroachment vary dramatically based on environmental factors, disturbance regimes, and land use. Increases in WPE cover for North American ecoregions vary between 0.1 to 2.3 % per year. (Barger et al. 2011). WPE rates for Africa, Australia, and South America were similar but a lower magnitude with rates varying between 0.1 to 1.1% cover (Stevens et al. 2017). Woody cover encroachment rate of change is determined by the kinds and intensities of disturbances. Also, the rate of encroachment is directly related to the amount of precipitation the area receives. Changes in the plant community associated with WPE affect many grassland animals, birds, and insects, principally by changing the habitat and altering a suite of fundamental ecological processes. Archer et al. (2017) argues “Unless subsidized, brush management is rarely economically feasible based solely on increases in forage production and livestock performance.”

2.3.2. Vegetation History

Rangelands are disturbance ecosystems with disturbance frequency and intensity controlling the state of the ecosystem (Anderson 2005). Prior to European settlement, American rangeland vegetation was predominantly grasses, grass-like plants, and forbs, with few woody plants. Explorers recorded the Great Plains as “tremendous areas of luxuriant grass” (Frémont 1842) and “not a tree, shrub, or any other object, either animate or inanimate, relieved... the dreaded 'Llano Estacado'” Randolph Marcy (1850). These open areas were counter balanced by wooded areas along ridges, bottoms, etc. creating a mosaic of vegetation types driven by the interaction of disturbance with climate, soils, and topography. The disturbance regimes of these rangelands have undergone drastic changes since these early explorers reported their findings.

The patterns and scale of land use have changed drastically since those early explorers. Herbivory shifted from a shifting grazing mosaic composed of migratory and sedentary grazers to primarily enclosed continuous grazing. Fire patterns shifted with removal of anthropogenic fire and reduction of fuel loads from over grazing, resulting in passive fire suppression which transitioned to active fire suppression with advent of mechanization. The historic regime of grazing and fire acted as a repeated disturbance creating a feedback loop that suppressed WPE across rangelands (Hart and Hart 1997). The historic plant communities of the majority of North American rangelands were the result of the disturbance regimes of fire and grazing selecting for disturbance adapted species (Brown et al. 2005). As these disturbance regimes were altered by the settlement of the rangelands, WPE increased from the lack of fire as a controlling disturbance to suppress their growth (Twidwell et al. 2013).

2.3.3. Management Regime History: Transition from Dynamic to Static Regimes

The disturbance regimes for North American rangelands can be separated into two broad types based on disturbance patterns, static and dynamic. Historical (pre 1880s) rangeland disturbance regimes were dynamic with frequent fire and non-continuous grazing shifting across the landscape. Traditional (post 1880s) rangeland disturbance regimes tend towards static inputs with continuous grazing and fire exclusion. Rangeland management arose during the period of transition from dynamic to static disturbance regimes. The prior dynamic regimes were characterized by migratory grazing, uncontrolled fire, and drought coupled animal populations. The current static regimes are characterized by integrated fencing, water development, supplemental feeding, and fixed stocking rates. These changes altered the grazing regime, which altered the fire regime due to decreases in fine fuel and active fire suppression. Management has attempted mitigation of these altered fire regimes with mechanical and chemical treatments of woody plants without changing the static grazing and fire management regimes.

Rangeland management in the United States originated in the late 1880s. By the 1920s rangeland science was flowering with the first textbook on rangeland management by Arthur Sampson in 1923. The research of these early periods was focused on the effects of stocking rates on the rangeland. The modern roots of rangeland management can be traced to the 1940's with the development of 2,4-D herbicide, E.J. Dyksterhuis (1949) publishing *Condition and Management of Rangeland Based on Quantitative Ecology* and the founding of the Society for Range Management. (Holechek 1981) The 1950’s saw the development of treatment approaches to rangeland management and WPE. Treatments included brush control, reseeding, stocking rate adjustments and grazing period adjustments (Hamilton 2004). Most rangelands are still managed with a treatment approach that was developed during the 50s-60s. Rangeland managers select a treatment to achieve a specific result. Non-consumptive uses of rangelands began increasing by the 1970s with a decrease in livestock stocking rates. As livestock stocking rates decreased, especially small ruminants (sheep and goats), WPE accelerated in the absence of fire (Archer et al. 2017). Control of WPE by treatments of herbicide or mechanical clearing incurs high economic and ecological costs that are unstainable for most practitioners (Conner 2004). Fire has been recognized as integral for “solving” WPE, but application of fire requires integration with the grazing to create an effective disturbance regime (Archer 1994; Archer et al. 2017).

Twentieth century management primarily focused on treatments to solve range condition problems without the development of an integrated management system. Grazing management was treated as a stocking rate problem with limited feedbacks between varying treatments. The concept of Integrated Brush Management Systems successfully increased the effectiveness of treatments by integrating multiple treatment methods to increase effectiveness or the lifespan of an initial treatment through maintenance treatments (Scifres et al. 1985).

2.3.4. Adaptive Management in Rangelands

Successful rangeland management requires the integration and synthesis of knowledge and skills from multiple disciplines (ecology, animal science, economics….). Successful managers balance competing economic, social, and ecological needs to create a sustainable operation in a stochastic environment. The process of adaptive management is characterized by explicit structure, careful description of the management vision, objectives, hypotheses of problem causation, alternative management approaches, predicted consequences of management alternatives, procedures for collection and analysis of monitoring data, and a mechanism for updating management as learning occurs (Allen et al. 2017).

Rangeland management is inherently uncertain because of external variables that are not controlled by the manager. The process of handling uncertainty is critical for successful rangeland management. Adaptive management is a systematic approach for improving management under uncertainty by learning from management outcomes; i.e., monitoring (Johnson et al. 1999; Williams et al. 2007). The adaptive management process is designed to improve how managers handle uncertainty through structured learning and iterative decision feedbacks (Allen et al. 2017). “Adaptive management is not really much more than common sense, but common sense is not always in common use” (Holling 1978).

Adaptive management is a process for managing dynamic systems over time and is required for the design and application of effective disturbance regimes. It involves consideration of multiple variables in dynamic systems (Holling 1978). It is difficult to apply because successful adaptive managers follow an intuitive or mental model that is not explicit. The individual analyses are not complex, but the need to evaluate the interaction of many factors and multiple steps over time makes the process complex. This suggests that a guided structure is necessary the ability of humans to process dynamic systems decreases significantly between three-way to four-way interactions (Halford et al. 2005).

2.3.5. Management Science

Rangeland management is a synthesis science of multiple disciplines (ecology, animal science, soil science, economics…). As a synthesis science rangeland management practitioners utilize art and science. Forester (1961) the founder of system dynamics discussed the interaction of the art and the science of management.

> The art develops through empirical experience but in time ceases to grow because of the disorganized state of its knowledge. Management science develops to explain, organize, and distill experience into a more compact and usable form… As the science grows, it provides a new basis for

> further extension of the art of management... Management is in transition from an art based only on experience, to a profession, based on an underlying structure of principles and science.

Leading managers master the art; however, they may not have an explicit understanding of the process that is easily extended to novice managers. Management science distills their application of principles and knowledge into a form (wisdom) that other practitioners of the art of rangeland management (Scarnecchia 2003) can use to improve their management.

The development of management science is necessary for effective adaptive management. The Data-Information-Knowledge-Wisdom-Decision hierarchy (Figure 1) illustrates the various levels from which management can be implemented with the process used to move up or down the hierarchy. Additionally, the boundaries of traditional science and management science are made explicit, as each deals with a unique set of levels within the hierarchy, overlapping with knowledge. All managers apply some form of management science. Innovators and early adopters draw heavily from the application of science-generated knowledge. Late adopters learn from the management wisdom generated by the early adopters. Management science can facilitate both the generation of wisdom and the application of that wisdom by the larger community of managers.

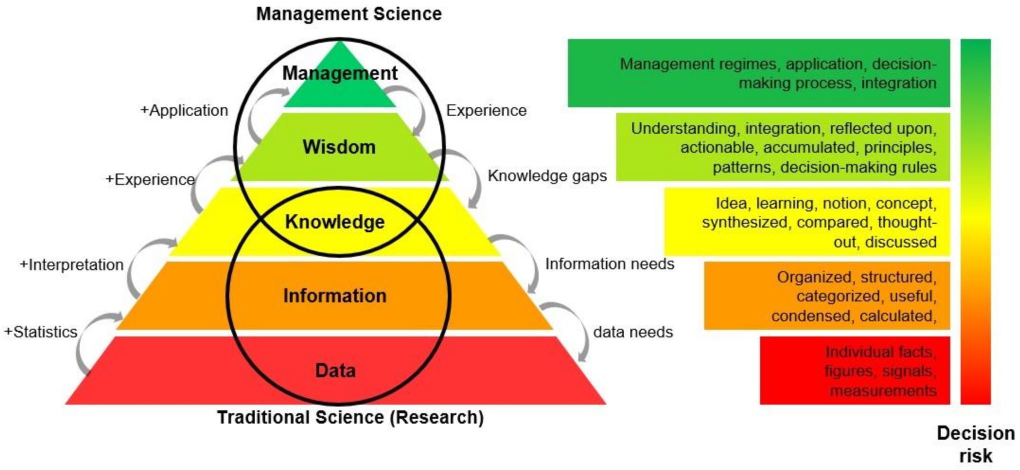

Figure 2.1: A modified data–information–knowledge–wisdom [management] (DIKW) hierarchy as applied to adaptive management. Modified from (Atzori et al. 2019). The modifications were the addition of management as the application of wisdom and the delineation of Management Science and Traditional Research.

The traditional role of science is to formulate hypotheses, gather data, analyze and interpret it, and create knowledge. Management science translates scientific knowledge into a language with which the manager is familiar (Forrester 1961).The traditional role of extension services is to transfer this knowledge to managers; i.e. Texas A&M Agrilife, Natural Resource Conservation Service technical assistance. The development of management science will facilitate the integration of treatments (e.g. herbicides, mechanical brush control, animal health, etc.) into a management regime. Management science will thus enhance the transfer of knowledge from traditional science into applied management

2.4. METHODS

2.4.1. Need for Conceptual Framework of Adaptive Rangeland Management/philosophy

IRMS is a conceptual framework that supports adaptive decision making for rangeland managers to facilitate the transfer of scientific knowledge and experiential wisdom to managers. Managers evaluate knowledge obtained from both research and experience and integrate it through trial and error, which generates the wisdom base for management. Although the specific decisions are unique to the individual and are difficult to transfer to other managers, the process for making wise decisions can be generalized to form a framework for guiding specific decisions.

IRMS begins by identifying the manager’s desired values that determine the management goals. The second level is to identify more specific management objectives, based on the values and goals. These objectives direct the selection of management practices and the development of management prescriptions and regimes. IRMS divides the planning process into three horizons, with an associated timeframe and concept (Table 1). This allows a simplified planning process while providing explicit structure for practitioners to incorporate adaptive management into practice.

Table 2.1 Management planning horizons and time frames

Planning Horizon	Planning Timeframe	Concepts
Strategic Vision	Decades	Values
Tactical Planning	Years	Criteria
Operational Implementation	Days, Weeks, Months	Indicators

2.4.2. IRMS Design Principles

IRMS was designed as a general model for adaptive management of rangeland. The following general criteria were used to guide model development: (1) Begin with the simplest model of the system possible; (2) The hierarchy of organization selected for the variables should be the same as the decision level targeted by the model; (3) Variables should be aggregated based on temporal and spatial scales that are comparable to the management decisions; (4) Variables should be the minimum number possible to address the desired decision analysis; (5) Both the strategic and tactical components need clear avenues for logical adaptive information feedback loops from the operational level (e.g., monitoring); (6) Management vision should direct the adaptive management planning process; (7) The model should not be site or decision specific; i.e., model structure should be applicable across many rangeland types and levels of user experience (novice to skilled practitioners)[5].

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[5] *See Appendix A Rationale for a New Model*

2.4.3. The Role of Monitoring Within Adaptive Management

IRMS incorporates values, criteria, and indicators into the process for planning adaptive management (Table 1). **Values** are the qualities which stakeholders consider worthwhile. **Criteria** are the assessment points, which provide dimensions for values. **Indicators** are measurement endpoints and serve as surrogates for the status of criteria. Since adaptive management requires feedback loops that identify the effectiveness of management practices and regimes, monitoring is an essential component.

The scientific method is implicitly embedded within the IRMS decision process cycle. Managers have a hypothesis for the expected responses when they design management prescriptions (experiments) and implement prescriptions (management). Monitoring allows managers to evaluate outcomes, and learn (develop wisdom) through iterative application of management. Adaptive management may not have multiple replicates in space, but it has replication in time. Application of the IRMS model across many enterprises will accumulate meta-data and is the basis for developing the ‘wisdom’ base for managers to draw on in planning their management prescriptions.

2.5. Results: IRMS Conceptual Model for Adaptive Management of Rangelands

The conceptual framework guides a top down implementation where values focus the vision, which shapes the goals of management (Figure 2). Each horizon of the planning process (i.e., strategic, tactical, and operational) is based on the higher level. Monitoring feeds information from operational level back up to the tactical and strategic levels.

2.5.1. Model Overview

The adaptive management process is divided into three temporal horizons strategic visioning, tactical planning, and operation implementation. These horizons are inspired by Clausewitzian military strategic theory [(Clausewitz 1962) 1836]. Each temporal horizon provides information necessary for successful adaptive management. 1) Strategic visioning provides the **why** we manage. 2) Tactical planning provides **how** we manage. 3) Operational implementation is **where** management occurs. A hierarchal layout is necessary to guide adaptive management that accomplishes management goals.

Temporal horizons reduce decision complexity by matching decision scale with time scale. Monitoring management effects in operational implementation is critical for providing feedback. Identifying breakdowns between decisions, actions, and outcomes through monitoring enables users to learn how their unique situation responds to management. IRMS is a heuristic process to increase a manager’s ability to analyze ecologic, economic, and social factors to create management regimes that meet management objectives for woody and herbaceous vegetation on the management unit. IRMS provides a common framework for managers to customize management to their specific situation.

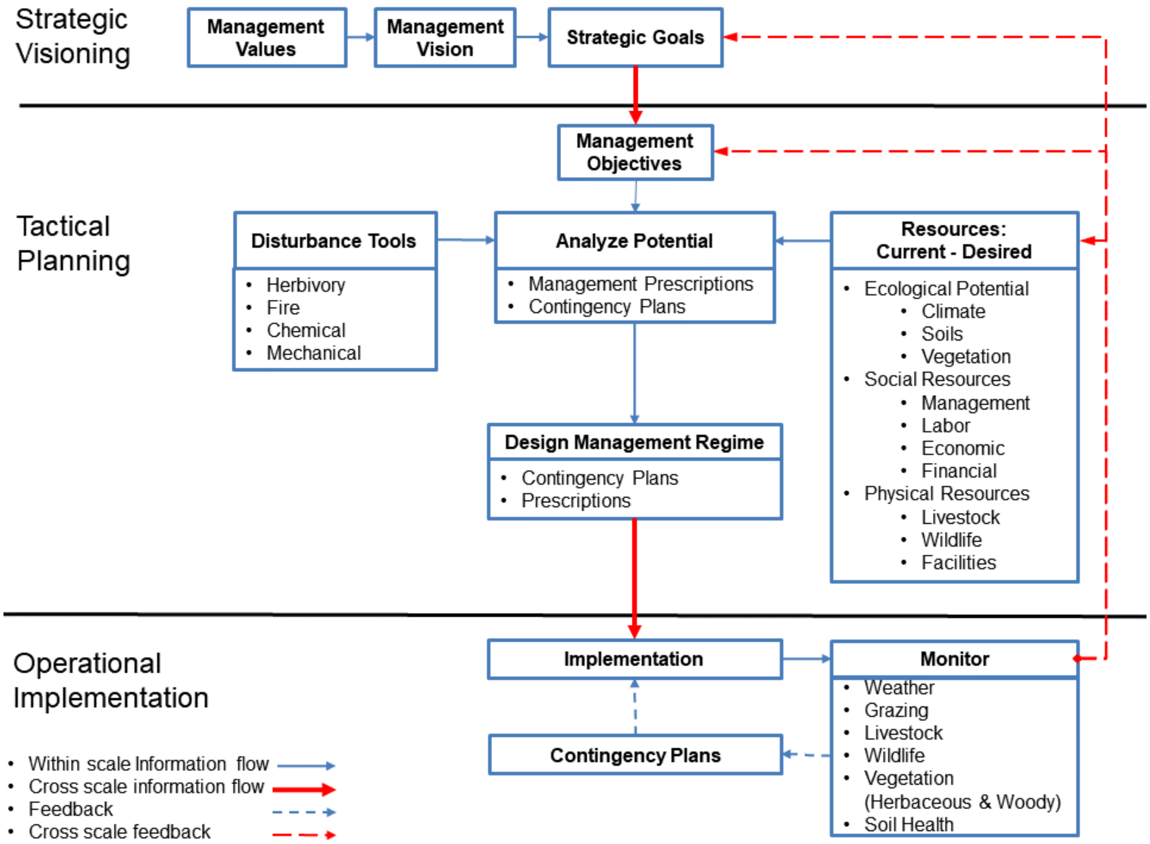

Figure 2.2 IRMS conceptual model for adaptive management of rangelands.

2.5.2. Strategic Visioning

A clear vision is critical for guiding successful adaptive management; more simply stated “begin with the end in mind”(Covey and Collins 2013). Strategic visioning initiates from the identification of management values. Management values are the product of the owner’s desires and these desires are typically of a heuristic nature and not set analytically. Strategic visioning is a heuristic process that provides a guide for analytical analysis in tactical planning.

Strategic goals, identified from the management vision, serve as qualitative metrics that give direction to management. Strategic visioning guides subsequent decisions by providing direction and boundaries for analyzing potential management regimes. This process is not complicated, but it is of critical importance for guiding management decisions.

Monitoring is critical for determining if management is successfully accomplishing the strategic goals. Monitoring enables feedback between the implemented management regime and the strategic goals to inform whether the strategic goals are being accomplished. With every cycle of feedback from operational implementation to strategic goals, knowledge and wisdom are created for the manager.

2.5.3. Tactical Planning

Tactical planning (Figure 2) processes the strategic vision into a planned management regime. Tactical planning initiates with the creation of quantifiable management objectives from strategic goals. These objectives guide the analysis of potential management prescriptions from available disturbance tools and resources (current and desired) to a coherent management regime plan. Monitoring from operational implementation provides feedbacks that update the resources allowing analysis to become an adaptive cycle. Analysis is the engine that drives tactical planning to translate the strategic vision into a planned management regime.

Available resources are twofold, current resources and desired resources. Current resources are the initial inventory of ecological, social, and physical resources present on the management unit. Desired resources are the resources needed to accomplish the management vision and associated objectives. Ecological potential is determined by the climate and soils on the management unit. The current vegetation is a result of the past management on the unit and the desired vegetation community is set by the objectives of management. Social resources are the management skill, available labor, economic power, and financial resources for the management unit. Physical resources are the livestock, wildlife, and facilities on the management unit. Disturbance tools are management practices used to change the status of current ecological resources into desired resources that achieve management objectives. Disturbance tools include herbivory, fire, herbicides, and mechanical. Physical, ecological, and economic components are analyzed to create the management prescriptions and contingency plans. The management regime will consist of the management prescriptions and the contingency plans. Management prescriptions are the planned management actions. Contingency plans are planned deviations from management prescriptions in response to unexpected changes in stochastic external factors (weather and resources) determined by monitoring. Contingency planning is vital for successful adaptive management of rangeland systems.

Managers filter available information through their experiential knowledge and wisdom. Management science facilitates predicting how components interact and informs the manager on how to analyze component information. The science of rangeland management is of particular importance for tactical planning. Predicting and understanding how a management regime interacts with the rangeland is critical for sustainable management.

2.5.4. Operational Implementation

Operational implementation (Figure 2) is the application of the planned management prescriptions. Monitoring is used to determine if contingency plans need to be implemented. As management is implemented, monitoring creates information to modify the implementation of management. Information from monitoring provides feedbacks to all planning horizons: operational planning, tactical planning, and strategic planning. Successful monitoring enables managers to learn dynamics inherent in rangeland systems. Monitoring of weather, grazing, livestock, wildlife, vegetation, and soil health are key components for creating useful information for adaptive management. Successful operational implementation requires monitoring because rangelands are inherently dynamic and require adaptation. Feedbacks between application of practices, the art of implementation, and the application of science in tactical planning increases the ability of a manager to successfully meet the vision and goals of the management unit.

Monitoring categories include grazing, livestock, vegetation, and soil heath. Grazing and livestock monitoring are critical for guiding operational management. Vegetation trend (woody & herbaceous) monitoring is critical for evaluating the effectiveness of disturbance prescriptions in changing the status of the rangeland to transition to the desired status. Operational monitoring directs implementation of management and determines when a contingency plan should be implemented. Monitoring vegetation and soil health provides feedback to tactical planning to evaluate if management objectives are being met.

2.6. Discussion: Model Application

IRMS incorporates values, criteria, and indicators into the adaptive management process. This process allows the user to iteratively process their inherent values into management, and then evaluate the indicators of that management to cycle back up the chain to determine if the planned management is accomplishing the vision (Walters 1986). Adaptive management follows the scientific method. Practitioners have a hypothesis for the expected responses to the management they design and apply. The management prescription (experiment) is implemented and monitoring is used to evaluate outcomes. Learning occurs through iterative applications.

Adaptive management uses management science to design models/decision aids that are suitable for tactical and operational level decisions and management. Not all rangeland models are suitable for use by individual managers. Large complex simulation models contain many variables and parameters, such as the BEHAVE fire model (Burgan and Rothermel 1984). These models require skilled scientists to build and operate. These models can be useful for developing mechanistic understanding of the system processes, but they are not well adapted for use by individual land managers to plan and implement practices. The challenge for management scientists is to design and build models that address critical decisions, are ecologically and economically sound, and can be used by an individual manager.

The philosophical background for the structure of IRMS comes from military strategic planning which originated from the Prussian general Carl Von Clausewitz seminal book *On War* originally published in 1832 [(Clausewitz 1962) 1832].

> Simplicity in planning fosters energy in execution. Strong determination in carrying through a simple idea is the surest route to success. The winning simplicity we seek, the simplicity of genius, is the result of intense mental engagement…..But in war '**management**' more than in any other subject we must begin by looking at the nature of the whole; for here more than elsewhere the part and whole must always be thought of together.

IRMS is the unification of Clausewitzian strategic theory with adaptive management into a structured process for rangeland management.

2.6.1.1. Strategic Visioning

RMS is defined by the linkage of strategic reasoning with adaptive management. Clausewitz's discussion on military strategy and war is directly applicable to strategic visioning and management processes on rangelands. *The political object* ***'vision'*** *is the goal, war '****management'*** *is the means of reaching it, and means 'it' can never be considered in isolation from their purpose…war* ***'management'*** *should never be thought of as something autonomous, but always as an instrument of strategy*" [(Clausewitz 1962) 1832]. In short, Clausewitzian thinking stresses – managers have long ignored to their peril – that of all of the factors in rangeland management, strategy ought to guide management, although no part of the trinity may be neglected (strategical, tactical, operational) (Clausewitz 1962; Devereaux 2020) . The reasoning pattern for IRMS mirrors this philosophy by initiating from the why manage (strategic visioning), to the means (tactical planning) to accomplish the strategy; only then to the implementation of those means (operational implementation). This organization guides the practitioner in the broad implementation of IRMS, thus allowing a similarly structured planning process across varied users.

Clausewitz argues there are three great strategic sins that must be avoided in war: 1) the lack of an overarching strategy, 2) the elevation of tactical/operational concerns over strategic ones, and 3) lastly the failure to update the strategy as conditions change. These three "sins" are directly applicable to adaptive rangeland management and are addressed by the structure of the IRMS model: 1) IRMS begins with strategic visioning building the overarching vision for management; 2) the structure hierarchal (strategic-tactical-operation) of IRMS leads higher levels to drive lower levels of the planning process; and 3) adaptation from monitoring information leads to the process reflecting the conditions of the resources.

Rangeland management is based on inherent values of the practitioners. Values can be split into general categories exploit, protect, and conserve. Exploitation does not require complex management and the rangeland community still feels the effects from exploitation of the resources. Protection of the resource may require complex management to maintain the current state of a dynamic resource. Conservation of the resource requires complex adaptive management for use and improvement of the resource. IRMS process is useful for implementation of adaptive management under conservation or protection of rangeland resources.

IRMS is suitable for management planning on public or private settings since the structure flows from the identification of inherent values. Owner operators have a single source of values, so forming a management vision is relatively straight forward. Public/multi-stakeholder operations have a challenge due to the multiple sources of inherent values. Public/multi-stakeholder values can arise from regulations, stakeholders, managing agency, and the manager. In public/multi-stakeholder settings identification of the inherent values and creation of a common management vision is critical for harmony.

2.6.1.2. Tactical Planning

Tactical planning facilitates practitioners in translating qualitative vision/goals into a planned management regime. Management science is of particular importance for analyzing potential management events to create a regime that achieves the management vision. Decision aids such as State & Transition, Disturbance Regime Theory, and The Grazing Manager are important for facilitating analysis of why, how, and when disturbance tools are applied to change the current resources into desired resources. Within the planning process, contingency planning for stochastic events (drought, market crashes…) is of critical importance in the creation of successful management regimes.

Tactical planning requires information in a language and format comprehensible by managers for analysis within tactical planning. This requires management science to transform scientific information into principles and processes that managers can apply. Implementation of adaptive management requires management science research that supports adaptive management. This research must match the temporal and spatial structure at which adaptive management planning and the decision process occurs (Teague and Barnes 2017). IRMS can facilitate practitioners in synthesizing the many and varied components that adaptive management of rangelands incorporates into management. Management science can serve as a vehicle for communication and information transfer between traditional research and applied adaptive management.

2.6.1.3. Operational Implementation

Operational implementation is the application of designed management prescriptions with nested adaptation from monitoring within the existing horizon and into prior horizons. The first adaptive cycle is within operational implementation with monitoring information driving contingency application. The second cycle is to tactical planning wherein monitoring provides information for planning and feedback for tactical goals. The last adaptive cycle addresses strategic visioning to monitor the trend of the management unit in relation to the strategic goals set by the management vision. These nested feedback cycles depend on monitoring to provide relevant information for the practitioner.

Monitoring is the keystone which enables IRMS to function as an adaptive management process. The information created through monitoring is critical for repeated operation of IRMS. IRMS requires monitoring techniques that create the information that is usable by the practitioner. These monitoring techniques are practitioner-oriented by design and should incorporate these five key characteristics:

1) technically feasible; within the managers ability,
2) timely for decisions making with the IRMS process,
3) economically feasible; time and money,
4) easy to interpret and apply to decision making,
5) reliable and repeatable.

These characteristics form a keystone that enables the iterative aspect of adaptive management. If a monitoring method fails to meet these criteria, it is unlikely to be utilized by the manager. These characteristics can guide management scientists in designing monitoring protocols and methods suitable for use in adaptive management of rangelands.

2.7. Conclusions for Management Implications

IRMS provides a structured process that can facilitate adoption of adaptive management. IRMS moves the science of rangeland management from saying “do adaptive management” to a having a structured process to rangeland managers in implementing adaptive management on their properties. Structuring the decision process can enable novice managers to implement more complex forms of management: e.g., pyric herbivory, disturbance regime management, etc. The focus on strategic planning to create clear management visions is critical for successful implementation of adaptive management. IRMS is not a destination as an individual treatment but a process for implementing adaptive management that continues indefinitely. Its broad structure allows freedom by practitioners to adapt to their specific situations. Scientists can utilize the framework to facilitate communication of their research to managers with relevant decisions. An avenue for communication between the perspectives of the practitioner and the researcher will benefit both parties.

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3. DISTURBANCE REGIME THEORY: MANAGEMENT OF WOODY PLANT ENCROACHMENT FOR THE TWENTY FIRST CENTURY

3.1. Overview

Woody plant encroachment (WPE) on rangelands decreases ecosystem services and economic viability. Practitioners lack ecological theory for the interaction between disturbance and WPE in a language and format accessible by the majority of practitioners. Disturbance regime theory (DRT) was developed as ecological theory for practitioners seeking to utilize disturbance, specifically fire to control WPE. DRT utilizes thresholds between population resistance to disturbance intensity and species resilience to disturbance frequency to estimate effects of disturbance regimes to WPE. Disturbance regime management worksheets were developed to assists practitioners in the application of DRT to create prescribed fire disturbance regimes for control of WPE.

Although the concepts of DRT are applicable to mechanical, chemical, or biological control treatments, this paper is focused on prescribed fire as a primary disturbance utilized to control WPE. Prescribed fire is ecologically effective and economically viable for WPE on rangelands, but the planning and implementation of prescribed fire as a management practices is complex and not easy for managers to apply. Many different sources of knowledge exist for planning single fire events. This paper reviews and presents theory and tools to support practitioners in creation and application of prescribed fire disturbance regimes to manage WPE.

Keywords: adaptive management; rangeland management; disturbance; disturbance regimes; woody plant encroachment; prescribed fire; resistance; resilience.

3.2. Introduction

Woody plant encroachment (WPE) on rangelands across North America and throughout the world has caused undesired ecosystem transitions that reduce ecosystem services and decrease economic welfare (Sala and Maestre 2014). The impact of WPE is heightened by a disconnect between WPE knowledge (control/cause) and widespread application of prescribed fire as a control by practitioners. Top practitioners have successfully utilized fire as a targeted disturbance within adaptive management regimes to control WPE. For example, a common theme among persons awarded for excellence in rangeland management by the Society for Range Management is integration of grazing and fire within adaptive management regimes. There exists many different resources for individual disturbance events: however, a process for adaptively creating disturbance regimes is needed.

This paper translates ecological theory into processes that **practitioners** can use to design and implement disturbance regimes for control of WPE. Disturbance regime theory (DRT) is an ecological theory for qualitative prediction of woody population dynamics by rangeland managers. DRT predicts plant response to disturbance via resistance and resilience to disturbance. This paper focuses on fire as a specific disturbance for directing WPE (Venter et al.

2018). We present disturbance regime management (DRM) methodology for rangeland managers practicing WPE management. This methodology guides managers in the creation of customized disturbance event prescriptions to form disturbance regimes that accomplish management WPE objectives.

Rangeland management has been described as the art and science of managing rangelands (Stoddart and Smith 1943). Management science is the interface for describing the structural process leading managers use and creating explicit processes so that others can also apply it (Forrester 1961; Scarnecchia 2003). Managers use ‘experiential’ knowledge to evaluate science knowledge as they apply adaptive management of rangeland. This paper identifies and organizes existing scientific knowledge that managers require to create effective woody plant management prescriptions. This is accomplished through the application of DRT to the development of prescriptions for application of prescribed fire for management of WPE on rangelands.

Both the historic plant communities and the vegetation changes on United States rangelands from pre-European settlement to current are a product of the disturbance regimes. Removal of the primary controlling disturbance (fire) has created a new disturbance regime which favors WPE. Traditional management has attempted to solve WPE resulting from the removal of fire through species focused treatments (mechanical and chemical). Scientific knowledge about how disturbances (grazing, fire, drought….) direct WPE has been described by multiple researchers (Archer et al. 2017; Fuhlendorf et al. 2009). However, this knowledge has not been translated into a process for sustainable management of WPE. This paper applies management science concepts from Forrester (1961) and Scarnecchia (2003) to help rangeland managers translate existing ecological and science knowledge about disturbance regimes into vegetation management prescriptions and practices. Specifically, processes and principles managers can use to develop customized management prescriptions for control of WPE. This organization is critical for extending DRM to non-expert managers.

3.3. Literature review

3.3.1. Range Condition Model History

The rangeland science profession in the United States has its roots in the vegetation degradation resulting from widespread overgrazing and recurring severe droughts of the late19th century and early 20th century. Ecological theory to explain vegetation dynamics was critical for the establishment of rangeland science. Key authors include Clements, Gleason, Sampson, Tansley, and Weaver. Clements (1916, 1936) described a regional mono-climax based on climate with the community likened to an organism. Gleason (1917) described "the Individualistic concept of ecology," in which "the phenomena of vegetation depend completely upon the phenomena of the individual". Sampson (1917, 1919) described the relationship of grazing to vegetation/plant community response based on grazing intensity, which serves as the basis for disturbance theory. Tansley (1939) described a poly-climax. Weaver (1929) described poly-climax, based on soils and disturbance (e.g., grazing ‘disclimax’, post-climax from sandy soils in arid region, pre-climax based on heavy clay soils in arid climates). Dyksterhuis (1949) developed the work of Sampson and Weaver into a management tool for assessment of rangelands based on management scale sites (range sites) and application of ecological theory for disturbance (grazing intensity) and secondary succession. Dyksterhuis measured the degree of disturbance as the degree of departure from the historical climax vegetation (range condition) (Dyksterhuis 1949).

The first widespread applications of ecological theory on rangeland for vegetation management were the range site concept, range condition, and the range condition model (RCM) (Dyksterhuis 1949; Sampson 1919). The range site concept is based on soils and topography within a climatic zone (temperature & precipitation). Range site is an area with similar potential with respect to the kinds and amounts of vegetation it can produce and its response to management.

Range condition is a measure of the degree of disturbance/departure of current vegetation of a range site from the climax (natural potential) plant community for that site(SRM 1974). Sampson (1917) and Humphrey (1947) proposed a linear model of range condition classes (poor, fair, good, excellent) with secondary succession following the reverse path of retrogression. In contrast, Dyksterhuis (1949) proposed describing the herbaceous climax community using vegetation response groups instead of the specific plant species composition. Depending on the kind and amount of disturbance, the species composition of vegetation could differ greatly within a range condition class. Secondary succession of the herbaceous vegetation, starting from the various disturbed states, would move towards the climax vegetation composed of decreaser species with some increasers. Recovery of disturbed rangelands through secondary succession towards climax type community will follow different pathways than the retrogression. The RCM did not include frequency of disturbance since it was regarded as an unnecessary complication since most managers used continuous stocking, not rotational grazing. Modern rangeland management that incorporates many types of deferred and rotational grazing has shown that frequency is a necessary disturbance factor that must be included within management theories.

The failure of range site and condition to predict WPE can be attributed to incorrect assumptions about the relationship between soils, vegetation, grazing, and fire. Dyksterhuis assumed that there were rangeland soils (range sites) and forest soils (forest sites) (Kothmann 2019). Succession on rangeland sites would produce grasslands and succession on forest sites would produce forests. In his paper, The Savannah Concept and its use in Ecology (1957), Dyksterhuis recognized the importance of fire in creating the transitions between rangelands and forest. However, grazing was the only disturbance factor he included in the RCM. He assumed that on rangeland soils removal of the overgrazing disturbance would result in secondary succession producing climax rangeland (Dyksterhuis 1957). He recognized the need for mechanical or chemical treatments to remove long-lived perennial woody invaders, but did not recognize the need for a continuing fire regime to develop and maintain the climax plant community. The absence of fire as a driving disturbance within the RCM explains why the model failed to account for woody plant dynamics at the range site level.

The RCM methodology has been effective for perennial herbaceous rangelands with a long term history of grazing and mature soils, but the omission of fire as a critical disturbance factor in forming the climax plant community caused the RCM not to function adequately with respect to woody plant dynamics. The failure of the Dyksterhuis' RCM to predict WPE was a primary cause of the range management profession shifting from the RCM to the State and Transition model (STM) for vegetation dynamics as an alternative model for rangeland vegetation dynamics that incorporated observed WPE (Briske et al. 2017; Westoby et al. 1989). The STM is similar to the range condition classes described by Sampson (1919) and Humphrey (1947).The STM is a descriptive model. It describes possible ecosystem states and the disturbances that cause transitions between states (Rodriguez Iglesias and Kothmann 1997; Westoby et al. 1989). STM does not provide prediction through ecological theory but explains observed dynamics. STM is not a dynamic model of vegetation changes in that it does not include time for transitions between possible states.

3.3.2. Ecological Theory

The concept of plant succession arose in North America during the early 20th century with Clements offering a comprehensive theory(Glenn-Lewin et al. 1992). Clementsian theory predicts that with stability of the historical disturbance regimes and given an adequate period of time (thousands of years), that a vegetation will reach a stable equilibrium with the climate and soil. “Modern successional theory has emphasized the importance of repeated, relatively frequent disturbances and accepts continuous change in vegetation as the norm”(Glenn-Lewin et al. 1992).

Equilibrium ecology is founded on the assumption that ecosystems are self-regulated by internal biotic processes that result in a single stable state that will return after disturbances cease (Briske et al. 2017). Non-equilibrium theory is founded on the assumption that ecosystems have a finite capacity for internal regulation resulting in the potential for multiple stable states (Briske et al. 2017). Examination of the STM reveals that the multiple states are a product of different disturbance regimes, indicating that vegetation will establish different stable states in the presence of different disturbance regimes. The key to understanding STM is understanding the multiple disturbance regimes incorporated as causes of transitions.

The RCM was based on resilience of the vegetation to an equilibrium state; whereas, STM is descriptive and loosely based on non-equilibrium/resilience theory. STM does not use general properties or attributes of the components (e.g., plant species assemblages, individual species) or processes (e.g., growth, reproduction, and mineralization) of the system to generate prediction rules of wider than local relevance (Rodriguez Iglesias and Kothmann 1997). Rodriguez Iglesias and Kothmann (1997) showed that every published STM proceed though secondary plant succession to a woody state in the absence of human caused disturbance and in the absence of fire. Disturbance (fire and grazing) controls the balance of resource allocation between herbaceous and woody species through removal of photosynthetic structures. Succession theory predicts that higher successional species (woodies) will out compete lower successional species (grasses) in the absence of disturbance (Clements 1936). Following removal of above ground biomass woody plants take longer to restore photosynthetic structures than grasses (Jarvis and Jarvis 1964). Fire and grazing by large ungulates are considered integral to the persistence of grassland ecosystems (Teague et al. 2008). The ecological cost of **not** burning is not understood by many ranchers.

3.3.3. Vegetation History

United States rangelands have undergone drastic change stemming from European settlement. Explorers record the Great Plains as “tremendous areas of luxuriant grass” (Frémont 1842) and “not a tree, shrub, or any other object, either animate or inanimate, relieved the dreaded 'Llano Estacado’” Randolph Marcy (1850). The scale and pattern of land use has altered the frequency and intensity of grazing and fire drastically since those early explores, shifting from migratory grazers and frequent fire to enclosed continuous grazers with permeant water sources and fire exclusion. As these disturbance factors have changed, woody encroachment has increased (Hart and Hart 1997).

"Rangelands are characterized by spatial heterogeneity in soils, topography, landscape positions, historical disturbance patterns, weather, and management influences" (Derner and Augustine 2016). The complexity and dynamics of rangelands eliminates the applicability of broad top down management prescriptions that are one size fits all. Management of vegetation dynamics requires goal oriented management that utilizes ecological principles and experiential knowledge to create managed disturbance regimes.

WPE has been observed on rangelands across the globe (D'Odorico et al. 2012). Proposed factors for WPE are complex with numerous factors including climate, fire, and grazing/browsing regimes, concentrations of atmospheric CO2, and levels of N deposition (Archer 1994; Archer 1995). These changes are occurring at local and global scales with the interaction between factors confusing primary drivers. Local scale drivers of fire, herbivory, and anthropogenic (chemical and mechanical) disturbance are the predominate WPE drivers (Venter et al. 2018). Altering fire and herbivory management regimes has the potential to mitigate WPE (Venter et al. 2018). Analysis of published STM show that over 50% of state changes can be explained by combinations of fire and grazing (Rodriguez Iglesias and Kothmann 1997).

The historic plant communities of the United States are the result of disturbance regimes of fire and grazing selecting for disturbance adapted species (Brown et al. 2005). These plant communities serve as reference or historic plant communities in STM and range site and condition. Modern plant communities do not have the same frequency and intensity of disturbances as the historic plant communities (Briske 2011). This requires the development of new management tools and approaches to explicitly incorporate the disturbance regimes into management plans.

Regime based research and theories enable adaptive feedbacks between individual events and long-term regimes. The effects of disturbance regimes are greater than the sum of the events. Successful management incorporates feedback between single events to form a coherent regime. The goal of DRM is to manage the trend of the changes in the woody plant community. Regime management requires development of ecological principles for application at the regime level while incorporating event level feedbacks.

3.4. Disturbance Regime Theory

3.4.1. Disturbance Regime Development Criteria & Methods

DRT and the DRM worksheets were designed by following general criteria for model development[6]. (1) It should not be site specific; i.e., model structure should be applicable across rangeland types and user experience

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[6] *See Appendix A. Unpublished work of Dr. Mort Kothmann when developing TGM*

(novice to skilled practitioners). (2) Variables should be aggregated to reduce variability within variables and place variability between variables. (3) Variables should be the minimum number possible to address the desired decision analysis. (4) Assessment information should be easy to collect, repeatable, and accurate. (5) The hierarchy of organization selected for the variables should be the same as the decision level targeted by the model. (6) Begin with the simplest model of the system possible.

3.4.2. Disturbance Regime Theory

DRT explains observed vegetation-management interactions between disturbance events that form a disturbance regime. DRT enables practitioners to predict woody population dynamics. The predictions are based on identifying thresholds between population resistance-resilience and disturbance intensity-frequency. The organization of these principles (Table 1) allows practitioners to utilize ecological theory to implement disturbance regime management (DRM). DRM seeks to move management from one-time events, into a series of events over decades that achieve management objectives for WPE. Success is the result of the series of the events not a single event.

Table 3.1: Disturbance regime theory principles with explanations.

Principle	Explanation
Disturbance Regime	Directs Woody Population Dominance (cover)
Disturbance	A temporary change in environmental conditions that causes a pronounced change in an ecosystem. (Wikipedia)
Resistance	Vegetative features that resist the impact of disturbance.
Resilience	Vegetative features that enable recovery following disturbance; e.g., re-sprouting from protected bud zones and propagation from seed sources

DRT is a set of qualitative ecological principles for predicting WPE under adaptive management. DRT utilizes population resistance and resilience to disturbance. It qualitatively identifies thresholds for impacting and not impacting woody plant management. It ‘equips’ managers with ecological theory that explains observed management effects and can also be used to predict responses to DRM plans. DRT is designed as a qualitative ecological theory for application by rangeland managers through the adaptive management process of IRMS. DRT was inspired by the processes used by Dyksterhuis in the RCM. Dyksterhuis based RCM on a model of resilience where secondary plant succession would restore the original climax plant community. The absence of fire in the disturbance regime model caused a lack of fit with the plant community shifting towards a different path of secondary succession because the current DRM. DRT is modern reimaging of concepts from the RCM to create ecological theory applicable and usable by range managers.

WPE is directed by the response of populations to disturbances based on their resistance and resilience. Woody plant dominance is a function of and regulated by the disturbance regime of the rangeland site. Climate, soils, slope, and other abiotic factors determine the range of possible vegetation states as the dynamic framework that a manager can ‘select’ based on management actions. DRT facilitates practitioners in planning what disturbance events are necessary to form a successful regime. A disturbance regime consists of the frequency and intensity of disturbances specific to a management unit. Four primary disturbance tools are available for management to use on rangelands: herbivory, fire, mechanical, and chemical.

This paper analyzes woody vegetation response to prescribed fire disturbance through qualitative descriptors of plant characteristics that affect their resistance and resilience. Woody species are combined into response groups by grouping species with similar resistance and resilience characteristics. Creation of the response groups simplifies both planning and monitoring and makes the model easier to apply. Practitioners apply DRM by identifying woody population thresholds for resistance (intensity) and resilience (frequency) to disturbance events. They plan disturbance events with intensity and frequency greater than the thresholds for resistance and resilience of the response groups targeted for reduction of cover. These thresholds for resistance and resilience are the central focus of DRT. We present methodology for practitioners utilize these concepts to manage WPE within their management unit.

3.4.3. Resistance

Resistance is the relationship between an individual plant and/or a population’s innate resistance to fire and the intensity of a specific disturbance event. The resistance value of a woody population is determined by the physical features that provide plants protection from fire. Table 2 provides four factors for estimating resistance to fire: bark resistance, tissue volatility, structure, and live fuel moisture. These factors were chosen to be universally applicable and adequately represent the variability among species. The application of these features enables managers to predict the effects of fire intensity operating against the resistance characteristics of the woody populations present within the management unit. These factors (Table 2) enable practitioners to qualitatively rate the resistance of a woody population to a specific to a disturbance event.

Table 3.2 Fire resistance characteristics

Bark fire resistance	The physical features that determine bark resistance to fire intensity effects
Plant tissue volatility	The physical composition that determines volatility
Population stature/structure	The structure of the population in relation to fire intensity effects
Live fuel moisture	The live fuel moisture of the woody population.

To utilize these resistance factors, the user must understand the interaction with event intensity. The relationship between resistance and intensity is graphed in Figure 1. For demonstrating the relationship between event intensity and population resistance the factors are qualitatively displayed from low to high with a threshold between impact and no impact. To be effective a disturbances must cross the threshold from no impact to impact for the response group to be impacted. The vertical distance of an event from the threshold indicates the probability of impact or no impact. Point A represents a resistance and intensity combination that does not impact woody cover. Point B represents a resistance and intensity combination that impacts (decreases) woody cover.

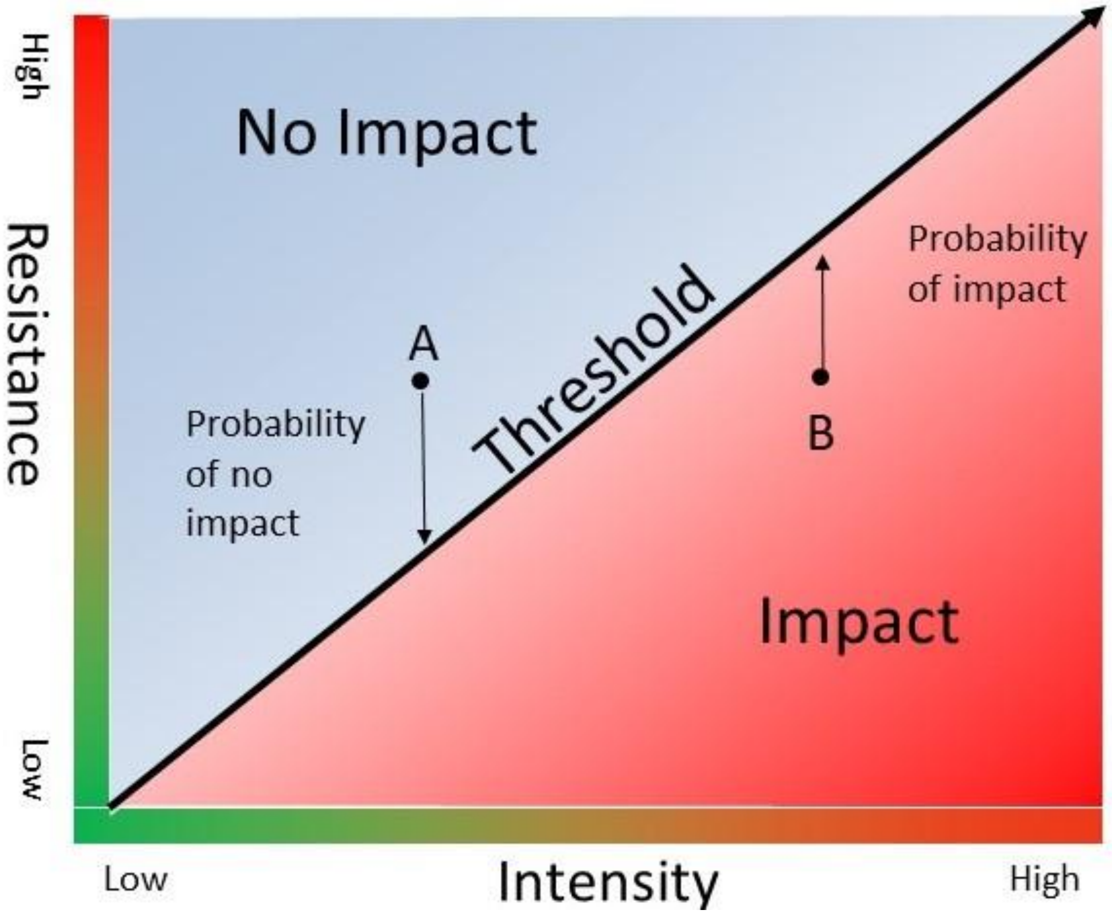

Figure 3.1 Disturbance event impact: the relationship between intensity and resistance. The effect of a disturbance event on an individual plant is determined by relationship between the intensity of the disturbance and the resistance value of the individual. The two possible outcomes are impact or no impact. The threshold between impact and no impact is linear one to one proportion (45 degree slope). The distance from the threshold is the certainty of impact (cover reduction). Points A and B illustrate how a population of moderate resistance responds to two different intensities of impacting events. Point A represents moderate resistance and low intensity for no impact on the individual. Point B represents moderate resistance and high intensity for impact. Impact occurs when the disturbance reduces the measured value (cover, dominance…) of an individual plant.

Managers can utilize population resistance to plan fire intensities that cross the resistance threshold from no impact to impact for the target populations. This facilitates the long-term outlook for planning successful prescribed fires that either overcome the woody vegetation resistance to fire (impact) or avoids an intensity that would impact plants that are designated for protection from fire effects (no impact). Understanding resistance thresholds enables planning for items such as requisite fuel and environmental conditions for a prescribed fire plan that achieves the desired management effect

3.4.4. Resilience

Resilience is the relationship between the response of a species and the frequency of the impacting disturbance events. Resilience is species specific, whereas resistance was specific to a population within a management unit. Key resilience characteristics include resprouting ability, resistance maturation rate, reproduction maturation rate, and competitive ability (Table 3). Practitioners may think of each resilience characteristic as most limiting thresholds crossed via frequency of impacting events with resprouting ability the most limiting characteristic to overcome with the other resilience characteristics secondary until resprouting is overcome. Overcoming the resilience value requires a frequency of impacting disturbance events greater than the resilience value.

Table 3.3 Characteristics for determining species resilience from series of impacting disturbances

Resprouting ability	The ability of a populations members to re-sprout following a top killing disturbance.
Resistance Maturation Rate	The relative time to reach resistance maturity
Reproduction Maturation rate	The relative time to reach reproductive maturity
Competitive ability (longevity of seedbank)	The ability of the species to re-establish from the seedbank.

The relationship between species resilience and impacting event frequency is shown in Figure 2. Species resilience and disturbance frequency form two zones split by a threshold. The relationship between disturbance frequency and population resilience the factors are qualitatively displayed from low to high with a threshold between impact and no impact. Effective control requires disturbance frequency to exceed species resilience. The vertical distance of a regime frequency from the threshold indicates the probability of impact or no impact. Point A represents a resilience and frequency combination that does not impact woody cover. Point B represents a resilience and frequency combination that impacts (decreases) woody cover.

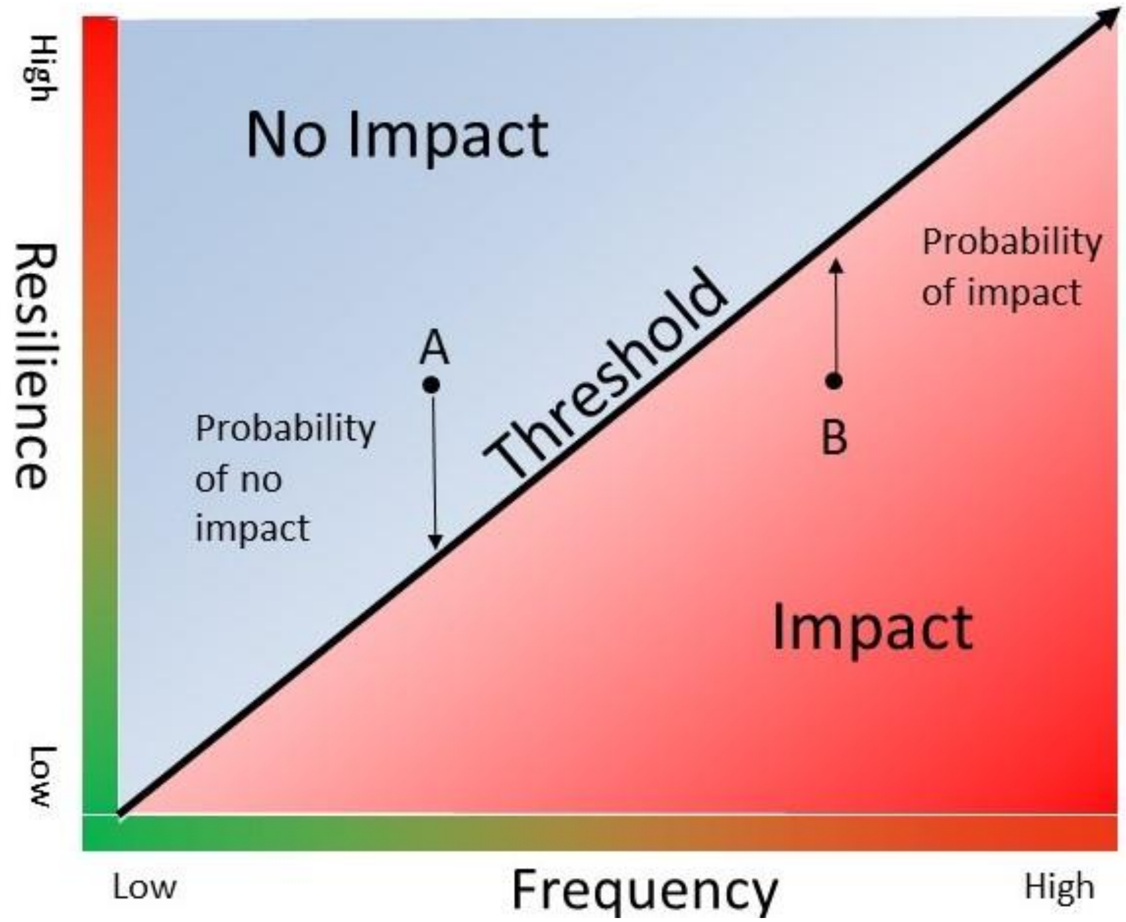

Figure 3.2 Disturbance events impact: relationship between disturbance resilience and disturbance frequency. The effect of disturbance events on an individual species is determined by relationship between the frequency of impacting disturbances and the resilience value of the species. The two outcomes are impact or no impact. The threshold between impact and no impact is linear one to one proportion (45 degree slope). Points A and B illustrate how a species of moderate resilience responds to two different frequency of impacting events. Point A represents moderate resilience and low frequency for no impact on the species. Point B represents moderate resilience and high frequency for impact. Impact occurs when the disturbance frequency reduces the measured value (cover, dominance…) of a species. The distance from the threshold is the certainty of impact (cover reduction)

Understanding resilience enables a manager to plan the frequency of impacting disturbances. Overcoming resilience requires a disturbance frequency greater than the resilience of the species. The principle of resilience guides the frequency of disturbance event implementation by managers. Adaptive management allows the practitioner to alter the event frequency of the management regime. Monitoring the effects of each disturbance event allows practitioners to make adaptive modifications to a disturbance regime that effectively directs WPE.

3.4.5. New Grouping of Woody Plants (VRG)

Resistance and resilience are continuous variables with complex interactions. Simplification to categorical variables can decrease the complexity while maintaining value to the practitioner. Simplifying resistance and resilience from continuous variables to binary variables creates non-resistant-non-resilient, resistant only, resilient only, and resistant-resilient as the four basic vegetation response groups (VRG) (Table 4). Each VRG has a unique response (increase, decrease, no effect) to a disturbance regime. Categorizing woody plant species into VRG enables managers to more easily apply disturbance principles to a management unit.

VRG facilitate making decisions at pasture management spatial scales. Species are evaluated based on their response to the intensity and frequency of fire. VRG reduces management complexity by categorizing individual species into four VRG. The resistance and resilience of an individual species to a specific disturbance determines its classification to a VGR. Grouping species by response to disturbance enables managers to plan the management regime around the VRG. Disturbance effects occur at a species level but management by prescribed fire generally occurs at a pasture management unit level.

Table 3.4 Vegetation response groups for resistance and resilience to disturbance

Vegetation Response Group	Resistant—Resilient (VRG 1)	Resistant Only (VRG 2)	Resilient Only (VRG3)	Sensitive (VRG 4)
Resistance (Vegetative features that provide protection from a disturbance)	Resistant	Resistant	Non-Resistant	Non-Resistant
Resilience (Vegetative features that promote regrowth following removal from a disturbance, re-sprouting from protected bud zones, propagation from seed sources)	Resilient	Non-Resilient	Resilient	Non-Resilient
Example Species	Honey Mesquite	Post Oak	McCartney Rose	Ash Juniper

This allows general categorization of how populations will **respond** to disturbance regimes. Even simplified, resistance and resilience are more complicated then prior management methods (range condition). However, the additional complexity is required for WPE management. These response groups are for regime level planning of management units seeking to utilize prescribed fire to control WPE. The value in VRG's is in general regime planning. VRG enables communication of general ecological concepts to mangers and facilitates use of complex adaptive management. VRG's allow prediction of vegetation response to generalized long term disturbance regimes. VRG's allow what-if analysis for what happens to different groups.

Thresholds are critical for predicting how VRG respond to a disturbance event and how disturbance events combine to form disturbance regimes. For a disturbance event to reduce the cover of VRG the event intensity must exceed the resistance threshold. For a disturbance regime to reduce the cover of VRG the frequency of events must exceed the resilience threshold. For events to affect frequency they must exceed the resistance threshold. The combination of disturbance event frequency and intensity forms a disturbance regime that directs how woody populations respond (Figure 3). The effects of individual disturbance events are cumulative when implemented as part of a disturbance regime spanning one or two decades. The key to successful management is designing and disturbance regimes that accomplish management objectives.

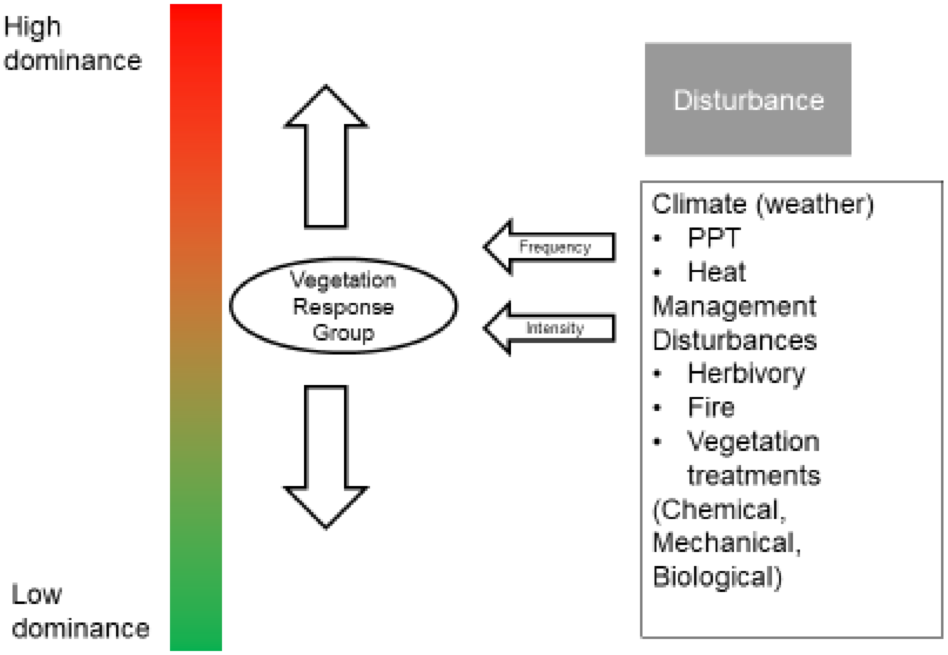

Figure 3.3 Interaction of vegetation response group with frequency and intensity of disturbance directing woody plant dominance

3.4.6. Designing Disturbance Regimes: Resistance and Resilience

A disturbance regime is the combination of frequency and intensity of individual events. A disturbance regime that controls WPE requires that impact thresholds for resistance and resilience must be crossed. Simplification from an infinity of possible resistance and resilience combinations to four main VRG enables managers to plan a disturbance regime and adapt the implementation of each event to actual conditions.

Visualizing how a VRG interacts with possible disturbance regimes facilitates regime planning. Figure 4 shows a continuum of theoretical long-term disturbance regimes (frequency & intensity combinations) with a delineated threshold between presence and absence the VRG. The area above a VRG threshold represents long-term disturbance regimes where the VRG cannot dominate an ecosystem due to regime intensity and frequency. The area below the VRG threshold represents long-term regimes where presence of the VRG is not limited by regime intensity and frequency. An example of a sensitive VRG species is McCartney Rose (*Rosa bractata*). McCartney Rose when present on coastal prairies, its dominance is controlled by fire frequency. As long as the regime intensity exceeds the minimum required, regime frequency is the driving factor for sensitive VRG populations.

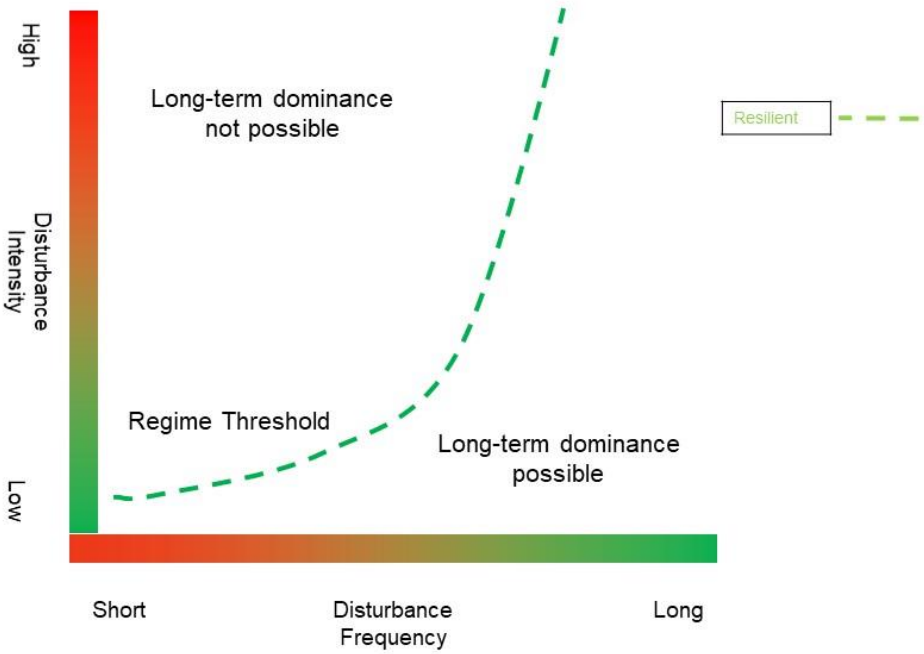

Figure 3.4 Managed equilibrium regime: VRG 3 Resilient probability of presence under long-term disturbance regimes. Long-term disturbance regime creates an equilibrium threshold separating presence or absence. Each curve represents a threshold between possible and not possible dominance for long-term regimes. The presence of a VRG is a continuum from dominant to absent with farther from a curve indicating a higher probability of absence or presence. Above the curve the VRG is unable to dominate due to the regime intensity and frequency but below the curve the presence of the VRG is not limited by the regime frequency and intensity.

Figure 5 shows the managed equilibrium thresholds for the four VRG's (Table 4). These curves show the effects of disturbance regimes on the limiting each VRG. This enables managers to plan disturbance regimes that exceed the equilibrium threshold of undesired woody populations. Visualizing these Equilibrium thresholds enables managers to plan possible disturbance regimes necessary to control VRG's present on their management units. This strategic planning is key to successful long-term WPE management.

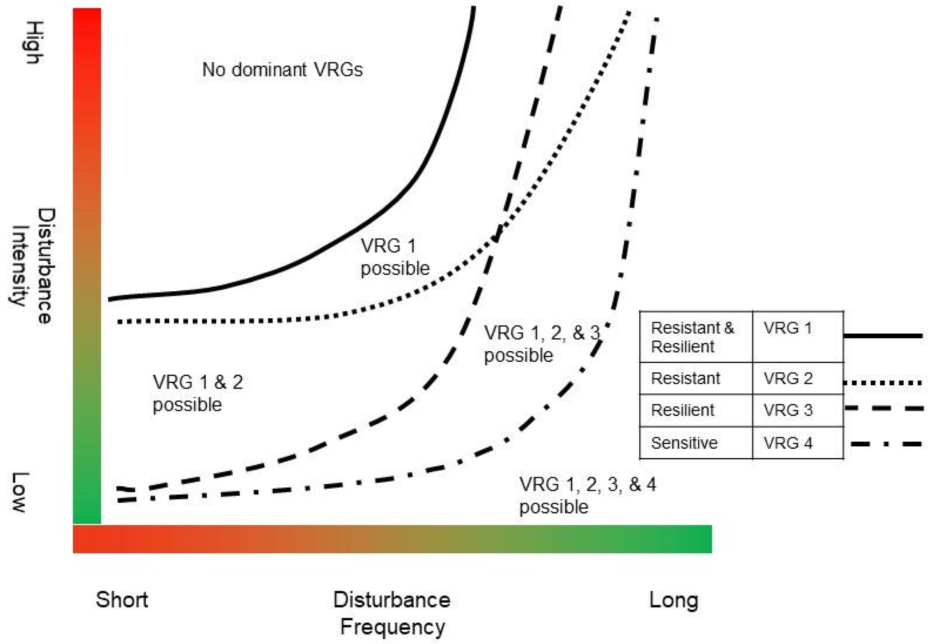

Figure 3.5 Managed equilibrium regimes: VRG's probability of presence under long-term disturbance regimes. Long-term disturbance regime creates thresholds for each VRG probability of presence or absence. Each curve represents a threshold between possible and not possible dominance for long-term regimes. Presence of VRG are a continuum from domination to absent with farther from a curve indicating a higher probability of absence or presence. Above the curve the VRG is unable to dominate in the regimes and below the curve the VRG may occur within the regimes.

When a planned regime is implemented it becomes a realized regime where monitoring can measure the trend of WPE to determine if the implemented regime meets management objectives. Since planned DRM may extend over decades, monitoring following the application of individual disturbance events will allow for adaptive adjustments to be made to the plan to keep vegetation trends moving towards the management goal. The implemented regime is unlikely to match the initial planned regime due to stochastic variables inherent to rangeland management. These regimes are adaptively created by a manager. Adaptive management utilizing resistance and resilience principles enables managers to design disturbance regimes that will create the desired trends to manage WPE for their management units. The disturbance regimes should be site specific with adaptation through application of key principles creating management regimes that ‘control’ WPE meeting management goals.

3.5. Disturbance Regime Management

Application of DRT principles by practitioners through adaptive management creates DRM. The base idea (thresholds) of DRT is simple but the factors for determining resistance and resilience to prescribed fire intensity are complex with interactions between the variables. This creates a challenge for implementation since research on the ability of persons for mentally processing multiple variables shows, “a significant decline in accuracy and speed of solution from three-way to four-way interactions”(Halford et al. 2005). To solve this challenge management science must organize ecological principles, create conceptual models, and create decision aids that increase the ability of manager to utilize complex multivariable concepts.

3.5.1. Disturbance Regime Response Worksheets

DRM **worksheets** function as a common starting point for implementing DRM. Similar to worksheets used by pilots before and during flights. DRM worksheets contain factors critical for successful implementation. Users customize the worksheets to their specific management unit through addition or subtraction of factors they know as critical for success. Practitioners qualitatively rate each factor within a checklist as low, moderate, or high. Qualitative ratings allow for differentiation between various rangelands since what is low for one location may not be low for another location. The worksheets are designed as simply as currently conceivable to provide qualitative ratings of factors useful for determining thresholds for DRM. They provide a basis for applying general ecological theory to create customized management regimes.

Worksheets are composed of component type and component rating. Component type is the key variable that determines the qualitative rating of resistance and resilience to intensity. Component ratings are the text descriptors for low, moderate or high to enable easy evaluation of a population by the user. The primary purpose of a checklist is the display of the individual factors for evaluating the dependent variables of population resistance and population resilience to the independent variable, prescribed fire intensity. The secondary purpose is to evaluate the individual factors to form a composite qualitative rating. The individual factors are estimated then composited by the user. This allows managers to determine the importance of each factor to their specific situation. This compositing is based on user experience. A simple average of equal factor weights is the base composite. However, as managers become more familiar with their management unit, they develop ratings unique to their management unit. The average rating may be useful for general comparisons but the components are of greater value for a checklist approach. A simple average may be of value for beginners but experienced practitioners can go beyond equal weight average to a complex compositing unique to the user and their situation.

The population resistance (Table 5) displays four primary factors for estimating a population's protection/avoidance from a prescribed fire: Bark resistance, tissue volatility, live fuel moisture, and fuel structure & abundance. These were chosen as the first four limiting factors necessary for evaluating population resistance. A woody population is rated low, moderate, or high for each factor. This allows the manager to summarize critical DRM information quickly and easily. The rated populations' factors are then compared to the planned prescribed fire.

Table 3.5 DRT qualitative disturbance resistance checklist for estimating woody population's resistance to fire.

Characteristics	Low=0	Moderate=1	High=2	Rating
Bark fire resistance	Population Bark provides little to no protection from scorch or heat transfer	Bark provides moderate protection from scorch and heat transfer	Bark provides high protection from scorch and prevents heat transfer	
Plant Volatility	Plant structures are highly volatile	Plant structures are moderately volatile	Plant structures are not volatile	
Live fuel moisture	Live fuel moisture is low with live tissue approaching dehydration	Live fuel moisture is moderate with plant not fully saturated	Live fuel moisture is high with live tissue completely saturated	
Plant stature/structure	Plant population structures are predominantly within the expected flame height	Plant population structures are partially outside of the expected flame height	Plant structures are outside of the expected flame lengths	
Ladder fuels	Ladder fuels are highly abundant among the population	Ladder fuels are moderately abundant among the population	Ladder fuels are sparse among the population	

The population resilience checklist (Table 6) displays four primary factors for estimating species response to impacting disturbances: resprouting ability, resistance maturation rate, reproduction maturation rate, seedling competitive ability, and seedbank lifespan. Woody species are rated low, moderate or high for each factor. Designing management to the first limiting factor is key for planning event frequency. Resprouting ability is generally the first limiting factor followed by resistance maturation rate. Resistance maturation is the time required for the species to transition from non-resistant populations to resistant populations. These factors are critical for planning the interval between impacting events. Identifying first limiting factors then applying adaptive management to modify event frequency allows the frequency to be adapted to the current vegetative status of the management unit. When the desired frequency of fire cannot be obtained, intensity may be increased to increase the impact of the individual disturbance.

Table 3.6 DRT qualitative disturbance frequency checklist for estimating species resilience by characteristics.

Characteristics	Low=0	Moderate=1	High=2	Rating
Resprouting ability	Species does not resprout from below ground	Species moderately resprout from below ground	Species vigorous resprouting from below ground	
Competitive ability	Species establishment is uncompetitive in comparison to surrounding species	Species establishment is moderately competitive in comparison to surrounding species	Species establishment is highly competitive in comparison to surrounding species	
Maturation rate	Maturation to reproductive capability is slow (16 years)	Maturation to reproductive capability is moderate (8 years)	Maturation to reproductive capability is rapid (4 years)	

The prescribed fire intensity checklist (Table 7) displays six factors for predicting fire intensity/effect: fuel continuity, fuel load, topography, live fuel moisture, relative humidity, and wind speed. For every prescribed fire these factors will lead to different intensities based on type of fire: head-fire, back-fire, and flank-fire. Variability of management units and possible prescribed fires requires understanding of concepts for application within an adaptive management framework. These were chosen to represent critical factors that practitioners must consider when designing prescribed fire events. Considering all factors at once is highly complex. The practitioner plans prescribed fire to exceed the resistance of the targeted population. The checklist guides the user in factors critical for estimating the intensity of the prescribed fire. Prescribed fire is a complex process for which experience is essential (Safety especially). These worksheets can facilitate the planning process for an effective prescribed fire.

Table 3.7 DRT Qualitative checklist for estimating prescribed fire intensity.

Characteristics	Low=0	Moderate=1	High=2	Rating
Fuel continuity	Fuel bed is not continuous with large discontinuities	Fuel bed is moderately continuous without large discontinuities	Fuel bed is continuous with no discontinuities	
Fuel Load	Fuel load is low	Fuel load is moderate	Fuel load is high	
Live fuel moisture (KBDI)	Live fuel moisture is high with live tissue completely saturated	Live fuel moisture is moderate with plant not fully saturated	Live fuel moisture is low with live tissue approaching dehydration	
Dead fuel moisture	Standing dead fuel is moisture saturated: 1, 10, 100 hour fuels are not dry	Standing dead fuel moisture is mixed: 1 hour fuels are dry, 10 and 100 hour fuels are not dry	Standing dead fuels are extremely dry: 1, 10, 100 hour fuels are dry	
Wind speed	Wind speed is low	Wind speed is moderate	Wind speed is high	
Topography	Topography does not have relief that influences intensity	Topography relief moderately influences intensity	Topography relief highly influences intensity	

These worksheets allow managers to visualize population resistance, species resilience, prescribed fire intensity, and prescribed fire frequency estimates for their management unit. This facilitates planning disturbance regimes that control WPE. Viewing all the relevant factors allows users to isolate variables they know are critical for successful application and plan their management around those variables. Live fuel moisture is of critical importance for fires targeting woody species. For example, *Juniperus ashei* can be volatile fuel or a fire break depending on live fuel moisture. As users gain experience with DRM each practitioner develops knowledge for which factors and combination of those factors are critical for success on their management unit. The adaptive management process (such as IRMS) is critical for successful application of DRM due to the complexity and dynamic nature of rangelands. The individual effects are relatively simple; however, considering all of the possible important interactions of these effects is complex. Implementation of DRT through DRM can be greatly enhanced by the use of these decision tools.

The basic outline for application of DRM is shown in Figure 6. It begins with an inventory of the relevant woody populations. Next, a vision for the management unit is set with goals for each population. The worksheets are then utilized to rate the resistance and resilience for each woody population. A prescribed disturbance is planned to effect the woody populations in accordance with the management vision. After implementation of an event the effects are monitored to provide feedback to the disturbance planning process and track trend towards achieving the management vision. Adaptive management is critical for successful WPE management.

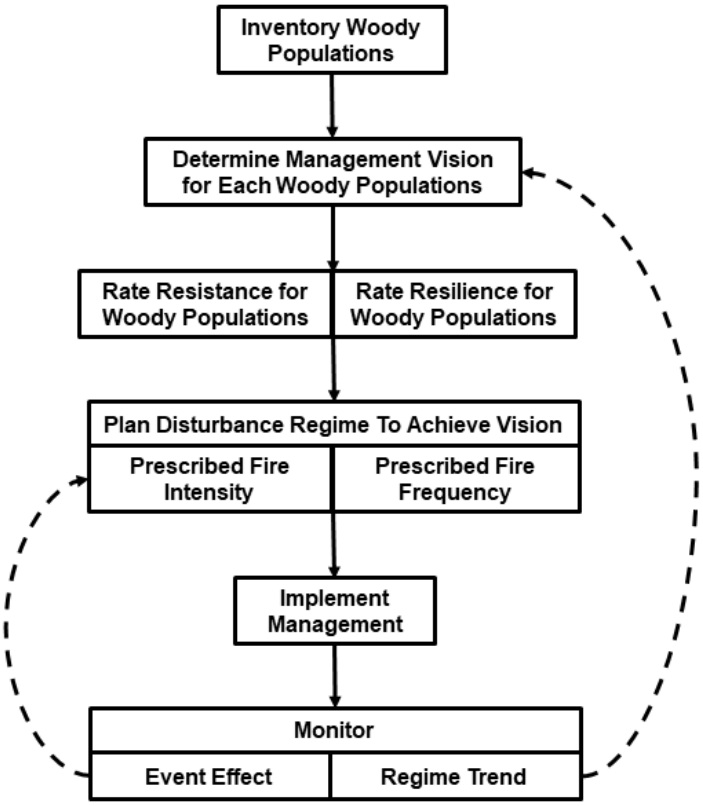

Figure 3.6 Disturbance Regime Management process outline.

3.6. Future Research on Decision Aids

Decision aids, such as Bayesian probability models, could be utilized to form decision aids that assist a manager in integrating the multiple factors considered in DRM. The nature of Bayesian models lends it to use by individual managers. Since Bayesian probability can be established between the factors to output a composite rating. Bayesian probability models could be utilized to evaluate the probability of success for a proposed management prescription. For instance, to identify threshold between impact and no impact for a proposed disturbance event on a woody population. Evaluation of the results following the application of prescriptions can be used to update the probability relationships in the Bayesian model. A successful decision aid adds value to the decision process beyond the ‘cost’ of using the decision aid. Proof of the relevance of the factors within the worksheets is necessary for the creation of a decision aid. The proof of relevance requires traditional research to evaluate hypotheses within DRT.

3.7. Conclusion

DRT enables practitioners to apply ecological concepts and principles to WPE management. DRT sets resistance and resilience as the key population characteristics that a disturbance regime is planned to overcome. Overcoming resistance requires fire intensity to exceed the threshold for resistance. DRT qualitatively applies resistance and resilience to assist practitioners in designing prescribed fire intensity and frequency to form disturbance regimes that direct WPE. These principles can be utilized by managers to plan and implement DRM that achieves their objectives for the management unit. Resistance principles inform planning for effective individual disturbance events. Resilience principles inform planning for the effect of multiple disturbance events. The combination of resistance and resilience principles enables the planning of **long-term disturbance regimes** that successfully manage WPE. Implementation of these regimes will require adaptive management to handle the environmental stochasticity inherent to rangelands.

For the science of rangeland management to ‘solve’ WPE we must support the development and extension of successful management practices from expert managers all the way to novice managers. The extension of these practices must not but static best practices but dynamic processes that enable the individual to learn, customize, and grow. DRM when combined with adaptive management can extend complex management practices such as prescribed fire to novice users.

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4. DISTURBANCE REGIME THEORY AND WOODY PLANT ENCROACHMENT: AN ADAPTIVELY MANAGED PRESCRIBED FIRE-GRAZING REGIME CASE STUDY

4.1. Overview

This paper is a case study of woody plant encroachment management (WPE) on a working ranch on the Texas coastal prairie. A disturbance regime was applied with adaptive management to control McCartney Rose (*Rosa bracteata*) on the Duncan Spade Ranch Wharton County, Texas. The woody cover of the ranch was monitored with National Agriculture Imagery Program airborne digital images, permanent line transects, and plot photographs. Monitoring data were utilized to evaluate the effects of the disturbance regime, consisting of one herbicide treatment and prescribed grazing and fire, on McCartney Rose cover. The monitoring data were used to modify the grazing and fire prescriptions following adaptive management procedures, and to test disturbance regime theory (DRT). Disturbance regime management worksheets were utilized to apply DRT to make qualitative predictions of impact or no impact for resistance to fire intensity and resilience to fire frequency for McCartney Rose. McCartney Rose was rated as low-moderate resistance to fire intensity. Resilience to fire frequency was rated high. Estimated prescribed fire intensities varied between low-moderate to moderate. Classified aerial photography measured 24% woody cover in 2010 which decreased to 6% in 2018. A paired t-test for mean cover measured by line transect measured a significant (P= 0.02, 14 df) 50% decrease in woody cover from 16% in 2012 to 8% in 2018. These data support the validity of the DRM worksheets and process.

Keywords: woody plant encroachment; *Rosa bractata*; McCartney Rose; adaptive management; rangeland management; prescribed fire; disturbance regime.

4.2. Introduction

Woody plant encroachment (WPE) is a serious problem for rangeland managers (Archer et al. 2017). Adaptive application of managed grazing-fire regimes has been advanced as a potential solution for managing WPE (Allen et al. 2017). An adaptively managed disturbance regime was implemented on the Duncan Spade Ranch, Wharton County, Texas from 2012 to 2018 to control McCartney Rose (*Rosa bracteata*) encroachment on the Spanish Camp Unit. This case study evaluates adaptive management and applied ecological theory for managing WPE that developed in part from the experiences of this case study. Disturbance regime theory (DRT) was developed to facilitate designing disturbances regimes (event intensity and event frequency) for control of WPE.

The management regime of the Spanish Camp Unit was designed with ecological concepts that became part of DRT. DRT is the interaction between woody population resistance to disturbance (fire) intensity and woody population resilience to disturbance frequency. Disturbance regime management (DRM) is the adaptive application of disturbance events through time to create a disturbance regime, which accomplishes management objectives for woody population cover. Adaptive management was utilized to alter planned grazing and disturbance management prescriptions refined with monitoring data and learning by the ranch manager. This case study provides validation of DRM in the context of adaptive management on a working ranch. DRT concepts, resistance and resilience were evaluated for providing ecological information useful for management of WPE.

The prescribed fire regime was analyzed for effect on WPE on Texas Coastal Prairie rangeland at a management scale. The WPE monitoring data were compared to resistance and resilience predictions made with DRM worksheets for McCartney Rose. McCartney Rose resistance and resilience were rated using DRM worksheets to create a prediction of impact (decrease in cover) or no impact (stable or an increase in cover) for the managed disturbance regime. The study area was the Spanish Camp Unit, a 400-HA unit of the Duncan Spade Ranch. The primary encroaching woody species was McCartney Rose. The primary goal of the management regime was to reduce McCartney Rose cover with a managed prescribed fire regime without repeated application of herbicide. The effectiveness of the prescribed fire disturbance regime for controlling WPE was determined through remote sensed image classifications, key area line transects for woody cover, and key area plot photographs. Remotely-sensed National Agriculture Imagery Program (NAIP) airborne digital images were classified to track woody cover trend for the whole Spanish Camp management unit. Data from yearly sampling of key areas for woody cover with line transects and plot photographs were utilized in the adaptive management process.

Our objectives were to: (1) evaluate the effectiveness of a disturbance regime to control McCartney Rose encroachment, (2) evaluate DRT concepts resistance and resilience, and (3) evaluate DRM worksheets for making qualitative predictions for WPE. To our knowledge, at the time of writing this article, there were no other studies of McCartney Rose control with a prescribed fire regime that used NAIP images to evaluate response to management.

4.2.1. Remote Sensing of Woody Plant Encroachment

Monitoring WPE through remote sensing is a common technique utilized by many studies (Hartfield and van Leeuwen 2018; Mirik et al. 2013; Wang et al. 2017; Xuebin 2019). The accuracy of land cover classification is impacted by both algorithms and remote sensing images (spatial, temporal and spectral resolutions) (Wang et al. 2017). Remote sensing for WPE monitoring enables complete enumeration of the study area and repeatability that is not feasible with traditional ground based monitoring. The use of high spatial resolution images such NAIP digital images is common for pasture scale remote sensing is common in rangelands (Davies et al. 2010; Michez et al. 2019; Mirik et al. 2013).

4.2.2. Woody Plant Encroachment

WPE has been observed on rangelands across the globe (D'Odorico et al. 2012). Proposed factors for WPE are complex with numerous factors including climate, fire, and grazing/browsing regimes, concentrations of atmospheric CO2, and levels of N deposition (Archer 1994; Archer 1995). These changes are occurring at local and global scales with interactions between factors. Interactions among the primary drivers of WPE make it difficult to separate the effects of local scale drivers of fire, herbivory, and anthropogenic (chemical, mechanical) disturbances from climatic drivers. However, local WPE drivers predominate (Venter et al. 2018). Thus, altering fire and herbivory management regimes has the potential to mitigate WPE (Venter et al. 2018). Analysis of published state and transition models showed that over 50% of state changes (transitions) could be explained by a combination of fire and grazing (Rodriguez Iglesias and Kothmann 1997).

4.3. Methods and Management History

Rangelands are disturbance driven ecosystems. Derner and Augustine (2016) described Rangelands as “characterized by spatial heterogeneity in soils, topography, landscape positions, historical disturbance patterns, weather, and management influences”. The interaction of these characteristics create dynamic complexity that eliminates the applicability of broad top-down management prescriptions that are one size fits all. Management of vegetation dynamics requires goal oriented management that utilizes ecological principles and experiential knowledge to create managed disturbance regimes.

Disturbance (fire and grazing) impacts the resource allocation between herbaceous and woody species through removal of photosynthetic structures.

Succession theory predicts that higher successional species (woodies) will out compete lower successional species (grasses) in the absence of disturbance (Clements 1936). Following removal of above ground biomass, woody plants take longer to restore photosynthetic structures than grasses (Jarvis and Jarvis 1964). Fire and grazing by large ungulates are considered integral to the persistence of grassland ecosystems (Teague et al. 2008).

DRT incorporates population resistance to fire intensity and species resilience to fire frequency for predicting the effect of a management regime. Resistance is a result of the physical characteristics that protect plants from disturbance destroying/removing tissue. Resilience is the sum of physical characteristics that determine the regrowth potential following an impacting disturbance. DRM planning occurs at the regime level. Implementation by practitioners occurs event by event with adaptation of event intensity and frequency to create a regime with the desired vegetation effect. Four primary disturbance tools (herbivory, fire, mechanical, and chemical) are available for use by management on rangelands. Prescribed fire was the primary disturbance utilized for control of McCartney Rose. Grazing was designed to facilitate prescribed fire.

4.3.1. Site Description

The Duncan Spade Ranch is a historic ranch near Egypt, Texas in the Gulf Coast Prairies and Marshes ecoregion. The ranch enterprises include livestock grazing, hay production, rice, and crop production. The Spanish Camp

Unit consists of 400 ha of unplowed coastal prairie rangeland. The traditional management of the Spanish Camp Unit was continuous grazing and yearly herbicide spraying application for McCartney Rose control. The stocking rate began at 2.5 HA/AUY and rose to 2.1 HA/AUY at the beginning of 2015, at which time a management decision was made to reduce to the original stocking of 2.5 HA/AUY. In 2012, the unit was cross-fenced into five pastures (Figure 1). A severe drought during 2010-11 resulted in extreme overgrazing of grasses in 2011 and a dense stand of weeds in the spring of 2012. To reduce the herbaceous weed density, all pasture accept the northwest pasture were sprayed during the spring of 2012. The Northwest Pasture was not sprayed because it was adjacent to a cotton field. It was dominated by herbaceous weeds in 2012 but was sprayed during early spring of 2013.

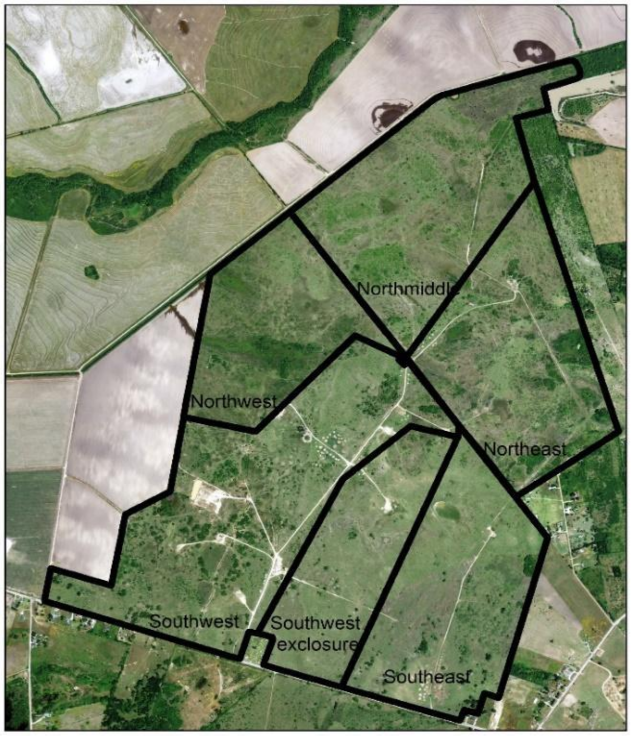

Figure 4.1 Duncan Spade Pasture Map NAIP airborne digital image 2016

The climate is humid subtropical with mild winters and an average rainfall of 11 cm per year. Standing water is common for low-lying areas for multiple weeks following heavy rains. The pastures are dominated by Bahiagrass (*Paspalum notatum*) and Brownseed paspalum (*Paspalum plicatulum*) with remnants of tall grasses little bluestem (Schizachyrium scoparium), Indiangrass (*Surgastrum nutuns*), and Switchgrass (*Panicum virgatum*) remaining primarily in areas protected by McCartney Rose cover. McCartney Rose is the primary encroaching woody species, a vigorous re-sprouting evergreen shrub that can dominate the landscape by forming large hedges. Small amounts of Chinese tallow (*Triadica sebifera*) and Honey mesquite (*Prosopis glandulosa*) are present, although neither are vigorous encroaching species on this location and they have relatively stable cover. Honey mesquite is present primarily in the Southwest pasture, which was the original watering location before cross-fencing. Chinese tallow is limited to low areas where standing water is common after rains.

4.3.2. Management Strategy

The management regime for the Spanish Camp Unit was designed to accomplish two primary objectives: first, control McCartney Rose cover, second, improve forage quality and quantity. The management regime was adaptively modified based on monitoring data during the six years of the study. Management originally planned a pasture fire return interval of approximately 2-3 years to accomplish the WPE management objectives: However, the fire regime for each pasture was independently and adaptively managed to best utilize available resources. This study evaluates the primary goal of McCartney Rose encroachment control.

The Spanish Camp Unit was rotationally grazed with one herd of approximately 160 cows. The cows were cross of approximately half Hereford, Angus, and Charlotte with half Brahman. The cattle were bred to Charlotte bulls with calving mid-December through March. Calves are weaned during the last two weeks of September. The herd was feed hay during the winter months. As pasture management and range condition improved the duration of winter hay feeding was reduced. Pasture forage growth and herd demand were modeled with The Grazing Manager (TGM) (Kothmann 2007), a decision aid software program which enables dynamic planning for forage allocation to grazing and prescribed fire. The herd rotations were planned with TGM, usually between four days to several weeks in a pasture depending on forage growth rate and total available forage. Grazing schedules were designed to meet planned fuel continuity and quantity required for impacting prescribed fires. All prescribed fires were conducted on dormant fuels during the winter months between December and February.

4.3.3. Fire Disturbance Regime History

The fire regime of the Spanish Camp Unit began in 2012 following spring herbicide application for weed control. The management regime was monitored for six years. Table 1 shows the burn history by pasture with the average percentage of each pasture burned for the six-year monitoring period. Table 1 shows the fuel load for each prescribed fire in KG/HA. Fuel load was estimated from the TGM simulation model that was used for pasture management. The original unit of measure was Demand Days[7] (DD) with one DD equivalent to 11.8 kilograms of fuel

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[7] *Demand Days are based on the amount of energy required for animal body maintenance and gain. One Demand Day equals 12 megacalories per day, which is roughly the amount of energy required by one 1000 lb. lactating cow and calf for one day*

Table 4.1 Spanish Camp Unit fire regime history. Fuel load estimates are in kilograms per hectare. Fuel load was estimated from demand days at time of burning from the TGM management model. One demand day was considered equivalent to 11.8 kilograms of fuel. Fire return interval was calculated as the inverse of the average percent burned from 2012-2017.

Unit Name	Variable	2012	2013	2014	2015	2016	2017	Fire Return Interval
South east	**Fuel load**	465	586	-	1467	-	492	-
	% burn	100%	90%	-	30%	-	25%	1.9
South west	**Fuel load**	-	-	368	845	1029	-	-
	% burn	-	-	15%	100%	80%	-	3.0
North east	**Fuel load**	303	-	-	1077	-	1104	-
	% burn	60%	-	-	100%	-	100%	2.3
North Middle	**Fuel load**	-	594	807	-	1807	1424	-
	% burn	-	40%	50%	-	100%	100%	1.4
North west	**Fuel load**	-	558	159	434	575	681	-
	% burn	-	100%	60%	80%	80%	100%	1.4
Ranch	**% burn**	26%	34%	22%	54%	57%	52%	2.4
	Avg. fuel load	384	579	445	956	1137	925	-

4.3.4. Disturbance Regime Response Evaluation

The analysis of DRT concepts begins with the qualitative rating of the primary woody species, McCartney Rose and Honey Mesquite, present on the Spanish Camp Unit, with DRM worksheets. McCartney Rose was the primary species of interest to management and thus, the majority of data are for McCartney Rose. Two data sources were utilized to monitor woody cover, permanent key area McCartney Rose cover line transects and classified airborne digital images for ranch woody cover. Honey Mesquite cover could only be measured in the latest aerial digital image classification in 2018 due to image acquisition dates.

4.3.5. Disturbance Regime Worksheets

DRM worksheets were developed using the following design principles[8].

1) They should not be site specific; i.e., model structure should be applicable across rangeland types and user experience (novice to skilled practitioners).
2) Begin with the simplest model of the system possible.
3) Aggregate variables to the minimum number possible to address the desired decision analysis.
4) Rating criteria should be applicable to any plant species and functional group.

The worksheets (Tables 2, 3, & 4) were designed to facilitate qualitative rating of population resistance, species resilience, and prescribed fire event intensity. Text descriptors allow practitioners to categorize woody populations quickly and easily for comparison to a planned fire event intensity. Monitoring event effects on targeted populations after each disturbance event is critical for improving rating estimates. Resistance and resilience operate as first limiting factors. Initial resistance to disturbance must be overcome before resilience to event frequency is meaningful.

The Spanish Camp woody cover is primarily composed of two species McCartney Rose and Honey Mesquite. McCartney Rose was rated as having low-moderate resistance to fire intensity and high resilience to repeated

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[8] *See Appendix A Rationale for a New Model, Unpublished work of Dr. Mort Kothmann from the development of TGM.*

impacting fires (Table 2, 3). Honey Mesquite was rated as having high resistance to fire intensity and high resilience to impacting fires (Table 2, 3). The winter prescribed fires were rated as low to moderately intense (Table 4) with the primary variation for fire intensity resulting from fuel load and fuel continuity at time of burning. Burns after 2014 were generally conducted with higher fuel continuity and quantities. The fire intensity was also affected by the fire weather conditions on the day of the burn. DRM resistance and intensity prediction is summarized in Figure 2 with McCartney Rose under the impact threshold and Honey Mesquite above the impact threshold. DRT predicts that woody populations with resistance ratings below the prescribed fire intensity threshold will be affected by the fire events. Once resistance is overcome population resilience determines response to the frequency of regime events. The resilience and frequency prediction is summarized in Figure 3 with Honey Mesquite and McCartney Rose under the impact threshold; however, Honey Mesquite is not predicted to cross the intensity threshold in Figure 2; therefore, Honey Mesquite should show no impact from disturbance frequency.

Table 4.2 DRT Disturbance Intensity worksheet for McCartney Rose and Honey Mesquite populations. Key 0= low resistance to fire 10= extreme resistance to fire

Characteristics	Low=0	Moderate=1	High=2	McCartney Rose mature hedge	Honey Mesquite Mature
Bark fire resistance	Population Bark provides little to no protection from scorch or heat transfer	Bark provides moderate protection from scorch and heat transfer	Bark provides high protection from scorch and prevents heat transfer	0	2
Plant Volatility	Plant structures are highly volatile	Plant structures are moderately volatile	Plant structures are not volatile	0	1
Live fuel moisture	Live fuel moisture is low with live tissue approaching dehydration	Live fuel moisture is moderate with plant not fully saturated	Live fuel moisture is high with live tissue completely saturated	2	2
Plant structure	Plant population structures are predominantly within the expected flame height	Plant population structures are partially outside of the expected flame height	Plant structures are outside of the expected flame lengths	1	2
Ladder fuels	Ladder fuels are highly abundant among the population	Ladder fuels are moderately abundant among the population	Ladder fuels are sparse among the population	1	1
Rating Sum				4	8

Table 4.3 DRT Disturbance frequency worksheet for McCartney Rose and Honey Mesquite species. Key 0= low resilience to impacting fire frequency, 6 = high resilience to impacting fire frequency

Characteristics	**Low=0**	**Moderate=1**	**High=2**	**McCartney Rose**	**Mature Honey Mesquite**
Resprouting ability	Species does not resprout from below ground	Species moderately resprout from below ground	Species vigorous resprouting from below ground	2	2
Competitive ability	Species establishment is uncompetitive in comparison to surrounding species	Species establishment is moderately competitive in comparison to surrounding species	Species establishment is highly competitive in comparison to surrounding species	2	2
Maturation rate	Maturation to reproductive capability is slow (16 years)	Maturation to reproductive capability is moderate (8 years)	Maturation to reproductive capability is rapid (4 years)	2	1
Rating Sum				**6**	**5**

Table 4.4 DRT Qualitative fire intensity worksheet. Key 0=low, 10=extreme

Characteristics	**Low=0**	**Moderate=1**	**High=2**	**2012 - 2014**	**2015 - 2017**
Fuel continuity	Fuel bed is not continuous with large discontinuities	Fuel bed is moderately continuous without large discontinuities	Fuel bed is continuous with no discontinuities	1	2
Fuel Load	Fuel load is low	Fuel load is moderate	Fuel load is high	1	1
Live fuel moisture (KBDI)	Live fuel moisture is high with live tissue completely saturated	Live fuel moisture is moderate with plant not fully saturated	Live fuel moisture is low with live tissue approaching dehydration	1	1
Dead fuel moisture	Standing dead fuel is moisture saturated: 1, 10, 100 hour fuels are not dry	Standing dead fuel moisture is mixed: 1 hour fuels are dry, 10 and 100 hour fuels are not dry	Standing dead fuels are extremely dry: 1, 10, 100 hour fuels are dry	1	1
Wind speed	Wind speed is low	Wind speed is moderate	Wind speed is high	0-1	1
Topography	Topography does not have relief that influences intensity	Topography relief moderately influences intensity	Topography relief highly influences intensity	0	0
Sum				**4-5**	**6**

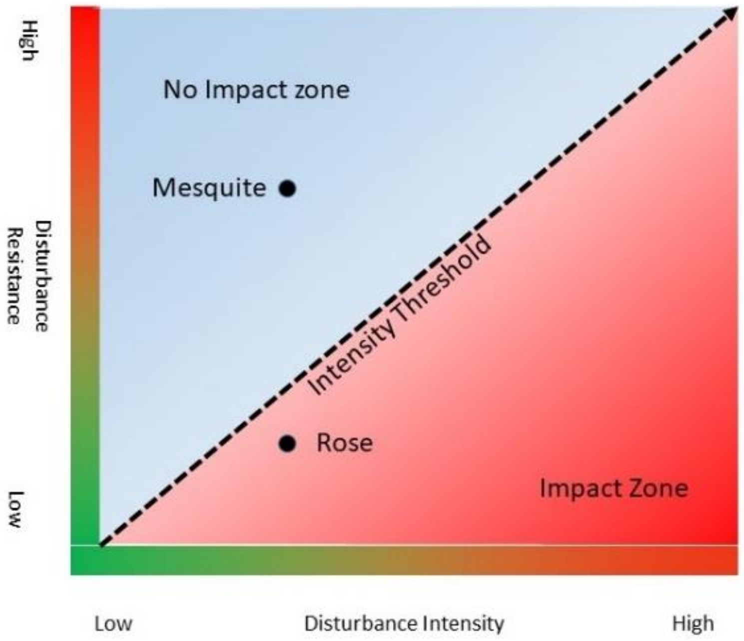

Figure 4.2 Visualization of Mesquite and McCartney Rose resistance ratings from table 2 under a low to moderate fire event intensity.

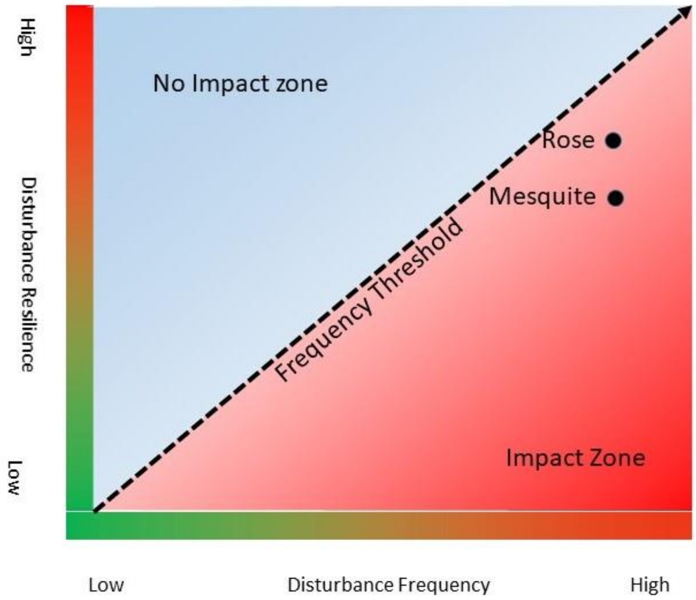

Figure 4.3 Visualization of Mesquite and McCartney Rose resilience ratings from table 3 under highly frequent impacting disturbances. Figure 2 places mesquite as no impact therefore mesquite does not pass the first limiting factor

4.3.6. Woody Plant Cover Data Collection

Effects of the management regime on woody plant cover were monitored at two scales: complete ranch enumeration, and line transects at key areas within pastures. Ranch enumeration monitoring was through classification of NAIP digital images to track cover changes from 2010 to 2018. NAIP digital images are acquired every two years. The acquisition month shifts later in the year for each photograph (Table 5). Key areas were monitored from 2012 to 2018; except for 2015 where no sampling occurred. Fifteen permanent key area sampling points were selected to represent areas for monitoring for adaptive management. McCartney Rose cover was monitored at each key area along each cardinal direction (north, south, east, and west) with 30-meter line transects and plot photographs.

Table 4.5 NAIP airborne digital images date, spatial resolution and spectral resolution from 2010 to 2018.

Image Date	Spatial Resolution
5/3/2010	1.0 m^2
6/1/2012	1.0 m^2
8/1/2014	1.0 m^2
9/29/2016	1.0 m^2
11/1/2018	0.5 m^2

4.3.7. Key Area: McCartney Rose Cover Data Analysis

The line transect data for McCartney Rose was analyzed with International Business Machines Corporation Statistical Product and Service Solutions version 27 software package. A univariate general analysis of variance (ANOVA) model was run to evaluate the line transect data. Years were analyzed as random and pastures and key-areas were treated as fixed variables. A paired t-test was conducted to analyze the difference between the initial (2012) and final monitored years (2018). These tests were conducted for the complete ranch data set and two of the pastures. The southwest and northwest pastures were chosen to evaluate the effects of high and low fire frequency regimes. The individual pasture ANOVA allows direct analysis of the effects of event frequency on population resilience; whereas, the ranch analysis shows aggregates of frequency and intensity for management regime success or failure. The variance was highly correlated to the mean: therefore data normalized with a square root transformation before analysis. Because there were many zeros for transect direction data, .5 was added to all data entries.

4.3.8. Remote Sensing: Data Analysis

Four-band spectral resolution airborne digital images from the NAIP (Figure 4) were classified through ENVI version 5.1 (L3Harris 2013) image analysis program. The general workflow process in Figure 5 was implemented for each image. The spread in image acquisition dates from May to December and time of day of acquisition resulted in each image requiring different numbers of initial cover classes. The cover classes for each classified image were combined to woody and non-woody to allow comparison between the varied images and classes. Two unique classes were not combined into woody or non-woody, Spray 2012 and Honey Mesquite 2018. Spray 2012 cover class consists of broadleaf vegetation top killed from a broadcast herbicide application for weed control following overgrazing from the 2011 drought. The primary sprayed vegetation is Euthamia (*Euthamia graminifolia*) and McCartney Rose. However, top killed McCartney Rose could not be reliably separated from top killed Euphemia in the NAIP. Honey Mesquite 2018 was left as a separate class from the woody cover due to acquisition date enabling separation from McCartney Rose.

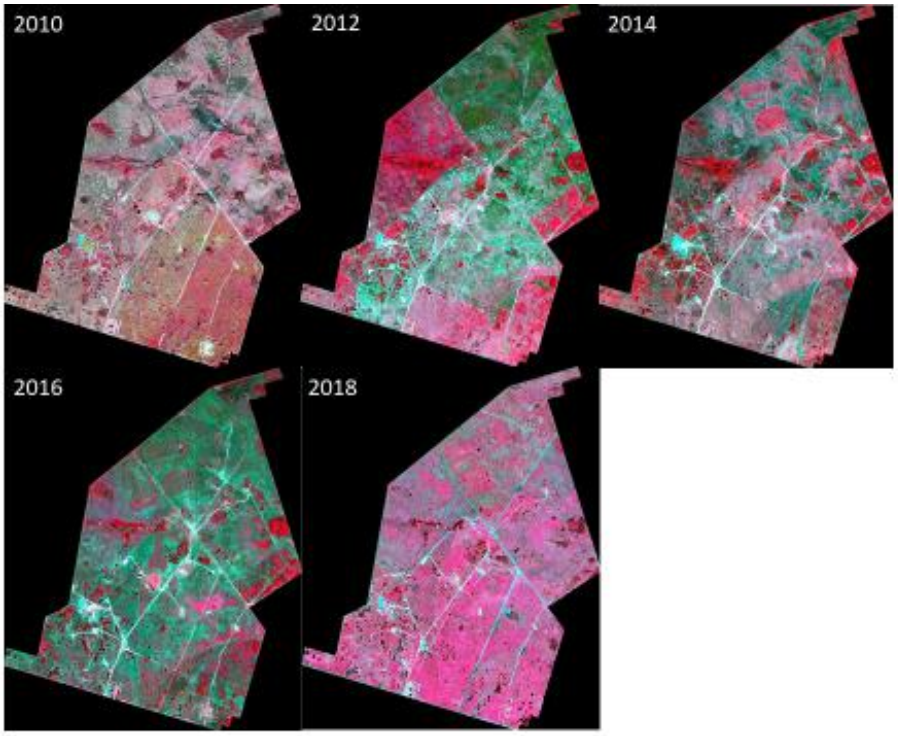

Figure 4.4 False color NAIP airborne digital images of the Spanish Camp Unit from 2010 to 2018

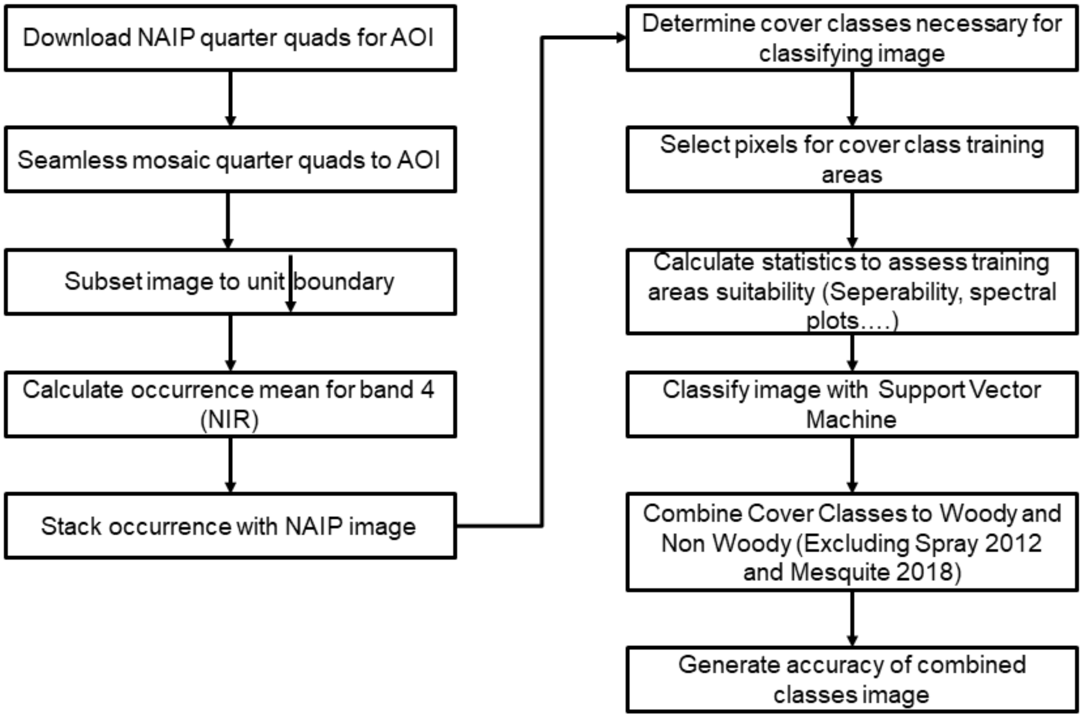

Figure 4.5 Remote sensing image analysis workflow for NAIP airborne digital images.

4.3.9. Remote Sensing Accuracy Assessment

Accuracy assessment for each classification was conducted by constructing an error matrix for overall accuracy, omission, commission, and kappa coefficient. Error matrices for each classification map were generated by comparing the classified cover classes with manually classified pixels. Error matrices were calculated to evaluate classification accuracy and kappa coefficient. 100 random pixels were manually classified for each cover class

Table 4.6 Accuracy Assessment for 2010, 2012, 2014, 2016, & 2018.

Year	2010	2012	2014	2016	2018
Overall Accuracy	99%	93 %	99%	96%	98%
Kappa Coefficient	0.99	0.90	0.99	0.93	0.97

Each image classification had unique challenges that affected classification accuracy due to the varying ground conditions occurring and the shifting acquisition date. The lowest accuracy image of 2012 has omission error for woody cover of 16%. 2012 was the only year with high omission error for woody cover.

Table 4.7 2012 Omission and commission accuracy assessments

Cover Class	commission	omission
Woody	1.2%	16.0%
Non-woody	16.%	0.0%
Spray	0.0%	4.0%

4.4. Results

4.4.1. Results: Key Area Photo Points

The photo point series for key area two (Figure 6) shows Honey Mesquite cover as mature trees with McCartney Rose cover next to and under the mature trees. These photographs indicate that the disturbance intensity was not sufficient to overcome the resistance value of a mature Honey Mesquite population. The photo point series for key area six (Figure 7) shows mature McCartney Rose hedge reducing to recent regrowth. McCartney Rose is still evident in the 2018 image but does not dominate the landscape as in the 2012 image. The stature reduction of McCartney rose due to prescribed fire is only captured in the photo point series results.

Figure 4.6 Duncan Spade key area two east photo series 2012, 2014, 2018: an example of Mesquite cover stability from 2012 to 2018.

Figure 4.7 Duncan Spade key area six south photo series 2012, 2014, 2018: an example of McCartney Rose hedge decreasing in response the disturbance regime from 2012 to 2018.

4.4.2. Results: Key Area Line Transects

The line transect data for the Spanish Camp Unit (Table 8) shows the individual pastures, key area average, and pasture average by year. The ranch average decreased from 20% McCartney Rose cover in 2012 to 11% cover 2018. The ANOVA of these data (Table 9) illustrates interaction for year (P = 0.004) and pasture by year (P= 0.004). The prior indicates that McCartney rose cover decrease through time is significant. The latter indicates that McCartney Rose cover change is significant for the individual pasture management regimes. The paired t-test for means (Table 10) for 2012 and 2018 shows the decrease in McCartney Rose key area cover from 16% in 2012 to 8% in 2018 was significant (P= .000).

Table 4.8 Spanish Camp Unit McCartney Rose percent cover from key area line transects for 2012 to 2018(2015 not sampled). Key area average is an unweighted average. Ranch average is the pasture average weighted by pasture area.

Year	Sout heast	South west	North east	North-middle	North west	Key Area Avg.	Spanish Camp Avg.
2012	63%	8%	14%	12%	21%	16%	20%
2013	19%	2%	7%	7%	11%	7%	8%
2014	20%	7%	7%	11%	10%	9%	10%
2016	18%	8%	12%	12%	13%	11%	12%
2017	8%	7%	6%	8%	4%	6%	7%
2018	38%	7%	7%	8%	1%	8%	11%

Table 4.9 ANOVA for Spanish Camp Unit all pastures.

Variable	df	F	Sig.
Pasture	4	7.42	0.001
Year	5	4.69	0.004
Pasture * Year	20	2.14	0.004
Key-area (Pasture)	10	10.29	0.000
Transect-direction (Key-area(Pasture))	45	1.28	0.120

Table 4.10 Table 10. T-test paired two samples for means 2012 and 2018 for Spanish Camp Unit, southwest pasture and northwest pasture.

Paired t test	t	df	Sig. (2-tailed)
Spanish Camp Unit	3.75	59	0.000
Southwest Pasture	0.48	19	0.634
Northwest Pasture	3.95	11	0.002

The pastures with the least frequent disturbance regime (southwest pasture) and the most frequent disturbance (northwest pasture) regime were analyzed individually. The southwest pasture averaged a fire return interval of three years with a non-significant cover decrease from 8% in 2012 to 7% in

2018. The ANOVA for the southwest pasture (Table 11) shows no significant interaction for McCartney Rose cover by year (P= 0.120) and key area by year (P= 0.556). Transect-direction was not significant (P=0.160). The paired t test (Table 10) confirmed no significant decrease in McCartney Rose cover (P=0.634). The northwest pasture averaged a fire return interval of 1.4 years with a McCartney Rose cover decrease from 20% in 2012 to 1% in 2018. The ANOVA for the northwest pasture (Table 12) showed no significant interaction for McCartney Rose cover by year (P= 0.142) but a significant interaction for key area by year (P= 0.000). Transect-direction was not significant (P=0.547). The paired t test (Table 10) showed a significant decrease in McCartney Rose cover (P=0.002).

Table 4.11 ANOVA for pasture southwest McCartney Rose cover 2012-2018 (2015 not sampled)

Term	df	F	Sig.
Key-area	4	4.11	0.014
Year	5	2.02	0.120
Key-area * Year	20	0.93	0.556
Transectdirection(Key-area)	15	1.42	0.160

Table 4.12 ANOVA for the northwest pasture McCartney Rose cover 2012-2018 (2015 not sampled).

Term	df	F	Sig.
Key-area	2	10.71	0.003
Year	5	2.15	0.142
Key-area * Year	10	6.06	0.000
Transectdirection(Key-area)	9	0.88	0.547

4.4.3. Results: Remote Sensing

The classified NAIP digital images in Figure 9 show McCartney Rose responding to the management regime. Total woody cover decreased from 24%

in 2010 to 6% in 2018 (Table 13). Visual inspection of these images shows large patches of woody cover before prescribed fire was implemented in 2010 transitioning to smaller patches in 2018. The 2010 classification serves as the base line for traditional management at 24.6% woody cover. The 2012 classification captures broadcast herbicide application for Euthamia control following overgrazing in the 2011 drought with 9.2% woody cover and 15.1% sprayed vegetation. Sprayed vegetation was not combined into woody cover class because sprayed Euthamia (a weedy species) could not be separated from sprayed McCartney Rose. The 2014 classification captures the initial management regime and shows little progress towards reducing woody cover for the whole unit with woody cover a 24.8%. The 2016 classification captures a major reduction in woody cover at 14%. The 2018 classification shows total woody cover at 6%. The November acquisition allowed the separation of Mesquite (0.8%) as a unique class from woody cover (5.2%). These results are similar to the photo points (Figures 3 & 4) that show Honey Mesquite key area cover with no change and the McCartney Rose key area cover reduced from 2012 to 2018.

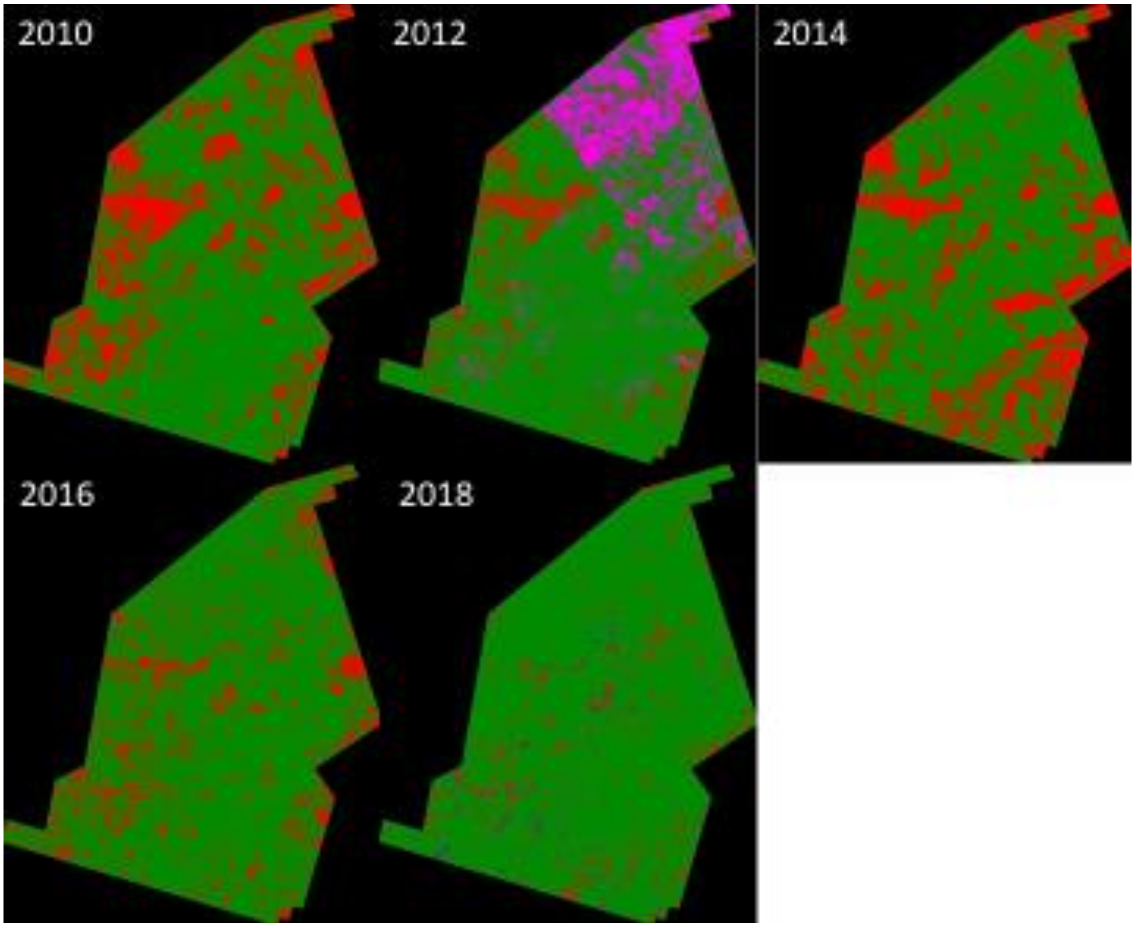

Figure 4.8 Classified images for the Spanish Camp Unit 2010, 2012, 2014, 2016, & 2018. Red represents woody cover, green represents non-woody cover, purple represents sprayed vegetation (Euthamia species & McCartney Rose) present only in 2012, and blue represents Honey Mesquite cover separated from combined woody cover only in 2018 (senesced leaves allow separation from other woody species) . See Table 13 for cover statistic

Table 4.13 Cover statistics for classified images 2010 to 2018. Sprayed vegetation was only present in the 2012 image due to broadcast herbicide application for weed control due to the 2011 drought. Mesquite is separated from general woody cover in 2018 since image acquisition allowed separation. Note: for 2010, 2012, and 2014 the %woody plus sprayed vegetation all equal 24 %. Then it drops. This was after we made the adaptation in stocking rate and selection of more effective burn weather in 2015.

Cover Class	**2010**	**2012**	**2014**	**2016**	**2018**
Woody	24.6%	9.2%	24.8%	14.0%	5.2%
Non-woody	75.4%	75.8%	75.2%	86.0%	93.9%
Sprayed vegetation		15.1%			
Honey Mesquite 2018					0.8%

4.5. Discussion

4.5.1. Management Regime

Adaptive management was critical in achieving a successful disturbance regime. The keystones for successful implementation of adaptive management were a clear management vision and relevant monitoring. Establishing a clear management vision allowed vision driven management. This enabled management to make critical adaptions necessary for control McCartney Rose by altering the fire regime. The management vision was the unifying driver of the adaptive management process with all parts of the adaptive management process united by the management vision.

4.5.2. Adaptive Management

Adaptive management requires relevant monitoring. Each monitoring method provided different data for adaptive management. Photo points provided qualitative evaluation of the regime effects and were easily obtained with little time allocation. Line transects provided quantitative data on the effects of the management regime at a moderate allocation of time and cost. Remote sensing provided excellent quantitative data for the past history of the management regime but the time lag between image acquisition and availability for classification limits the direct application for adaptive management. Of these monitoring methods photo points are the most useful for practitioners and the most likely method for actual use by ranchers.

The value of monitoring was illustrated with the management changes made in 2015 to increase prescribed fire frequency. The prior fire regime was evaluated as not frequent or intense enough for long-term success. Therefore, management changed the allocation of forage between fire and herbivory. The forage allocated to prescribed fire was increased by decreasing the stocking rate. This allowed grazing prescriptions to increase fuel continuity and quantity for prescribed fire and increase the area burned per year. TGM was critical in the initial decision making process and in adapting the grazing to actual forage growth. Embed within this process was knowledge building for the manager for weather conditions required for an effective burn and the implementation of burns on days with fire weather that was more conducive for effective burns.

The strategic vision of the ranch owners is a sustainable ranch were grass-fed beef is a possible economic output and improved wildlife habitat. To accomplish this vision the following tactical objectives were identified: McCartney Rose control using prescribed fire, rotational and deferred grazing to increase forage quantity and quality, and sustainable stocking rate. Prescriptive grazing and fire were the primary disturbance tools utilized to initiate the change from current conditions towards the desired resource conditions. The manager implemented the disturbance management regime and adaptively modified the regime based on actual conditions and effects. This adaptation, enabled by monitoring, was the keystone for success of the disturbance regime. The Duncan Spade has made significant progress towards their strategic goal of controlling McCartney Rose cover and improving habitat. However, this is not a one-time treatment; it is a process that they must continue to apply to maintain progress towards their strategic vision.

4.5.3. Disturbance Regime Theory

The disturbance regime monitoring data allowed insight into DRT resistance and resilience concepts. DRM resistance prediction summary (Figure 2) placed McCartney Rose under the fire intensity threshold and Honey Mesquite above the fire intensity threshold. The key area photo point series allows evaluation of these intensity predictions. Figure 5 shows Honey Mesquite with no visible impact from fire intensity. This indicates the DRM prediction (Figure 2) was correct; with fire intensity under the Honey Mesquite resistance threshold. Figure 6 shows McCartney Rose cover decreasing in stature from mature hedge to grass height regrowth. This indicates the DRM prediction (Figure 2) was correct; with fire intensity exceeding McCartney Rose resistance threshold.

The DRM resilience prediction summary (Figure 3) placed McCartney Rose and Honey Mesquite both under the management regime frequency threshold: However Honey Mesquite was not impacted by fire intensity, the first limiting factor. All monitoring methods showed a decrease in McCartney Rose cover from 2012 to 2018. Remote sensing (Figure 9, Table 13) showed Spanish Camp woody cover, primarily composed of McCartney Rose, decreasing from 24% to 6% with an average fire return interval of 2.4 years. The difference between the 2014 and 2016 classifications confirms that the increased fire regime in 2015 was a critical management decision. The average fire return interval from 2012 to 2014 was 3.6 years whereas from 2015 through 2017 it was 1.8 years. This decrease in fire return interval was facilitated by the decision to reduce stocking rate. These data indicate that the resilience threshold for McCartney Rose is between a fire return interval of 1.8 years and 3.6 years. This confirms the Figure 3 prediction that McCartney Rose has a high resilience to fire frequency. Adaptive management was critical for identifying the threshold and modifying management.

4.6. Conclusion

WPE was successfully reduced on the Spanish Camp Unit through a managed disturbance regime. The managed disturbance regime reduced woody cover from 24% to 6% through adaptive implementation of prescribed fire. The DRT concepts, resistance, resilience, and thresholds, were validated under management conditions at pasture scale. The predictions from DRT are not complex but involve multiple variables that must be considered. The DRM worksheets facilitate qualitative predictions for woody plant cover changes. DRM provide theory and tools useful for managers to implement adaptive management at a landscape level and develop custom disturbance prescriptions for WPE management. These tools are essential to meet the call forwarded by multiple authors to “do adaptive management” (Allen et al. 2017; Archer et al. 2011; Briske 2011). This case study is an example of successful application of adaptive management to create effective disturbance regime. Extending adaptive management from an art only practiced by leading managers to a science practiced by all rangeland managers is essential to meet the 21st century challenge of WPE.

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5. CONCLUSION

For the field of rangeland management to meet the challenge presented by WPE, it must foster novice practitioners to apply regime based management. This transition from static treatments to dynamic management regimes requires an ongoing system of management. It requires ongoing dynamic management to manage successional drivers that lead to WPE on rangelands. Moving practitioners to a dynamic application of principles instead of static individual treatments and recommended practices is necessary to 'solve' WPE.

This research utilized management science to develop processes and theory for adaptive rangeland management and WPE management. It is translational science, moving knowledge and wisdom into explicit processes to make better management decisions. IRMS combined with DRT extends an explicit process for adaptive management of WPE to practitioners.

IRMS moves the science of rangeland management from saying "do adaptive management" to a having an explicit structured process for implementing adaptive management. This can enable novice managers to transition from static recommended treatments to dynamic implement of principles that is required for more complex forms of management: e.g., pyric herbivory, DRM, etc. IRMS can serve as vehicle that management scientists can use to communicate principles, decision aids and tools in language that address critical decisions within the planning process. DRM is an example of a decision aid that addresses a specific issue faced by rangeland managers and fits within the IRMS model.

DRT enables practitioners to apply ecological concepts and principles to WPE management. DRT sets resistance and resilience as the key population characteristics that a disturbance regime is planned to overcome. Overcoming resistance requires fire intensity to exceed the threshold for resistance. DRM qualitatively applies resistance and resilience to assist practitioners in designing prescribed fire intensity and frequency to form disturbance regimes that direct WPE. DRM enables managers to utilize DRT principles to plan and implement disturbance regimes to achieve their woody plant management objectives.

The Duncan Spade case study successfully demonstrated application of adaptive management with a disturbance regime to control WPE. DRM worksheets were useful to explain the observed trends and facilitated qualitative predictions for woody plant cover trend. IRMS meets the call forwarded by Allen et al. (2017), Archer et al. (2017), and Briske (2011) "do adaptive management". DRT can facilitate the application of prescribed fire called by Twidwell et al. (2013) and Fuhlendorf et al. (2012). Extending adaptive management and prescribed fire regimes from an art only practiced by leading managers to a science practiced by all rangeland managers is essential to meet the 21st century challenge of WPE.

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APPENDIX A

The design principles utilized for IRMS and DRT are adapted from unpublished work by Dr. Mort Kothmann. They arose from his experience designing The Grazing Manager. At time of publishing these principles only exist in written form in the unpublished paper “Rangeland Inventory and Evaluation: Past, Present, and Future” by Dr. Mort Kothmann. To credit his work creating the design principles for modeling the draft paper is set below.

RANGELAND INVENTORY AND EVALUATION: PAST, PRESENT, AND FUTURE

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Abstract

From the 1940's until the 1990's, rangeland inventory and evaluation were based primarily on vegetation response to grazing using the ecological theories of succession and climax. The concept of biotic community has dominated the development of practices for rangeland inventory, evaluation and monitoring. The individualistic species response hypothesis has received renewed attention. The recognition of multiple stable states for a given site has been proposed as a more appropriate model for range management than the succession/climax model. Applications of the range condition model are reviewed and the use of state and transition models is discussed. The use of rangeland health assessment as a monitoring tool is discussed. Ecological theories related to the current and proposed models for range management are presented and discussed. I propose a model based on the individualistic hypothesis. This model allows for multiple states of vegetation, includes both native and exotic species, predicts vegetation change in response to grazing and fire management, and allows the evaluation of economic and ecological

values for alternative vegetation types. Management activities are considered a natural part of the ecosystem and are included directly in the model. The model provides for the classification of plant species into functional "response groups" based on multiple environmental and management factors. The proposed model is based on sound ecological theory and can improve methodology for inventory, evaluation, and management of rangelands.

Introduction

Rangelands are characterized by indigenous vegetation that is predominantly grasses, grass-like plants, forbs, and/or shrubs. Historically their primary economic value to society has been to produce forage for livestock and wildlife. Heady (1975) defined traditional range management as "... a land management discipline that skillfully applies an organized body of knowledge known as range science to renewable natural-resource systems for two purposes: (1) protection, improvement, and continued welfare of the basic range resource, which may include soils, vegetation, and animals; and (2) optimum production of goods and services in combinations needed by mankind. The range management profession has certain objectives that distinguish it from other vocations. The central objective of range management is to manage land to produce forage that will be used by domestic and wild animals." While this definition was appropriate 20 years ago, the discipline has changed markedly in the direction of resource management for multiple products and uses. With the new values come new clientele and new objectives for vegetation management (Pieper and Beck 1990).

The discipline of range management is undergoing a change in the scientific basis for its management paradigm. Schlatterer (1989) criticized current vegetation classification systems. He called for a new approach to classification that can satisfy the needs of the user for short-term predictions in early succession and can be used to make rational management decisions and minimize the risk of making wrong decisions.

Range scientists have long claimed ecology as the basic science that provides theory for the development of range management (Dyksterhuis 1949, Parker 1954). The range condition (RC) procedure, based on the succession/climax model, has been the primary basis for range management through most of this century (Sampson 1919, Dyksterhius 1949, Humphrey 1949a, Stoddart, et al. 1975, RISC 1983). However, the appropriateness of the succession/climax model as a basis for range management on arid, semi-arid and annual rangelands has been questioned (Smith 1979, Friedel 1991, Laycock 1991, Svejcar and Brown 1991). Johnson and Mayeux (1992) propose that the individualistic hypothesis for plant response is more appropriate than the succession/climax hypothesis. The state-and-transition model (STM) has been proposed as an alternative to the succession/climax model as a basis for range management (Westoby et al. 1989, Laycock 1991). Laycock (1991) called for a dialogue to be initiated on the concepts and theory underlying the range management paradigm.

Ecological theories, especially regarding succession (McIntosh 1980), competition (Price 1984), and community stability (Johnson and Mayeux 1992), are also undergoing paradigm shifts. Range scientists are examining alternative ecological models to serve as a basis for assessing condition and structuring management of rangelands. The Society for Range Management formed the Range Inventory Standardization Committee (RISC 1983) in 1978 and the Task Group - Unity in Concepts and Terms (1991) for the purpose of examining terminology and ecological concepts related to range classification, inventory, and monitoring. The NRC Committee on Rangeland Classification report, "Rangeland Health: New Methods to Classify, Inventory, and Monitor Rangelands" (1994) concluded "...a standard method and a common data base for evaluating rangelands is needed...". However, they did not propose a methodology in their report. Recently an interagency committee, representing the primary federal rangeland management agencies, has produced a document "Interpreting Indicators of Rangeland Health: Version 3" (2000) that outlines a procedure for applying the approach outlined in the NRC (1994) report. However, they also caution that their proposed procedure is NOT to be used to: identify the cause(s) of resource problems, make grazing and other management decisions, monitor land or determine trend, or independently generate national or regional assessments of rangeland health.

Thus, we enter the new century with a consensus to reject the old methods and to pursue dialogue on new approaches, but without a new methodology and protocol to replace the old. The objectives of this paper are: (1) to discuss ecological theory related to range inventory and evaluation procedures, (2) to describe the RC procedure as it has been applied, (3) discuss the STM and rangeland health concepts, and (4) to propose a new model for rangeland inventory and management.

Ecological Concepts

Community.

The concept of community has been debated for the past 70 years. Odum (1953) stated that biotic community is, and should remain, a broad term which may be used to designate natural assemblages of various sizes, from the biota of a log to that of a vast forest. He stressed the importance of the community concept to the practice of ecology because "as the community goes, so goes the organism." Price (1984) considered the conceptual basis of community ecology to be in a state of flux and called for testing of alternative hypotheses. He considers the individualistic response paradigm (Gleason 1926) as the null hypothesis. Since concepts of succession and climax are founded on the hypothesis of community dynamics, the evaluation of alternative hypotheses governing the organizing forces in assemblages of organisms is critical. Researchers have tended to test only a single hypothesis and have not designed studies to discriminate among them. The limited time scale for research studies prevents many biotic interactions from running their course. This is especially true of arid and semi-arid rangelands where vegetation changes may proceed slowly and erratically.

Community ecologists were divided between the hypotheses of "biotic community" and "individualistic response" for much of the 20th century. The concept of biotic community developed from the work of Clements and may have reached its extreme in Phillips (1931, 1934, 1935a, 1935b). Phillips (1935b) concluded that the biotic community is a "complex organism", to which he linked the concepts of "emergent evolution" and "holism". He stated, "... it should be plain that they are inherently interrelated: holism the causal factor: emergence arising from this factor: the complex organism an integration of emergents, of wholes of potential development to yet a more efficient whole." The individualistic response hypothesis proposed by Gleason (1926) stated, "...every species of plant is a law unto itself, the distribution of which in space depends upon its individual peculiarities of migration and environmental requirements." These two approaches represent opposite views on the dynamics of species composition. The biotic community approach states that individuals respond under the control of the community; whereas, the individualistic approach takes the opposite position, that any community is the cumulative expression of the reactions of individuals.

Tansley (1935) responded to Phillips' series of papers with the purpose of rejecting the concept of the biotic community as a complex organism and holism as a *cause*. With the recent reemergence of the concept of holism in range management (Savory 1988), it is interesting to note Tansley's earlier reaction. He stated, "It is difficult to resist the impression that Professor Phillips' enthusiastic advocacy of holism is not wholly derived from an objective contemplation of the facts of nature, but is at least partly motivated by an imagined future "whole" to be realized in an ideal human society whose reflected glamour falls on less exalted wholes, illuminating with a false light the image of the complex organism." Tansley referred to holism as a faith rather than a science.

After an exhaustive analysis of climax theory, Whittaker (1953) countered the mono-climax and poly-climax hypotheses with the climax pattern hypothesis. Instead of recognizing discrete climax associations, he considered the diversity of climax stands as parts of a single, often continuously grading climax pattern. The pattern concept and the emphasis on continuity led to research methods relating populations of species and growth-forms to environmental gradients and to the approach of gradient analysis which is fundamentally different from the traditional approach through discrete units. This approach has characteristics of Gleasons' individualistic hypothesis. Examination of data on plant populations as continua also lends support to the individualistic hypothesis (Curtis and McIntosh 1951, Curtis 1955).

Dyksterhuis (1958a) accepted the concept of climates, plant communities, and soils as continua with horizontal gradients. Sharp boundaries at abrupt changes in relief, soils, and land use were interpreted as irregularities in the continuum rather than as the foundation for a natural classification. Thus, the logical units (range sites) will differ with different intended uses and may be difficult to map. Dyksterhuis (1958a) stated, "Community types are abstractions based on logic with objective though necessarily arbitrary criteria to meet specific needs. ... Despite necessary approximations, the natural and stable types provide the logical basis for any classification of range sites."

Succession/Climax.

The succession/climax model is based on the following ecological concepts: 1) community, 2) primary succession, 3) stability, dynamic equilibrium, and climax, 4) disturbance, and 5) secondary succession. Succession has been defined as the successive occupation of the same area by different plant communities until a relatively stable community (climax) is evolved which is in equilibrium with the local conditions (Weaver and Clements 1938, Odum 1953). Under either the rigid mono- or more equivocal poly-climax theories, there is only one final stable plant community for a given range site. Climax, a key concept for the range site and condition model of Dyksterhuis (1949), is considered to be one of the major problems in its application (Smith 1979, Svejcar and Brown 1991).

That vegetation is dynamic and that several plant communities may successively occupy the same site over time (plant succession) is generally accepted in range management. The primary concerns appear to be the uni-directional concept of secondary succession and the existence of only one "final stable plant community" for a site, i.e., climax. Whittaker (1953) and Stoddart et al. (1975) present the concept of "climax" or "vegetation equilibrium" shifting in response to changes of many factors including abiotic, biotic, and fire. This alteration of the climax hypothesis essentially allows for the potential existence of multiple stable states on a given type of site. This might be interpreted as similar to the STM which describes multiple stable states based on varying combinations of environmental, biotic, and management factors. This appears to be a logical extension of classical ecological theory that recognized many different "disclimaxes" (Weaver and Clements 1938).

The RC model considers only the vegetation changes that lead towards the climax community as secondary succession with other changes considered as disturbance. Deterioration is a departure from climax that results in accelerated erosion that reduces potential site productivity (Dyksterhuis 1949, Ellison 1960). Ellison (1960), after an extensive review of the influence of grazing on secondary plant succession of rangelands, concluded that changes in vegetation may proceed in several directions, depending on the types of grazing pressure applied. He objected to the term "retrogression" introduced by Sampson (1919) because: 1) it includes trends involving accelerated soil erosion that are not successional, and 2) it leads to the false conclusion that changes in the course of retrogression are presumed to retrace in reverse order changes involved in the original development of vegetation and soil.

Dyksterhuis (1949) stated that the attempts to describe a floristic composition for each condition class in a series for a site ignored the different kinds of disturbance and was not acceptable. Based on Clements' principle of convergence; i.e., that all seres converge to the final community, Dyksterhuis (1949, 1985) stated that one description for each range condition class of a series for a site was inadequate because a site with one plant community when in climax condition often supported many different plant communities when in poor condition. Thus, the only description required was for the climax, and that should be based upon functional groups of species, not by assigning percentages to each species.

The RC model has had two general approaches to applying successional concepts. Westoby et al. (1989), Friedel (1991), and Laycock (1991) state that the RC model assumes a single linear continuum of possible states of vegetation in secondary succession that are identical to, but the reverse of, those followed in retrogression. These authors and Dyksterhuis (1949) called for the rejection of this model based on much empirical evidence. The second approach to the RC model is that of Dyksterhuis (1949). It does not assume linearity and reversibility of disturbance and secondary succession. Schlatterer (1989) described alternative pathways of vegetation change as pages radiating out from the back of a book with each page representing different series of plant communities which depend on the nature of the disturbance and the back of the book representing PNC. This description of disturbance and secondary succession is similar to that of Dyksterhuis (1958a). Laycock (1991) rejects the climax concept. He assumes that secondary succession will not lead to only one final stable community (climax or PNC), but that multiple stable states are possible.

The influence of fire on plant succession has frequently been noted in a negative sense (Ellison 1960). Dyksterhuis (1948) in his study of the vegetation of the Western Cross Timbers, while noting that fire might have influenced the woody vegetation, described the area as having "grassland climate and soils." Dyksterhuis (1958a) stated, "grassland is not a stage in succession to forest when in grassland climate on grassland soil." He encouraged accepting fire as a part of the environment under which natural grazing lands were evolved and stated that it should be considered as a part of climax conditions, particularly on climax grasslands rather than considering it an unrelated phenomenon. Acceptance of the concept of grassland climates and soils, led Dyksterhuis to under-estimate the role of fire in suppressing woody vegetation on grasslands. He did not incorporate response to fire into his range condition model for classifying functional groups; thus, leaving grazing as the sole disturbance identified in the RC model as a cause of vegetation change. However, application of this model has always included range improvement practices that "facilitate secondary succession"; i.e., brush control and seeding (Scifres 1980). Range managers in Texas and many other regions have long been aware of the transitions between grasslands and shrublands and the difficulty of reversing this shift (Archer and Stokes 2000).

Functional Ecology.

Johnson and Mayeux (1992) examined the concept of temporal stability in communities. They conclude that natural ecosystems exhibit greater stability (inertia) in physiognomic structure and functional processes than in species composition. They find more support in the current literature for Gleason's (1926) individualistic hypothesis and the continuum concept than for Clements' climax theory. They call for a closer examination of the available information related to community structure, vegetation development, and ecosystem equilibria. Their approach calls for the classification of species based on structure and function with the description of plant assemblages based on the "goods and services" provided by functional groups of species. From their study of vegetation dynamics, they reach several conclusions: (a) no special significance should be attributed to the label "native", (b) biological invasions by exotic plants change species composition and may alter structure, but they rarely have dramatic ecosystem-level effects, (c) the sanctity attributed to the idea of climax vegetation because it is natural, repeatable, and stable in species composition is without merit, (d) dominant species appear to be interchangeable, within and among functional groups, (e) many of the expectations associated with the species-constant climax concept are incorrect and, thus, point us in the wrong direction. "The popular perception of balance in nature persists in most fields of applied ecology and resource management to the detriment of establishing realistic goals and guides" (Johnson and Mayeux 1992).

Functional classification of plants provides a sound conceptual basis for predictive ecology in contrast to phylogenetic systematics, which is most useful for descriptive ecology (Figure 1) (Keddy 1990). Functional classification provides information useful for predicting how to direct vegetation change.

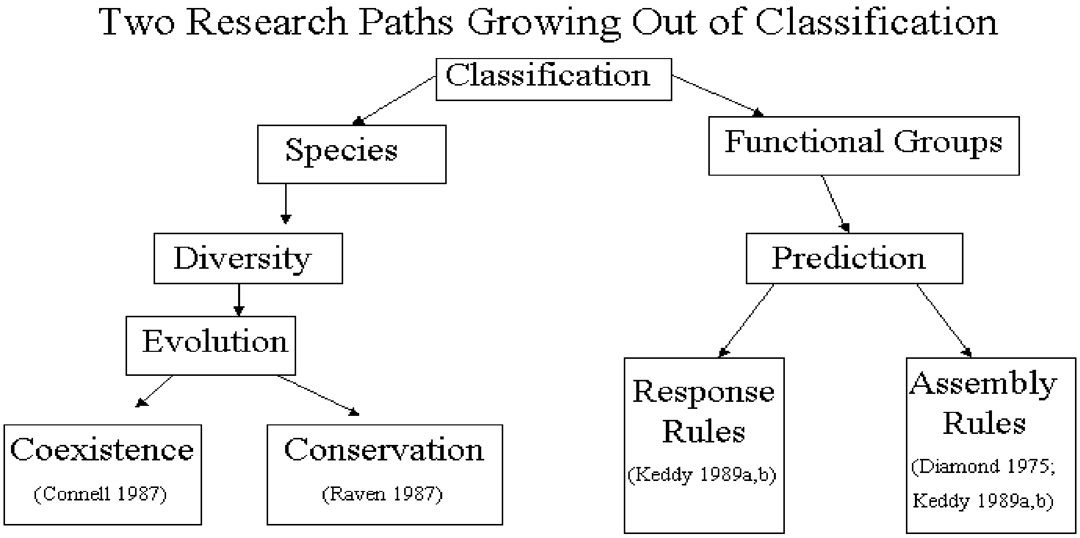

Fig. 1. Two research paths growing out of classification.

The well-traveled left hand path (phylogenetic classification) leads to questions of diversity and coexistence. The less-traveled right hand path (functional classification) leads to predictive community ecology (Keddy 1990). Models to predict vegetation responses to environment and disturbance have been constructed based on concepts of functional ecology (Moore and Noble 1990, Moore and Noble 1993, Keddy et al. 1993, van der Valk 1981). The potential for application of these concepts to a management model is obvious. The difficulty lies in conceptualizing a simple model that will be useful to managers.

Functional classification has been applied to rangeland vegetation. The response to grazing intensity of herbaceous Mediterranean species in northern Israel, based on structure and function, is illustrated by the study of Noy-Meir et al. (1989). Of the 73 most common species, 49 showed consistent responses to grazing intensity. Perennial species with long growing seasons were somewhat more frequent among those species that increased with reduced grazing pressure. Tall perennial and annual grasses dominated ungrazed grassland. The species that increased at the higher grazing intensities were small, prostrate, or rosette. Species that increased at moderate grazing intensities but decreased at heavy grazing or complete protection were mostly erect and of medium height. The effect of none to light to moderate grazing was interpreted as the opening of establishment gaps in the closed sward of foliage and mulch maintained by the dominants in the ungrazed grassland. The vegetation responses from moderate to heavy grazing were the result of the vertical differential defoliation gradient on species having different structural growth forms. Woody species were not present on these study areas.

Diaz et al. (1992) used morphological characteristics of herbaceous species to classify their responses to grazing. Using ordination and TWINSPAN they classified six morphological modes from 118 individual species. A description of each mode is provided with their response to grazing. The responses to herbivory were divided into two types, those that tolerated it and those that evaded it. One mode exhibited tolerance as young plants, but exhibited primarily avoidance during maturity. They suggest that their methods can be applied to study responses to other disturbance agents; however, the traits to be measured together with the appropriate scales of measurement should be defined independently for each particular situation. There is considerable similarity between the functional groups of herbaceous species derived by Diaz et al. (1992) with those derived by Noy-Meir et al. (1989).

Range Sites

The RC model and method for rangeland inventory used range site (ecological site) as the basic spatial concept to identify management level units with uniform vegetation management potential. Dyksterhuis (1958a) used the term range site to mean only the physical and chemical factors that operate upon the community. Biotic factors were not considered to be site factors. The range site is independent of the current vegetation type. It is based on the site potential as determined by the climax vegetation. This unit serves as the basic mapping unit for rangeland inventories. Range condition is evaluated within range sites. Provision was made for site deterioration in the form of accelerated erosion that significantly reduced potential productivity in that a new site was described (USDA-SCS 1962). The continued use of range site (ecological site) as the basic spatial element for range management has been affirmed by all federal agencies and the Society for Range Management.

The STM as presented by Westoby et al. (1989), Friedel (1991), and Laycock (1991) does not mention range sites; analysis is based on vegetation types. Soils are not explicitly included in the catalogues of potential states or transitions, except in reference to site deterioration. Potential vegetation is apparently determined from analysis of initial conditions and the combination of environmental, biotic, and management factors that may occur. The procedures for inventory of rangelands (mapping) were not considered. Application of the STM in the USA has used the ecological site as the spatial basis for its application (NRCS 1997).

The recommended application of the Rangeland Health (RH) assessment does not rely on the range site as its basic spatial unit (Pellant et al. 2000). It is to be applied at either the small patch or broad landscape scale.

What to Monitor

Range evaluation has been concerned with measuring both range condition and trend. Range condition establishes the current status of the vegetation relative to site potential, and trend assess the direction of change of the current community with respect to potential. Stoddart et al. (1975) note that determining trend is highly important since trend reflects the correctness of current management, whereas condition reflects the correctness of past management. Range scientists have debated which measurements should be used to evaluate range condition (Unity in Concepts and Terms 1991). The two primary applications of RC models (Dyksterhuis 1949, Humphrey 1949a) differ in which variables should be measured. Parker (1954) patterned his procedure after that of Humphrey who focused on measuring forage production, soil condition, species composition, litter cover, and vigor. Dyksterhuis considered only species composition based on relative coverage as a percentage of climax for the site.

Forage Production

Humphrey (1949a) proposed that forage production (he did not clarify the term) should be a linear indicator of range condition. He noted that the amount of forage produced on an area varies considerably as a result of annual variations within a climate, but maintained that this does not constitute a basis for reclassifying the range every year. He states, "Properly trained technicians, however, make little allowance for such temporary fluctuations." Dyksterhuis (1949) stated, "Attempts to base a quantitative system of range condition classification on potential production showed: 1) That there was often as much difference in forage production on one site from year to year as there was difference between sites in the same year; 2) That relative coverage (species composition based on cover) fluctuated less from year to year than forage production; 3) That climaxes which are different floristically may produce essentially the same amount of forage per unit of surface area; and 4) That in field operation, men could not classify a range with respect to potential production except as judged from relative coverage."

Frost and Smith (1991) evaluated the hypothesis that rangelands in low condition are biologically less productive than those in higher condition on 58 locations across southern Arizona using the RC model of the Soil Conservation Service. They found that after protection from grazing for 1 year, total annual standing crop averaged across range sites within precipitation zones did not differ between range condition classes. However, forage production for cattle, calculated by multiplying percent composition of forage species by the total estimated standing crop, did differ significantly among range condition classes for all three precipitation zones. They conclude, " The general trend of increasing forage for cattle as range condition improves (vegetation becomes more similar to `climax') indicates that either climax vegetation is more productive of cattle forage than seral stages, or a bias towards cattle forage has been introduced into the range site descriptions." They also note that while total production fluctuates widely among years, species composition would not change drastically in 1 or 2 years because most of the important species are long-lived perennials. This study supports the contention that the RC model is valid for evaluating livestock grazing value of vegetation, the primary use for which it was originally intended; however, it refutes the hypothesis that the total above-ground mass of vegetation produced decreases as a function of departure from climax.

Species Composition

Dyksterhuis (1949) used species composition as the sole basis of evaluating range condition; however, he used a functional classification based on three response groups (decreasers, increasers, and invaders). He stated, "...the herbaceous species listed ... as invaders will be virtually eliminated from the plant cover as a range improves..." Dyksterhuis generally avoided the problem of woody species. He supported Clements's belief that the community is a more reliable indicator than any single species in it. He recommended selecting 30-40 species or groups of species that are dominant for each site and determining their response to heavy and light grazing and to deferments. By this method the rancher could then predict vegetation change in response to grazing management. Stocking rate and site stability were related to range condition based on the relative departure from climax for the site. It was assumed that the greatest forage production and site stability would occur as herbaceous plant succession progressed towards climax.

Soil Condition

There have been repeated recommendations to include soil factors, especially rate of erosion, in range condition evaluations (Humphrey 1949a, Pratt and Gwynne 1977, Smith 1979, RISC 1983, Wilson et al. 1984, Floyd and

Frost 1987, Unity in Concepts and Terms 1991). In response to suggestions to include soil erosion, Dyksterhuis (1985) stated: "The method was purposely designed to avoid short-term trend factors in determining range condition class. This is because they are too much under the influence of temporary extremes in weather, degrees of grazing use, etc. Soil erosion in a drought year under close use can be followed by soil stabilization in a wet year with light grazing use." Dyksterhuis (1988) stated that the kind and condition of cover profoundly affect the rate of soil erosion by: (a) modifying the forces applied and (b) increasing the resistance of the soil to a given amount of applied force. Trend in soil conditions lags changes in vegetation. Parker (1954) noted the difficulties in correlating soil factors with current grazing management. By measuring soil conditions rather than vegetation, overgrazing that causes accelerated erosion would not be detected until the accelerated erosion had occurred. Vegetation characteristics such as frequency, cover (basal or aerial), density, species composition, or weight are difficult to relate to soil condition in a quantitative manner that has general applicability. By monitoring degree of use on vegetation, management changes can be made prior to the occurrence of accelerated erosion (Campbell 1943).

Stoddart and Smith (1955) outlined a "..complicated system.." of range condition evaluation that was being used in almost every western region of the U.S. Forest Service. This system included heavy reliance on measuring soil factors related to rate of erosion. These procedures were modified by the Forest

Service to evaluate ecological status based on species composition (Joyce 1989). In the U.S.F.S. Region 4 Range Analysis Handbook (1986) the procedure for soil ratings for ecological sites states that erosion rates are difficult to measure directly, so soil ratings are based on vegetation-litter cover of the test site relative to a reference area. It is noteworthy that the trend in evaluation of soil conditions has shifted away from direct measurements or estimates of soil erosion.

The Range Condition Model

Early reference to plant succession as a model for range management resulted from the work of Sampson (1919); he concluded that, "The grazing value of the vegetative cover is essentially determined by the stage of succession." The RC model was adopted by the Soil Conservation Service (SCS) for rangeland inventory and management and brought to prominence by Dyksterhuis (1949, 1958a 1958b, 1985, 1988). Alternative procedures for the RC model were proposed by Humphrey (1949a) and Parker (1954) and were applied by the US Forest Service (FS) (Stoddart and Smith 1955). Both the SCS and FS approaches were based on the succession/climax theory. The model as proposed by Dyksterhuis (1949, 1958a) included recognition of edaphic climaxes (polyclimax) and continuum principles for climate and soils (Dyksterhuis, 1958a).

The SCS developed the range site concept for rangeland inventory and range condition evaluation (Dyksterhuis 1949, 1958a). This concept replaced the procedure of classifying range forage types that was used for the first one-half of the 20th century (Humphrey 1949b). A range site is distinguished on the basis of potential vegetation rather than present vegetation (forage type); thus, it is linked to the succession/climax hypothesis. Dyksterhuis (1958a) noted that the pasture was the primary unit of management, thus, only major differences in soils and vegetation had practical import. The number of units (range sites) mapped and data gathered must be justified, considering value per acre and economical management. Therefore, while the range site is based on ecological concepts, its implementation is subject to management and economic considerations. The range site concept has been merged into the ecological site in recent years (RISC 1983, Unity in Concepts and Terms 1991).

In the Dyksterhuis (1949) application of the RC model, climax plant species were classified as decreasers or increasers based on their response to grazing. Species that were either not present in the climax or contributed 2% or less of the climax were classified as invaders. Range condition was quantified by calculating the percentages (based on relative weight or cover) of functional groups of species (decreasers and increasers) in the present vegetation that were considered representative of climax. Range condition was reported as classes (poor, fair, good, and excellent) based on the percentage of the current vegetation that was representative of climax. Using functional groups of key species rather than assigning percentages to all individual species in climax increased the flexibility of the model (Dyksterhuis 1985). The model was designed for use on range sites with grassland climax. It measured deviation from climax in response to various levels of grazing. Functional response of species to management and environmental factors other than grazing were not included in the model.

Parker (1954), following the approach of Humphrey (1949a), considered both vegetation and soil factors essential, but he did not distinguish between condition and trend in his range evaluation procedure. Vegetation factors included "density" (Note: Parker used the term density to refer to cover, not number of plants per unit area.), floristic composition, and vigor. Soil factors included litter and soil stability. "Total-density" frequently was not related to successional status or condition; thus, he suggested a "forage-density index" which was based on species that disappear or decline under excessive grazing use (similar to decreasers). Vigor was noted to be a reflection of past grazing use. Two of the objections given to the use of vigor were: (1) it may be obscured by the effects of current weather, (2) it is difficult to describe or measure. He notes that vigor is indicative of short-time trends. In support of including soil factors, he notes, "Litter and soil stability are of especial importance because of their direct influence on other factors, vegetation as well as soil. Litter and stability are also subject to ready measurement and observation." However, with respect to the measurement of accelerated erosion, defined as loss of soil at a rate greater than normally occurs under present conditions of climate and other environmental factors, in apparent contradiction, he states, "Their measurement by present-known field methods has been inexact and unsatisfactory. Their use as an indicator of trend, particularly in attempting to correlate present erosion with present grazing use is especially difficult." Thus, Parker did not present a viable method for including soil factors in the evaluation of range condition.

Viewpoints have differed on the primary objective for range condition assessment. Dyksterhuis' (1949, 1988) emphasized separation of ecological status from suitability for various uses. He considered range condition as providing information on ecological status of the present vegetation relative to climax. Smith (1979) and Floyd and Frost (1987) maintained that range condition should evaluate suitability of present vegetation for specific uses. However, Smith (1979) stated that separating ecological condition and condition for specific uses is a step in the right direction. There appears to be agreement that assessment of ecological condition and suitability for specific uses should be separated, but there are differences of opinion on which should be called "range condition."

Based on the RISC (1983) report, the U.S. Forest Service dropped the term range condition and developed a floristic procedure that evaluates "ecological status" (an use-independent rating) by comparing similarity of current vegetation to the potential natural community (PNC) (Joyce 1989). A "resource value rating" is applied to describe the value of the current vegetation for specified uses. PNC is the final stable community that would develop if the site were left without further perturbation by man. Ecological status was reported as classes designated early seral, mid-seral, late seral, and PNC. Although Joyce (1989) notes that on some sites PNC may be very different from the climax vegetation, the FS procedure is still very similar to the climax procedure. Evaluation is based on only one stable final community (PNC) as an end point for secondary succession. Johnson and Mayeux (1992) expressed concern with the concept of a final stable community. They suggest that no community is stable and that the idea of a community is a simplification, not necessarily a viable ecological concept.

State and Transition Model

The STM was published under the title, "Opportunistic Management for Rangelands Not at Equilibrium" (Westoby et al. 1989). This model rejects the concept of basing management on an "equilibrium condition", i.e. climax or PNC, as the goal of management. They propose a catalogue of alternative states and catalogues of possible transitions between states. The transition catalogue describes the combinations of climatic circumstances and management actions that would cause transition between alternative states. The object of management should be to direct or control vegetation change, to seize opportunities, and to evade hazards, so far as possible. The emphasis should be on timing and flexibility rather than on establishing a fixed policy. Their stated purpose in presenting the model was to develop alternative ways of formulating existing knowledge for purposes of management. Westoby et al. (1989) and Laycock (1991) provide examples of catalogues of alternative states and possible transitions between alternative states.

Friedel (1991) stated that existing methods of range condition assessment have an inadequate theoretical base. She presented the concept of thresholds as compatible with the STM and defined two essential characteristics of a threshold. First, it is the boundary in space and time between two states, e.g., grassland and shrubland. Second, the initial shift across the boundary is not reversible on a practical time scale without substantial intervention by the range manager, e.g., with herbicides, heavy machinery, or fire. Stocking-rate reductions alone will not cause a reversion to the former state.

The STM avoids value-oriented names for classes (excellent, good, fair, poor) or hierarchical names (early-, mid-, late-seral, PNC). It shifts the focus to describing the present vegetation and alternative communities that might occupy the site. The emphasis is on the environmental and management factors that would be required to maintain the present community or to cause a transition to a different community. The definition of "stable states" is based on a time frame of a few to several decades. Laycock (1991) notes that over longer time frames, the concept of stable states may not be applicable. This is in contrast to the RC model (based on climax or PNC), which assumes that a stable equilibrium will be reached as long as climate is stable.

An analysis of 29 STMs revealed that the number of transitions connecting states increased less than expected as the size of the model increased, probably because of the limitations in interpreting complex relationships and the need to produce simple applications (Rodriguez Iglesias and Kothmann 1997). Grazing, fire, and control of woody species were the most common man-related causes of transitions. Although autogenic causes of vegetation change no longer have a central role in vegetation change, many ST applications retain them. ST applications, as they have been formulated, do not provide any theoretical basis for the development of comprehensive predictive rules for vegetation change that have relevance beyond the system being described.

There is some degree of similarity between the description of multiple plant communities in the STM and many applications of the RC model that do not use the concepts of Dyksterhuis. Humphrey and Lister (1941) described the vegetation of 6 "condition classes" and included with the description of each, information on: (a) management practices responsible for each condition, (b) revisions to present management required to cause a transition between classes, and (c) erosion or flood control measures needed. Reid and Pickford (1946) described vegetation for 4 condition classes in eastern Oregon and Washington mountain meadows. More recently, Pieper and Beck (1990) present 4 condition classes for a sandy upland range site in southern New Mexico with a vegetation description for each class. Each of these examples fit the criticism of

Westoby et al. (1989) by presenting retrogression and secondary succession as linear, reversible processes. Although these examples are generally considered part of the successional model, they have more similarity to the STM than to the RC model presented by Dyksterhuis (1949). They describe various discrete states of vegetation and provide information on transitions between states. The primary similarity to the RC model of Dyksterhuis is that they assume that secondary succession will lead to a "final stable state". Rodriguez Iglesias and Kothmann (1997) note that many extant STMs also exhibit unidirectional successional trends when anthropocentric causes are removed.

Rationale for a New Model

Westoby et al. (1989) outlined two models (RCM and STM) for range evaluation and management. They called for a rethinking of the theory of range dynamics and suggested that the state and transition model was more appropriate for many rangelands than the succession/climax based RC model. I propose incorporating components of both models, but shifting the ecological basis from biotic community and succession/climax to the individualistic hypothesis and from single or multiple equilibria represented as stable states to vegetation change as continuous in both time and space.

The proposed model addresses the following concerns, which have been identified for the RC model. (1) Sites may support multiple stable states (Westoby et al. 1989). (2) The RC model does not function well on annual rangelands nor does it accommodate exotic species that become acclimatized to new environments (Svejcar and Brown 1991). (3) The concept of biotic community needs to be replaced with consideration of interchangeable populations of species that respond to continua of soil and environmental gradients (Johnson and Mayeux 1992). (4) The current model does not consider any management influences other than grazing as a cause of vegetation change (Laycock 1991). (5) Species response within communities relates more to structure and function than to taxonomy (Noy-Meir et al. 1989, Johnson and Mayeux 1992). (6) Assigning percentages to individual species in the description of plant communities is too rigid and unrealistic (Dyksterhuis 1949, 1958a). (7) Measurements need to be based on variables that can be related to current management and are economically feasible to measure on extensive rangelands (Dyksterhuis 1958a). (8) The data obtained should be useful for predicting short and long-term trends in vegetation and soil status and provide some measure of risk associated with alternative management decisions (Schlatterer 1989).

Any realistic model which meets the needs described above must include the following components: (1) management response units for land mapping and inventory, (2) estimates of site stability (indicators of past or potential accelerated erosion), (3) classification of vegetation based on functional response groups, (4) evaluation of vegetation status and trend, (5) resource value ratings for vegetation response groups for specific uses, (6) monitoring of environmental and management influences on vegetation and a methodology (model) for predicting vegetation change, (7) development of a management plan, (8) provisions for use of adaptive management.

Management Response Units

The *management response unit* (MRU) is the basic mapping unit for land management and inventory. It is defined as a management unit consisting of a kind of land with specific physical characteristics (soils, topography, and climate) that differs significantly from other kinds of land with respect to the potential vegetation response to management. Vegetation response to management inputs should be relatively consistent within the MRU. This definition differs from that proposed for ecological site in the Unity in Concepts and Terms (1991) report in that it does not include a "potential plant community". MRU is not defined by either climax or PNC, and a single MRU may support many different kinds of vegetation.

Soil and climatic factors that significantly affect vegetation should be noted. These are essentially the same as those identified by Dyksterhuis (1958a) for range sites. Soil texture and depth are most important with any unusual amounts of salinity, wetness, or rock. In addition, soil Ph, natural levels of fertility, average annual rainfall, elevation, and latitude also should be noted. The climatic factors generally occur as gradients and discrete boundaries between MRU may not exist. Therefore, ranges of precipitation and latitude may be used to define discrete management response units.

Desired vegetation for a management response unit should be evaluated based on all available evidence. This could include evaluation of reference areas and relics, but without the implication that they represent climax or PNC. Disturbance factors (climatic change, the actions of management, or the introduction of new species) may cause different vegetation types to occur on an MRU. This model considers vegetation management actions as a natural component of the ecosystem. It differs from the use of climax, which precludes the influence of modern man and his management and PNC, which includes past effects but excludes future management. To attempt to reconstruct pre-settlement vegetation (climax) or to try to envision future vegetation "...if left without further perturbation..." (PNC)(Joyce 1989) is not only difficult but frequently impossible. Also, when considering climax or PNC in countries with histories of thousands of years of livestock grazing, neither concept makes any sense. Even in North America, man has been burning, harvesting plants and seeds, and manipulating vegetation for thousands of years prior to settlement by Europeans. Thus, it only makes sense to assume that we (humans) have been part of these ecosystems for long periods and will continue to be present in the future. The emphasis must shift from excluding human influences to evaluating the sustainability and relative economical and ecological values of different vegetation types that may currently or potentially occupy an MRU.

Site Stability

Site stability is a function of the interactions of many factors. Quantitative measurements have not been defined to give objective criteria for its evaluation. The rate of erosion relative to soil development is generally identified as the primary criterion; however, measurement of erosion rates in a management context is not feasible. Thus, monitoring for erosion must depend upon evidence of its cumulative effects such as plants on pedestals, rock pavement, rills, gullies, litter dams, and excessive amounts of runoff and sediment in runoff. Humphrey (1949a) suggests that where erosion is active, more forage must be left ungrazed than if there is no active erosion; i.e., stocking rates should be reduced. This is complicated by heterogeneity of grazing and erosion patterns across the landscape, especiallly in arid and semiarid ecosystems.

Erosion and site stability are directly linked to the degree of grazing use by livestock and/or wildlife. The primary objective of management should be the monitoring of grazing and careful control of the degree of use to prevent the occurrence of accelerated erosion. Monitoring for the signs of accelerated erosion serves to detect errors in past grazing management. Stocking rates and grazing plans should be altered to arrest accelerated erosion where it is detected. Procedures for monitoring grazing and adjusting stocking rates that emphasize prevention of erosion are proposed in the section on monitoring grazing and fire.

Species Classification Based on Functional Response Groups

As Johnson and Mayeux (1992) point out, there is significant evidence that the individualistic response hypothesis may be the appropriate basis for structuring vegetation management. The biotic community response hypothesis, based on the description of a successional series of discrete communities leading to a climax or PNC for a site has proven inadequate as a general model for range management. Dyksterhuis (1949) classified plant species endemic to the range site into functional groups based on their response to overgrazing. This worked where grazing was the dominant influence, but falls short where the response of species is primarily to other management or environmental factors. It also presents problems where exotics and/or native long-lived perennial species invade range sites (Friedel 1991). However, the approach of classifying plant species into functional response groups is useful and needs to be expanded.

There are many examples of structural and functional classifications that are currently used. Structural classifications are based primarily on plant height and growth form; e.g., tall, mid, and short grasses; half-shrubs, shrubs, and trees; bunchgrass, rhizomatous, and stoloniferous; rosette, single stem, and multi-stem forbs. Functional classifications used include: perennial, bi-annual, and annual; cool-season and warm-season; deciduous and evergreen; herbaceous and woody; sprouting and non-spouting. Where grazing is involved, it is important to classify important plant species based on their preference value and antiherbivory characteristics for the herbivores of interest. The classification of vegetation into structural/functional response groups should relate to the goods and services expected from the ecosystem and to their potential responses to environmental and management influences.

Numerous examples may be found in the literature for such classifications. Branson (1954) created 3 functional groups using the heights of growing points and the ratio of fertile to vegetative stems to classify the resistance of grasses to grazing. Noy-Meir et al. (1989) analyzing the response of Mediterranean grassland plants to grazing and protection found that grazing response was only weakly associated with taxonomical affiliation. All important families were represented in each of the major response types. However, grazing response groups could be related to plant structure and function. Diaz et al. (1992) presented a morphological analysis of herbaceous communities under different grazing regimes. Using 15 structural plant characteristics, they identified 6 different functional types based on their response to grazing. These studies provide evidence that the response group approach might be used to develop structural and functional classifications for plant species.

Dominant species should be rated using gradient analysis to determine their degree of tolerance or sensitivity with respect to environmental factors such as heat, light, water (xerophytic to hydrophytic), salinity, pH, and nutrient requirements. These criteria are critical in determining the potential distribution and abundance of species across MRUs. Using the individualistic response hypothesis, all potentially important native and exotic species must be evaluated and classified to predict their responses to environmental and management influences.

This approach provides for direct application of physiological and morphological data into the classification of species. It will provide significant ecological information to predict short and long term vegetation trends. It will also facilitate the development of quantitative models to predict vegetation response to various management and environmental scenarios.

Predicting Vegetation Change in Response to Management and Environment

Managers evaluate information obtained from both research and experience and integrate it through trial and error. Thus, the decision process is unique to the individual and is difficult to transfer to other managers. There is a need to make this empirical knowledge more accessible to other managers.

Objectives for vegetation management are changing with the emergence of new values for rangeland ecosystems. Forage production, once the primary management goal on rangelands, is now only one of several competing values. Effective natural resource planning requires the ability to predict vegetation changes in response to environmental factors and management decisions. Models which managers, not scientists, can use to predict vegetation change are non-existent. Currently, successful vegetation management strategies rely on experienced individuals to evaluate and intuitively integrate data gathered from ecological and applied management research with their personal experience at specific locations. Critical voids in research data can be filled by expert knowledge from experienced individuals. This experience is seldom transferred and is often lost when these individuals retire or die.

Extensive research has been conducted on vegetation characteristics, processes, and responses to environmental and management influences. However, research studies are usually focused on single topics and the data are seldom synthesized for application in an integrated management context. For example, vegetation change has been studied in response to stocking rates, grazing systems, kinds of animals, season of grazing, fire, and chemical and mechanical control practices. Managers face the difficult problem of integrating data from various sources to predicting vegetation response when multiple practices are combined in a management plan. The human mind is not efficient at simultaneously considering several factors; however, a model can provide a mechanism to capture, organize, integrate, and analyze large amounts of information. There is a need to develop a management-level model for assisting managers to predict vegetation response to environmental conditions and management influences.

Critical life history characteristics of vegetation related to reproduction, establishment, potential longevity, generation interval, and mortality will be identified and used to establish functional response groups (Keddy et al. 1993, Moore and Noble 1990, van der Valk 1981). The response of these functional response groups to environmental and management factors will need to be determined for each MRU and entered into the model. Classification of species into a relatively few general functional response groups will simplify the development of vegetation models for vegetation monitoring and management.

Environmental conditions and management influences to be included in the model will be identified. The primary environmental factors will be temperature, moisture deficit, light, and nutrient levels. Management factors to be considered are grazing, fire, seeding, and mechanical or chemical control practices. Descriptive response scales will be developed for each factor. The number of levels that will be included in each response scale will depend upon the degree of precision with which the factor can be evaluated in the field. The objective is to allow managers to visually assess or easily measure the levels of environmental and management factors. The response scales will have a descriptive statement associated with each level. This will allow the user to assign values by comparing the description with the conditions observed in the field. The response scales are a mechanism for converting continuous responses to discrete data. These approaches reduce model complexity by reducing the number of vegetation components and reducing the demands on users to provide detailed quantitative input data. Model construction will utilize influence diagram methodology.

Influence Diagrams. Influence diagrams were originally developed during the mid-1970's as a description of decision problems that are both a formal way of structuring the problem and a computational method (Miller et al. 1976; Howard and Mathenson 1981; Schachter 1986). The diagrams are essentially compact representations of multi-attribute decision problems. The basic construct is a directed acyclic graph consisting of nodes which represent variables, and directed arcs that represent the relationships between variables (Schachter 1988). Influence diagrams may contain four types of nodes: *deterministic nodes* (certain quantities given the values of their conditioning variables), *probability nodes* (uncertain quantities), *decision nodes* (relationships or quantities controlled by the decision-maker) and *value nodes* (objectives). Influence diagrams which contain only uncertain quantities and constants are called *probabilistic*. Much like decision trees, the diagrams describe the probabilistic dependencies and flow of information in the system, but chronological ordering is not required. Relationships are structured in such a way that arcs are directed from a predecessor node to a successor. Arcs between probability, deterministic and value nodes represent conditioning relationships. Probability nodes, which have no predecessors, contain marginal (unconditional) probability distributions. In cases were a successor is a decision node, arcs represent flows of information and indicate that the predecessor will be observed before the decision is made.

The networks are solved sequentially through a process of *node reductions*, which preserve the underlying joint probability distributions but reduce nodes from, and thus solve, the diagram. *Directed cycles*, or pathways in the network beginning and terminating in the same node are not permitted because they preclude the existence of a unique joint probability distribution. Reduction of probability nodes involves taking the product of the marginal and conditional probabilities and substitution into the respective successors. Reduction of deterministic nodes is accomplished through direct substitution. In cases where the successor is an expected value node, a simple conditional expectation is evaluated. An extremely useful feature of influence diagrams is that knowledge may be encoded in a direction that is most comfortable or intuitive for the user, and then later transformed for use (Schachter and Heckerman 1987). This transformation is accomplished through the application of Bayes' theorem and is called *arc reversal*. Arc reversals are permissible between probability and/or deterministic nodes as long as no cycles are created in the network. Thus for instance knowledge may be specified in the causal direction and then reversed for diagnosis. For computational details of influence diagrams, I refer interested readers to (Oliver and Smith 1990; Pearl 1988).

Context-specific analytical protocols will be developed, including personal computer software, for ranch and landscape-level decision support. A generic ID inference engine, Netica, can be used to build the software component of the DSS (Norsys Software Corp. 2001). The DSS will provide facilities for probability assessment and analysis of influence diagrams. They will be structured so that users may parameterize the models with their own site-specific information.

Measurement of Vegetation Status and Trend

Natural resources management groups and agencies are seeking new methods for assessing ecosystem health/integrity. Assessing ecosystem health/integrity is inherently subjective and the debate over appropriate evaluation methods will continue because of divergent values of stakeholders. Evaluation methods currently used often fail to provide managers with adequate information to forecast vegetation responses to environmental and management influences. Natural resource managers need effective methods for forecasting vegetation responses. Description of the current status of vegetation and prediction of vegetation change in response to environmental and management influences are problems that can be addressed objectively through research to provide information for ecosystem evaluation and management.

Evaluation of vegetation will be based on desired vegetation, which is derived from a consensus of the values and objectives of the various stakeholders. Reaching consensus on the desired vegetation may be the most difficult aspect of vegetation evaluation.

Description of vegetation types will be based on the relative proportions of various functional response groups used to classify vegetation. Desired vegetation structure and function for a management response unit will be determined as a management decision, based on the site potentials. A given site may have one to several different desired vegetation states depending upon the objectives of the managers at a given time. The only requirement for desired vegetation is that it is potentially adapted to the site and that it can be managed to provide soil stability. Status will be measured by comparing the structure and function of the present vegetation relative to that desired for the MRU, based upon defined objectives and needs. This approach will provide flexibility and robustness. The concept represents ecosystem management and is not based on management for single species. It is not limited to any specific vegetation type, but can be applied to annual or perennial, herbaceous or woody, or any mix of these vegetation types.

The desirability of alternative vegetation types for a site can be determined by rating their relative economic and ecological productivity. The determination of whether a vegetation type is suitable or not is a management decision. While site stability must be considered, the financial and ecological costs required to either maintain or change the current vegetation type need to be factored into the analysis. The resource values of the current and alternative vegetation types for desired uses must be considered in the economic and ecological evaluations. The kinds and intensities of current uses have significant impact on site stability. Thus, changing either the kind or intensity of use rather than vegetation type may stabilize unstable soil conditions.

Trend in vegetation status will be evaluated by monitoring change in vegetation composition of functional groups over time. Apparent trend is evaluated by observing vegetation for degree of use of key plant species, signs of reproduction, presence of multiple age classes of species, and vigor of plants.

Close observation of these factors will indicate the probable direction of short-term changes in vegetation composition.

Monitoring of Grazing and Fire

Grazing and fire are two factors most subject to management control that have had both historical and recent effects on vegetation in may areas. Grazing and fire (or fire suppression) have been the dominant management influences on most rangeland vegetation. Much of the research and management of range vegetation over the past 100 years in the U.S. has attempted to treat grazing and burning as separate practices; however, they must be closely integrated if burning is to be incorporated as part of a long term vegetation management plan. With suppression of burning, vegetation of the southern Great Plains has changed. Fire sensitive species such as pricklypear, juniper, and other woody species have increased at the expense of fire tolerant species that dominated at the time of settlement.

Monitoring of fire should include the frequency, season, and intensity. Planning for fire should center on specific vegetation management objectives (Scifres and Hamilton 1993). Objectives may vary from fire suppression to changing vegetation structure or reclamation burning to shift species composition from woody to herbaceous species. Planning and monitoring the occurrence and characteristics of fire can be a powerful management tool to direct vegetation change. Since forage is also the fuel for fires, management of grazing is essential to allow adequate fuel to accumulate for effective fires. Post-burning grazing management is also critical to avoid undesirable changes in vegetation and/or deterioration of soils.

The effects of grazing are also determined by intensity, frequency, and season, and by their interactions with other environmental variables, especially climatic. Quantitative data are required that are suitable for use in development of vegetation management plans. The pasture or allotment will be the basic unit for monitoring grazing. Range management has focused much effort on identifying the average carrying capacity of each pasture. However, average carrying capacity has not been an adequate management criterion since the proper stocking rate varies widely among years. A procedure should be used to forecast and measure the current year's recommended stocking rate so that stock numbers can be adjusted to maintain proper use of vegetation in all years (Kothmann and Hinnant 1999).

In The Grazing Manager (TGM) model, forage production and demand are both measured as animal-unit-days of grazing. The level of forage demand is directly related to degree of use on forage and direct animal impacts on soil such as trampling. Monitoring forage demand requires records of the numbers of animals, their forage demand rates, and the dates of grazing. Forage supply must be monitored to evaluate the balance with forage demand. Forecasting of both supply and demand can be achieved by use of this simple forage balance model (TGM) to facilitate timely management decisions to adjust stock numbers or days of grazing in response to fluctuating forage production (Kothmann and

Hinnant 1997). Degree of grazing use is an annual or seasonal variable that must be monitored frequently to be of value in making timely management decisions. The evaluation of degree of use in the field provides the basis for calibrating TGM for each ranch application.

Resource Value Ratings for Specific Uses

A management response unit may support a variety of different sustainable vegetation types; however, the value of each forage type for specified uses will differ. Resource value ratings should be separated into two components, ecological and economic. Not all ecological goods and services have direct economic value at this time. For example, endangered species, reduced erosion, increased water quality, esthetic appeal, etc. are ecological goods and services that may not generate additional revenue to the land owner or general public. While both ratings need to be considered, current procedures for developing a common currency for combining economic and non-economic values are generally inadequate. Probably the best procedure is to provide information on ecological and economic values and allow management and policy level personnel to devise the procedures to factor them into the goals for vegetation management.

Resource value ratings of current and desired vegetation should be based on functional groups of species rather than individual species. Functional groups would be rated for grazing value, watershed value, habitat value, or other special needs associated with the vegetation management unit. Each of these ratings is use specific. For example, grazing value can only be defined in terms of the animal species and season of use. Watershed value is dependent on the kind of vegetation and also the intensity of grazing applied to vegetation. Likewise, habitat value, recreation value, etc. are all use specific. The degree of grazing use applied to the range has a dominant influence on the resource value for many associated uses and it should be incorporated into the rating system.

Development of a Vegetation Management Plan

It should be the goal of management to develop a *vegetation management plan* that will produce a sustainable ecosystem. Economic returns and yields of ecological goods and services should be considered. While a few cases may require the development of a plan designed to foster a single species, the plan should generally focus on the manipulation of functional groups of species. It should contain a description of the current vegetation with species grouped into functional categories and a description of the desired vegetation (again based on functional categories). Management actions to direct vegetation change in the desired direction will be outlined. Implementation of the plan should follow the principles of adaptive management.

Planning must encompass short term (operational), intermediate term (tactical), and long-term (strategic) levels. While the amount of detail is progressively reduced as the planning horizon lengthens, the inclusion of the long-term goals is vital to the success of a plan. Because weather conditions vary greatly among years, considerable flexibility will be required in implementation of specific management practices. Long term planning is necessary to keep the management directed towards the target as short-term adjustments are made to compensate for highly variable environmental and management conditions.

Summary

The proposed model for range inventory, evaluation, and management has similarities to both the range condition model and the state and transition models; however, there are significant differences. The principal differences from both models are: (1) the acceptance of the individualistic species response hypothesis of Gleason (1926) in the new model in contrast to the community based response hypothesis used in the previous models, and (2) the concept of "final stable plant community" or climax is replaced with the concept of vegetation continua in space and time. The MRU is proposed as the basic unit for land classification and mapping. MRU are distinguished by differences in potential productivity that have management significance. Site stability is evaluated from visible signs of erosion. Species are classified into functional response groups based on their structural/functional characteristics and their response to environmental and management factors. Native and exotic species are considered on the same basis in classification. Vegetation status is based on the composition of functional response groups relative to the desired composition. Change is considered a natural and constant part of the ecosystem. Man actions, past, present, and future, are considered as part of the ecosystem. Anthropogenic actions and values are considered along with other environmental and biotic factors that affect vegetation and soils. Resource values are rated for different vegetation/soil states for specific uses. The values can include social and ecological goods and services.

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