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Droughts and Weeds: A Correlative Analysis

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DROUGHT AND WEEDS: A CORRELATIVE ANALYSIS

A Master's Thesis

Submitted to the Faculty

of

American Military University

by

Christopher Dylan McCord

In Partial Fulfillment of the

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of

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Charles Town, West Virginia

I dedicate this thesis to my dear wife Natalie Kristine, whose continued love and support made the completion of this work possible; and to our beautiful children Waylon Eagle, Elizabeth Pearl, and Abigail Jane.

I wish to thank Dr. Elizabeth D'Andrea for leading me through this thesis writing process. Her guidance led me to discover the utility of correlative analysis. I wish to thank the faculty of the Environmental Policy and Management; I found my graduate coursework stimulating and thoughtful.

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ABSTRACT

DROUGHT AND WEEDS: A CORRELATIVE ANALYSIS

by

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American Military University, November 2015

Charles Town, West Virginia

Dr. Elizabeth D'Andrea, Thesis Professor

Non-native invasive weeds have exploded throughout northern Sierra Nevada recently, coinciding with extraordinary drought conditions. Their presences are affronting local ecosystem structure, function, and biodiversity by outcompeting native plant communities. This paper explores the correlations between recent drought conditions in northern Sierra Nevada and the increased presence of three non-native invasive weed species in Nevada County, California -- *Carduus nutans* (musk thistle), *Centaurea stoebe* (spotted knapweed), and *Chondrilla juncea* (rush skeletonweed). This study utilizes Pearson's product-moment correlation coefficient to quantify covariance between the numbers of observed infestation sites of these three species and decreased precipitation, increased temperatures, and total snowfall amounts. Results show observations of these species positively correlate with increased temperatures, and negatively correlate with precipitation departures from normal and reduced total snowfall amounts, over 15-year and 6-year timeframes. This correlative analysis serves to advance invasion ecology's understanding of the complex relationships between regional climatic changes and non-native plant species invasions.

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I. INTRODUCTION

An ecological explosion is underway in the Sierra Nevada bioregion. Non-native invasive weed species (NIS) are slowly bursting out of control throughout areas where they were previously restrained -- a process which has accelerated of late, coinciding with recent exceptional drought conditions. These invaders are outcompeting native plant communities and altering local ecosystem structure, function, and biodiversity throughout the region. There is a war going on, and the weeds are winning.

These invasive weeds waging war on ecological processes and economic systems represent only a small portion of the total introduced plant species known to exist throughout the United States, but they inflict considerable casualties. There are countless beneficial species which have been introduced to non-native environments throughout history. Corn, rice, wheat, and other food crops, for example, provide for a significant portion of our global and national food systems and are of considerable economic value (Pimentel, Zuniga, & Morrison, 2005). The "invasive species" launching attacks on ecosystems around the world, throughout the U.S., and northern Sierra Nevada are those which, according to the Invasive Species Advisory Committee and Executive Order 13112, are not native to an ecosystem and have the propensity to cause economic, environmental, or human-health harm (NISC, 2006). Non-native invasive weed species mete out considerable ecological damage throughout the U.S., and cost hundreds of billions of dollars in losses each year (Pimentel et al., 2005).

More than 50 years ago, Charles S. Elton, forefather of modern invasion ecology, recognized human intercontinental commerce as a primary cause of the invasion of continents, islands, and seas by animals, parasites, and plants, presenting mounting difficulties for man and nature to overcome (Elton, 1958). Today, NIS make up nearly half (>2000) of the some 4500 invasive animal, microbe and plant species known in the U.S. (Corn, Buck, Rawson, & Fischer, 1999). Nearly 600 of the invasive plant species in the U.S. are considered invasive and are targeted for management by federal or state agencies (USDA, 2015).

Several NIS have overcome large-scale geographical and environmental barriers to quietly infiltrate the Sierra Nevada, threatening the region's ecological, economic, and social sustainability (D'Antonio, Berlow, & Haubensak, 2004; Ditomaso, 2000; Schwartz, Porter, Randall, & Lyons, 1996).

Problem

Non-native invasive weed species virulently outcompete and displace native plants. They are known to deplete soil nutrients and disturb or eliminate forage and habitat for numerous wildlife species, degrade rangelands and significantly reduce agricultural yields (Brusati, 2009). Each year, California spends more than $82 million monitoring and controlling invasive plant species (Cal-IPC, 2008). Of course, there is no suitable economic valuation metric for non-market impacts, such as the value of endangered plant or animal species, ecosystem function, or environmental damages caused by invasive species. Non-native invasive species also accelerate erosion and flooding, reduce water resources (Cal-IPC, 2008), and have the propensity to alter fuel properties and local fire regime characteristics (Brooks et al., 2004). In addition to the ecological and economic detriments caused by NIS, losses of regional biodiversity and its ecosystem processes threaten aesthetic, cultural, intellectual and spiritual values important to the Sierra Nevada bioregion (Chapin et al., 2000).

The global interconnectedness of modern society is the primary transporter of NIS across great and vast geographical barriers (Elton, 1958). Prior to intercontinental trade and transport, invasive species were generally confined to their native and natural habitats. Simply because NIS are transported across significant physical barriers does not implicitly mean those species will be able to establish themselves in newfound environments. There are numerous and wide-ranging factors, which in many respects are largely unknown, that may induce opportunistic conditions for invasive explosions of NIS. A majority of NIS expansion pathways and factors of invasibility are man-made. Agriculture, including the raising of livestock and hay production, timber harvest and forest management practices allow for NIS pathway exploitation. Urban and suburban sprawl, the changing urban-wildland interface, and increased construction of dwelling and transportation infrastructures, too, are factors which add to the introduction of NIS into foreign landscapes. And regional environmental conditions, including episodic climate conditions, soil properties, natural disturbances, and the interrelated culmination of any of numerous activities or processes, undoubtedly contribute to the invasability of an ecosystem or bioregion.

Changes in climate have influenced species change within plant communities throughout North America since the Pleistocene era (Davis, 1986). Indeed, drought conditions including decreased precipitation (rain and snow) and increased temperatures may have the ability to advance and exacerbate the spread of NIS. Opportunistic species with known higher drought tolerances, or those which may complete reproductive cycles earlier and withstand soil salinity and extreme temperatures more efficiently than native species, thus forced to compete with invasives for limited soil nutrients and water resources, are of particular concern. Thakur et al. (2014) found soils with a warming history accelerate microbial activity which benefits the growth of different invasive plant species (grass, herb, and legume) in the temperate-boreal ecoregion of Minnesota. Recently, precipitation rates in northern Sierra Nevada have negatively departed from historical averages in 11 of the past 15 years (NCDC, 2015).

Climate and environmental conditions, the most natural of invasibility factors, serve as the prime impetus for this thesis research. By measuring the covariance of NIS and climatic variables, this simple correlative analysis attempts to draw meaningful conclusions about the complex relationships between NIS and regional environmental conditions. The results should serve as a valuable resource regarding current and future regional NIS management strategies in the face of changing environmental conditions.

Purpose

This paper explores the correlations between recent drought conditions in northern Sierra Nevada and the increased presence of three NIS in Nevada County, California. A quantitative correlative analysis is used to explore the interrelationships of NIS observation and various drought condition metrics. This analysis seeks to discover if changing climatic conditions increase the suceptability of the Sierra Nevada bioregion to infestations of *Carduus nutans* (musk thistle), *Centaurea stoebe* (spotted knapweed), and *Chondrilla juncea* (rush skeletonweed). These three particular NIS can have crippling ecological, economic, and social impacts if their current infiltrations are successful and lead to complete explosion throughout the region. The research examines recent historical trends to quantify of increases of observed infestations of *Carduus nutans*, *Centaurea stoebe,* and *Chondrilla juncea*. These rates of observation are used to establish covariance with increased temperatures, decreased precipitation, and total snowfall amounts in the northern Sierra Nevada bioregion during the last fifteen years (2000 – 2014). This study will further probe significant findings by exploring aspects of the historical spread, trending presence, and current management strategies for containing these NIS during drought conditions. I will also identify specific ecological and economic threats posed by the spread of NIS throughout northern Sierra Nevada.

Some questions motivating this research include: (1) What role do drought conditions play in the spread of NIS throughout northern Sierra Nevada? (2) Do observations of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* infestations increase or decrease in the region during drought years? (3) How do these NIS affect ecosystem processes within northern Sierra Nevada and what risks do these NIS pose to the bioregion's economic and social sustainability? (4) Have NIS diverted Sierra Nevada landscapes irreversibly from historically native structures?

I undertake this research with the hypothesis that warmer temperatures coupled with seasonally drier climates create conditions which make natural Sierra Nevada ecoregions more susceptible to herbaceous NIS range expansion than periods of cooler, wetter weather patterns. I predict warmer temperatures will reveal the strongest correlations with the spread of *Centaurea stoebe* because it is a highly-adaptable species with the greatest temperature range of seed germination (44^{o}F to 96^{o}F) of these three NIS, and under optimal conditions each plant can produce nearly 1000 seeds (Schirman, 1981). Decreased annual precipitation rates might expose strong relationships with *Centaurea stoebe* and *Chondrilla juncea* since both are highly adapted to semi-arid climates with well-drained, shallow rocky soils, similar to those of northern Sierra Nevada (Littlefield, Birdsall, Helsley, & Markin, 2000). Conversely, decreased precipitation may show weak correlations with *Carduus nutans* because, unlike *Centaurea stoebe* and *Chondrilla juncea*, it is partial to moist, alluvial soils (Gassmann & Kok, 2002). And even though *Carduus nutans* produces a significant amount of seed per flower head (<1500), I expect to find the weakest correlation with increased temperatures in *Caduus nutans* because flowering requires vernalization for at least 40 days at temperatures below 50^{o}F (Gassmann & Kok, 2002).

The ultimate objective of this simple correlative analysis is to provide a better understanding of the relationship between regional environmental change and plant-invasion ecology. Namely, I aim to explore the role current and predicted drought conditions play in increasing the invasiveness of northern Sierra Nevada to invasions of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*, and offer practical suggestions for their management in the region. This research is important to the future ecological health and sustainability of the northern Sierra Nevada bioregion. By quantifying the covariance of these three NIS and recent regional increases in temperatures and decreases in precipitation rates, I hope to add to and strengthen existing knowledge about the complex relationships between NIS and drought conditions, and improve NIS management strategies of governmental and non-governmental agencies, landowners, and stakeholders.

Lastly, I hope this correlative analysis of NIS and drought conditions in northern Sierra Nevada adds to previous works aimed at mitigating losses of native plant species, encouraging new growth of native species, and preventing further degradation of agricultural and wildlife habitats (e.g. Clewell and Aronson (2013), Moscovici, Coll, and Jones (2015), and Schlessenger, West, and Endress (2015)), and ultimately encourages future research in the field of invasive weed science and management.

II. LITERATURE REVIEW

The quality and quantity of ecological data and analytical technology in the field of invasion ecology has greatly improved since Charles S. Elton's seminal work, *The Ecology of Invasions by Animals and Plants*. Recent research has significantly progressed modern ecology's understandings of causal mechanisms of biotic homogenization (e.g., McKinney & Lockwood, 1999; Olden, Poff, & McKinney, 2006; Smart et al., 2006), helping to define concepts of NIS invasion and naturalization (e.g. Pysek, 1995; Richardson et al., 2000) and more fully express the impacts and consequences of their spread (e.g. Simberloff et al., 2012).

This literature review is designed to survey relevant invasion ecology literature which examines the relationships between NIS and climatic changes. I provide a basis for the need for original research which specifically considers the relationships between *Carduus nutans*, *Centaurea stoebe*, *Chondrilla juncea* and drought conditions in their newly-exploded northern Sierra Nevada bioregion. The significance of a simple correlative analysis to explore NIS-climate relationships is addressed. This review first traces the relatively recent evolution of invasion ecology by providing an underlying theory of how environments are, or become, susceptible to NIS attacks. Next I explore prominent ecological and socioeconomic pathways of NIS introduction into foreign regions. Finally, I review studies which emphasize the ecological and economic impact of NIS invasions.

Theory of Invasibility

A cohesive theory of plant community invasibility has yet to emerge in invasion ecology. Due to vast differences and complex interactions among environments and species, science may never know one all-encompassing theory of ecosystem's susceptibility to NIS invasions, though new data are permitting some synthesis regarding invasibility. One such theory which attempts to bridge some of these complexities with general environmental factors of NIS invasions is based on the notion of fluctuating resource availability. The theory of fluctuating resource availability simply predicts invading species are successful when they outcompete native species for available resources such as light, nutrients, and water (Davis, Grime, & Thompson, 2000). The ability of NIS to maximize those finite resources within a given ecosystem enables their expansion into native plant communities. Thus as resource availability increases, where either resources are introduced, say through eutrophication, or resource uptake by native species is reduced, like after a fire event, invasibility increases (Davis et al., 2000).

The theory of fluctuating resources is unlike some previous theories which imply a sort of ecological equilibrium between native species and their available resources. Assuming equilibrium in this way contends NIS are fundamentally different from resident species and utilize alternate niches within communities. Alternatively, the notion of fluctuation holds that plant communities rarely experience ecological equilibrium, and that their resource supply and native plant uptake fluctuate for many and widely-varying reasons. Reasons for available resource fluctuation may include anthropogenic activities, climatic conditions, disturbances, grazing pressure, site-specific events, or pest outbreaks, to name a few (Davis et al., 2000). The idea that invaders will be successful if they have access to resources, and particularly if strong competition for those resources is not present, is based on the premise that competition intensity is negatively correlated with unexploited resources (Davis, 1998).

The challenges of establishing a single, coherent theory of invasibilty to be applied across environmental, geographical, and species-community bounds are exacerbated by the diversity of resource-release mechanisms. These mechanisms exhibit a broad variety of occurrence and causes. Resource-release mechanisms are not static; they fluctuate and often occur within an ecosystem only intermittently, which may allow for the realization of NIS invasions as episodic events (Davis et al., 2000). Another significant challenge in nailing down a consistent theory of invasibility rest with researchers' limited successes in finding and developing consistent ecological correlates of invasibility, and the obscurity of predicting NIS invasions (Davis et al., 2000).

Pathways of Invasion

Non-native invasive species are naturally opportunistic. They take full advantage of available resources, whether causes of fluctuation are natural or a byproduct of anthropogenic activity. An exploration of the ecological and socioeconomic pathways of NIS invasions, and the impacts these factors have on the fluctuations of available resources in a given area, can provide data about an ecoregion's susceptibility to NIS invasions.

Ecological

A survey of literature which explores relationships between NIS invasions and prominent ecological pathways which facilitate infestation will shed light on those ecological factors of invasibility, such as soil disturbances, nitrogen (N) fluctuations, and the ability of NIS to adapt and wholly evolve to a foreign environment's soil-nutrient loads. This exposes how climatic conditions impact soils to further aid NIS invasions and abet range expansion throughout northern Sierra Nevada.

Soil

It is well established that disturbed soils play a significant role in the susceptibility of an ecosystem to non-native invasion (Elton, 1958), particularly when combined with soil nutrient additions (Hobbs & Atkins, 1988). Disturbances can be realized at the community level, but some may be as unsuspecting as a molehill and increase community invasibility and allow species persistence by exposing localized areas of unexploited resources (Hobbs & Mooney, 1985).

In naturally nutrient-poor soils where slow-growing natives with significant investments in belowground structures, and abilities to store and recycle soil N naturally dominate, like those of northern Sierra Nevada, NIS invasions are attributed to increases in soil N following disturbances (James, 2012). These soil disturbances allow fast-growing invasives to outcompete native plant communities (James, 2012). Desert environments are least invaded by plants due to their naturally lower levels of soil N, though Brooks (2003) indicates they are particularly susceptible to invasions at small levels of soil N increases. Brooks (2003) finds increases of soil N increase the dominance of non-native annual plants, decreasing diversity of native species soil N is added to three sites in the Mojave Desert at rates similar to deposition in adjacent urban areas for two years; measuring density, biomass, and species richness. Similarly, McLendon and Redente (1992) conduct a three-year study on a disturbed sagebrush site in northwestern Colorado which indicates supply of soil N controls the rate of secondary succession in semiarid ecosystems. Kolb et al. (2002) also show a strong relationship between high soil N and increased invasability in their study, by growing annual and perennial grasses at different levels of soil N and water. In general, chronic disturbances that increase nutrient availability favor increased invasability of an area, though resource supply rates, physiological and life history traits, coupled with abiotic and biotic stressors ultimately determine plant species performance (James, 2012).

Some studies suggest NIS evolve from their native ranges to utilize higher nutrient concentrations. In a reciprocal transplant experiment, Blank and Sforza (2007) indicate plants from California-derived seed of the non-native annual grass *Taeniatherum caput-medusae* [L.]

Nevski (madusahead wildrye) uptake soil nutrients more efficiently than those of their native Mediterranean range, which highlights the functional difference of vulnerable soils of western U.S. ecosystems. This evolution of NIS may indicate the newly invaded range of arid and semiarid western U.S. ecosystems' perennial-plant dominated nutrient and organic matter cycles are far more recently disturbed than the Mediterranean region -- where intensive ecosystem management depleted nutrients there much longer ago -- and native vegetation have adapted over time (Norton, Monaco, & Norton, 2007). In a study designed to evaluate the potential of establishing *Agropyron fragile* [Roth] P. Candargy ('Vavilov' Siberian wheatgrass) in sites dominated by *Bromus tectorum* L.(cheatgrass), a widespread NIS in sagebrush ecosystems of western North America, Mazzola et al. (2008) add sucrose to promote soil N immobilization, and find a sevenfold increase in *B.tectorum* density, not *A. fragile*. The Mazzola et al. (2008) findings suggest long-term soil N reductions are a key factor in management of invasive weed populations.

Climate

Changes in climate undoubtedly impact soils. Rising temperatures and alterations in water availability, for example, have direct impacts on nutrient cycling and N mineralization rates, soil respiration, and decomposition processes (Kleinman, 2015). These climatic changes may prove advantageous for virulent and highly-competitive NIS throughout northern Sierra Nevada.

The Sierra Nevada are currently in the midst of an exceptional drought (Belmecheri, Babst, Wahl, Stahle, & Trouet, 2015), and increasing temperatures are likely expected to last through the end of the current interglacial cycle, which began around 9000 B.C. (Eldredge and Biek, 2010). A recent multi-century evaluation of Sierra Nevada snowpack using tree-ring data from more than 1500 *Quercus douglasii* (Blue-oak), coupled with temperature and precipitation reconstructions reveal that, in 2014, the region received its lowest snowfall amounts in more than 500 years (Belmecheri et al., 2015). A similar study using tree-ring data from *Pinus balfouriana* (Foxtail pine) and *Juniperus occidentalis* (Western juniper) designed to reconstruct historical temperature and precipitation data to 800 A.D., Graumlich (1993) indicates 1000+ year-historical precipitation means were lower than 20th century levels. Graumlich (1993) finds temperature fluctuates on centennial and greater time-scales (e.g. a 275 year warming period between 1000 and 1375, and a cooling trend of 400 years between 1450 and 1850). A recent climatic change trending toward hotter and drier conditions consistent with millennial changes, and increased anthropogenic disturbances of soils recently, has encouraged alterations of native flora and invasive species throughout northern Sierra Nevada.

Climate change may have differing effects on various species in different regions, either enhancing risk of invasion or reducing NIS competitiveness (Bradley, Wilcove, and Oppenheimer, 2008). Bradley et al. (2008) use bioclimatic envelope modeling to show climate change can result in both the range expansion and contraction of five different NIS throughout the western United States. The contraction of NIS ranges within a region certainly creates opportunity for restoration efforts, though expansions of NIS ranges beckon a need for fiercer management. Beerling (1993) uses climatic correlation to find temperatures (particularly, length of growing season and minimum temperature) impact the northern distribution limits of two introduced perennial and annual species in northwest Europe. Based on a rise in global mean surface air-temperature between 2.7°F and 8.1°F, Beerling (1993) enables forecasts to predict a northward expansion of these invasive species of at least 5°N. In other parts of the world however, different NIS ranges are contracting due to climatic changes. In a South African study on the effects of climate warming on the distributions of invasive Eurasian annual grasses, Parker-Allie, Musil, and Thuiller (2008) suggest climate change will deter expansion of European grasses in the region. They predict significant range contractions of C_4 and C_3 grasses in South Africa under current and future climate scenarios with mean temperature of the coldest month as the strongest parameter. However, Bradley (2009) suggests relying on temperature change alone to predict species distribution change is inadequate. Her findings show change in precipitation strongly influences the invasion risk of *B. tectorum* throughout the Intermountain West, where decreased precipitation increases risk by expanding suitable invasible land in four states by more than 45%; and increased precipitation, conversely, reduces invasion risk by 70%. Episodes of warmer, drier climates will likely decrease soil N and increase phosphorus in many regions, including Sierra Nevada. The most efficient and competitive plant species will dominate during periods of fluctuating resources.

The effects of climate change will undoubtedly induce multifaceted changes in the range expansion and distribution of NIS worldwide. And these climate-induced changes to NIS ranges will require modifications of current management practices used to control them. Our understanding of the specific mechanisms and processes of NIS-climate relationships are presently inadequate to reasonably predict and respond to those changes on a broad scale. For now, NIS are most effectively examined and managed on a case-by-case basis (Runyon, Butler, Friggens, Myers, & Sing, 2012).

Socioeconomic

Ecological pathways of NIS invasions are often exaggerated or even created by socioeconomic activities which lead to environmental stress, and provide opportunities for NIS to exploit limited available resources. As such, a literature review of ecological pathways of NIS invasions would be remiss to exclude socioeconomic factors, as the two are inextricably linked. Here, I briefly review several recent studies which illuminate this broad human dynamic. The number of anthropogenic activities which help facilitate NIS invasions is great. Interactions of ecological processes with commerce, economics, and population growth can indirectly serve as pathways to invisibility. These interactions can alter soil properties or regional climates, for example, and signal the socioeconomic-NIS relationship's complexity and persistence.

A recent study suggest the current distribution of naturalized NIS is successfully predicted using a 20-year time lag of socioeconomic activity and, with predicted future climate change, the trajectory of non-native invasions for the next two decades shows increasing plant invasions in northern temperate countries, with decreasing NIS invasions in tropical and subtropical regions (Seebens et al., 2015). In a study which explores relationships between native and NIS in the U.S., and state-level physical and socioeconomic factors which contribute to naturalization, Guo, Rejmanek, and Wen (2012) find native species are generally controlled by natural environmental factors, like precipitation and temperature, whereas NIS naturalization often involves a dominant social, human dynamic.

Stohlgren et al. (2006) quantify species richness and density patterns for native and non-native flora and fauna within the continental U.S. and Hawaii. Using plant data from more than 3000 counties, multiple regression models show strong predictability of native and non-native plant species densities, particularly in low-elevation, coastal hot-spots. Stohlgren et al. (2006) models show abiotic and biotic factors can be used to accurately predict density and richness of non-native plant species. While humans contribute heavily to the transport and initial establishment of NIS, environmental factors allow for their subsequent control, distribution, and spread (Stohlgren et al., 2006).

Global trade will accelerate future NIS invasions. Pysek et al. (2010) contend trade and transport increasingly drive the mixing of biota from around the world, introducing NIS to new regions. The relative importance of the interrelationships between biogeographic, climatic, demographic, and economic factors is not yet uniformly understood or realized. In their European study, Pysek et al. (2010) find national wealth and population density are significant predictors of regional-scale invasability, reflecting the impact humans have on the level of non-native species invasions, and that solutions to the problem lie in mitigating negative environmental consequences of anthropogenic activity associated with wealth generation. Williamson, Myerson, and Auge (2011) similarly suggest economics and ecology are wildly intertwined with the problem of NIS invasions, and that the processes which lead to an ecosystem's increased vulnerability to plant invasions are direct consequences of economically-driven actions. Thus NIS invasions are externalities of market transactions of an epic, and global scale.

Impact of Invasions

The ecological and economic impacts caused by NIS invasions are well-documented in both historical and recent literature. Ecologically, NIS invasions are known to decrease biodiversity, diminish local ecosystem services, irreversibly alter natural landscapes, and shrink wildlife forage and habitat availability. Quantifying economic losses to NIS invasions presents inherent challenges. Non-native invasive species are known to significantly reduce agricultural production yields, impede recreation resources, and burden landowners and natural resource managers with significant costs in controlling and eradicating them.

Ecological

One of the earliest documented plant invasions is recorded in Darwin's (1872) *Origin of Species* in which he observed the European cardoon and tall thistle were, "…the commonest over the wide plains of La Plata [Argentina] … almost to the exclusion of every other plant." Non-native invasive weed species can significantly diminish biodiversity and alter native ecosystem's structure and function by overtaking and displacing naturally beneficial plant species. For example, *Lythrum salicaria* (purple loosetrife), an NIS from Europe now occurring in 48 U.S. states including California and northern Sierra Nevada, changes the basic structure of wetlands it invades and has notably reduced the biomass of dozens of native plants, and several wildlife species dependent on those native plants for forage and habitat (Pimentel et al., 2005).

Invasive weed species threaten ecologically valuable wildlands and wildlife habitats like protected forests, grasslands, national parks, and wildlife refuges. In Great Smoky Mountains National Park, NIS are impacting ecosystem integrity and health, as nearly one-third (400) of the vascular species there are introduced exotics, and 10 species are known to be displacing and threatening other plant and wildlife species (Pimentel et al., 2005). *Centaurea soltitalis* (yellow star-thistle), which can be deadly to horses, has completely overrun more than 16 million acres of once productive grassland ecosystems throughout California alone (Pimentel et al., 2005).

The ecological impacts of NIS not only negatively impact and reduce biodiversity worldwide, but NIS can also wholly alter soil structure, vegetation, fuel properties and fire regimes regionally. Commenting on the aforementioned thistles discovered by Darwin in La Plata, Hudson (1923) notes the incredible fire danger of those thistles. When they are beyond seeding and dead with their hollowed and dry stalks, observing their fire threat, they are as great a nuisance as those living. Today, it is well established that plant invasions can severely impact native ecosystems' fire regime characteristics, including frequency, extent, intensity, seasonality, and type. This extent of ecological alteration ultimately promotes NIS domination by establishing a regime conducive to continued invasive-plant expansion, effectively making restoration to preinvasion conditions more difficult (Brooks et al., 2004). *Bromus tectorum* has irreversibly increased fire frequency throughout vast regions of western North America by establishing monocultures of the invasive grass (Pimentel et al., 2005; Whisenant, 1990). Prior to *B. tectorum* invasions, fires regularly burned at 60-110 year intervals, now the hiatus between fire is a mere 3-5 years (Pimentel et al., 2005). The change in fire regime has trickle-up effects, as the reduction in native shrub-steppe species and their inability to recover due to shorter lag-time between fires directly impacts wildlife habitats for *Centrocercus urophasianus* (sage grouse), *Lepus californicus* (black-tailed jackrabbit), *Spermophilus mollis* (Paiute ground squirrel), impacting food webs, as these species are prey for *Aquila chrysaetos* (golden eagle) and *Falco mexicanus* (prairie falcon), and so on (Brooks et al., 2004). The relationships between NIS and local fire regimes are multifaceted, but an understanding of their severe impacts on critical ecological process is required for the facilitation of effective and efficient NIS management strategies.

Economic

Global economic growth is a significant contributing factor associated with the spread of NIS throughout the world. The economic impact of weed invasions including losses of crop and pasture agricultural production, as well as control and management efforts, cost hundreds of billions of dollars annually (Pimentel et al., 2005). However, attempts to sufficiently quantify economic losses due to NIS infestations are mired with uncertainty, particularly regarding long-term economic outcomes and the prediction of future losses. Given the inherent challenges associated with measuring economic losses, and generally assessing environmental values, it is reasonable to assume much literature on the topic of NIS economics is underestimated.

Pimentel et al. (2005) conservatively estimate nearly $30 billion per year in losses to crop production (a 12% yield reduction) and NIS management are attributed to invasions in the United States alone. And management of invasive weeds in gardens, lawns, and recreation areas account for $36 billion annually (Pimentel et al., 2005). In pastures, rangelands, and forests, NIS are responsible for more than $1 billion in forage losses of desirable natives for cattle and other ungulates and grazers (Pimentel et al., 2005). *Carduus nutans* infestations can reduce pasture and rangeland productivity by 23%, suppressing desirable forage, and the spiny nature of the leaves and stems prevent livestock from browsing plants in the vicinity of the thistles (Gassmann & Kok, 2002). In Australia, Cullen (1986) finds *Chondrilla juncea* reduce wheat yields by 80%, and Sheley and Hudak (1995) determine *C. juncea*, which infest more than 6 million acres of rangeland throughout the Pacific Northwest and California, severely impacts agricultural economies throughout the region. *Chondrilla juncea* infestations have reportedly contributed to significant reductions in agricultural land values, by 60% and 90% in North Dakota and Oregon, respectively (Zimmerman and Johnson, 2001). In an economic impact analysis conducted in Montana, Hirsch and Leitch (1996) find three common knapweeds, *Acroptilon repens* (Russian knapweed), *Centaurea diffusa* (diffuse knapweed), and *Centaurea stoebe*, which infest more than 1.6 million acres there, collectively account for losses of more than $56 million annually, not only to livestock producers but landowners, outdoor recreationists, hunters, and water users too.

Summary

The relationships between NIS invasions and climatic changes are complex and vary significantly between species-community, ecoregion, and external human impacts. While there is not one comprehensive theory on what makes a given region susceptible to NIS invasions, the theory of fluctuating resource availability, which simply states NIS are successful when resources increase or when native-plant uptake is reduced, provides a foundational theoretical basis for this correlative analysis.

Ecological and socioeconomic pathways provide means for NIS introductions and explosions. At the root of the matter are soils, when once an NIS has been introduced, nutrient resource availability becomes a vital component to species success. Soil disturbance caused by natural or anthropogenic processes alter nutrient availability to native plants and NIS. Climate conditions, namely temperature and precipitation, naturally impact NIS range expansion or contraction regionally, enhancing invasion risk or reducing competitiveness. Socioeconomic activities are becoming realized as drivers of NIS invasions around the world, which when coupled with biotic factors can prove ecologically and economically detrimental. The ecological impacts of NIS invasions have been documented for more than a century, though today their toll is realized in their diminishing of biodiversity, their alteration of ecosystem functions such as fire regimes, and their complete adjustment of plant-community structures. Non-native weed species are economically taxing too, chiefly in the form of lost crop and pasture agricultural production, and eradication effort costs.

This review of literature elucidates the significance and intricacy of the relationships between of NIS infestations and climatic changes, for which there are many unanswered questions, and reinforces the need for further research on the topic.

III. METHODOLOGY

This correlative analysis uses Pearson's *r* to establish covariance between *Carduus nutans, Centaurea stoebe*, *Chondrilla juncea*, and drought conditions in northern Sierra Nevada. Research was conducted entirely within Nevada County, California, an ecologically diverse and relatively rural area located in the northern Sierra Nevada bioregion. Each of the three target NIS are present within Nevada County, to varying degrees, and all are listed by the California Department of Food and Agriculture (CDFA) as species of concern and top-priority for control measures. Collectively these NIS ranges are expanding rapidly within the Nevada County and greater northern Sierra Nevada.

Study Area

The Sierra Nevada, an incredible deposit of granite rock shaped over tens of millions of years, which rises gradually out of the Central Valley and spans more than 400 miles from Tehachapi Pass in the south to Fredonyer Pass in the north, and nearly 70 miles west to east. Most of the soils throughout Sierra Nevada are thin and rocky with low nutrient fertility. The region generally provides for productive conifer growth, and the western edge of the Sierra support significant and diverse agriculture (USGS, 1997). Sierra Nevada is also home to abundantly diverse vascular plant communities. Some 3500 native plant species in Sierra Nevada alone comprise more than 50 percent of California's plant diversity (USGS, 1997), though NIS communities are establishing themselves throughout the region at alarming rates.

Nevada County, California, was selected as the research unit of analysis because it contains portions of each of the diverse ecological zones found within the Sierra Nevada ecoregion, including the western foothill savannah and chaparral-oak woodlands (500 - 3500 ft.), lower-montane (3000 ft. - 7000 ft.) and upper-montane forests (7000 ft. - 9000 ft.), and subalpine forests (9000 ft. - 10 500 ft.) (USFS, 2012; Wagtendonk & Fites-Kaufman, 2006). Nevada County comprises 974 square miles, predominately within the Yuba and Truckee River watersheds, and extends primarily west to east from the Sacramento Valley to the Nevada border, ranging accordingly in elevation from approximately 1400 feet to 9152 feet above sea-level. The human development period in the region, since about 1865, has experienced a relatively warm and wet climate when viewed on millennial scales. Perceptions of ecological processes and future development are often drawn on these anomalous climatic conditions (USGS, 1997). Today, a "Mediterranean" climate pattern of cooler, wetter winters and longer, dryer summers dominates the region where precipitation generally increases with altitude (USGS, 1997).

Species

Three NIS, *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*, found throughout northern Sierra Nevada, and Nevada County, were selected as species of analysis because their populations throughout the region are relatively abundant, which allowed for manageable and meaningful data, and each are considered high-priority NIS for control by CDFA.

Carduus nutans

Carduus nutans (musk thistle or Nodding plumeless thistle), a member of the *Asteraceae* family, is a biennial, though occasionally annual in warmer climates, herbaceous weed species of western European origin (USFS, 2013). *Carduus nutans* is expanding its range throughout the American West, northern Sierra Nevada, and Nevada County, and commonly invades sage scrub, range, pasture, forested areas, grasslands and disturbed areas, and undergoes rapid population growth (Cal-IPC, 2005a). There are some suggestions however, that CDFA has been able to effectively reduce the rate of *C. nutans* expansion, compared to other states with less active invasive plant management programs (Cal-IPC, 2005a). *Carduus nutans* has the propensity to induce long-term soil N depletion (Wardle, Nicholson, Ahmed, & Rahman, 1994), form dense stands up to 370 000/ac (Desrochers, Bain, & Warwick, 1988), and has the ability to colonize previously burned areas before native plant species, ultimately preventing native reestablishment, and altering natural fire regimes (Hanna, Romme, Kendall, Loy, & Colyer, 1993). Reproducing via seed, *C. nutans* first flowers can produce up to 1500 seeds per head (Desrochers et al., 1988), which commonly drop near parent plants (Smith and Kok, 1984), but can be transported long distance through natural dispersal (i.e. birds, smaller mammals, water, wind, etc.).

Centaurea stoebe

Centaurea stoebe (spotted knapweed), formerly *C. maculosa*, is a perennial, occasionally biennial, forb of western, central, and eastern European origin (USFS, 2013). *Centaurea stoebe* invades indiscriminately among both undisturbed natural areas and severely disturbed sites. *Centaurea stoebe* is spreading extensively throughout northern Sierra Nevada, and exponentially in most western U.S. states, where infestations are a detriment to water and soil resources (Cal-IPC, 2005b). In a Montana study, Lacey, Marlow, and Lane (1989) show runoff and sediment yield more than triple in sites dominated by *C. stoebe* versus sites dominated by bunchgrass vegetation. *Centaurea stoebe* is an effective colonizer by its efficient use of soil N and ultimately outcompeting native grasses (Blicker, Olson, & Engel, 2002). This species is particularly virulent, as one invasion of *C. stoebe* in Glacier National Park is thought to have contributed to the elimination of seven rare plant species in just three years (IPC-BC, 2003). Deer and sheep are known to browse *C. stoebe* and their flowers are particularly useful for pollinators; however, its infestation into rangelands is reducing grass and herb forage bases which traditionally support robust elk populations (IPC-BC, 2003). *Centaurea stoebe* reproduces via seeds nearly three weeks after flowers bloom in mid-to-late summer, averaging nearly 1000 seeds per plant (Schirman, 1981). Humans have become significant distributors of *C. stoebe* through numerous modes of modern transportation, via the undercarriages of vehicles, trains, and light aircraft, or through the movement of hay or lumber. Cattle, deer, and other ungulates, as well as some birds and rodents can also disperse *C. stoebe* seed long distances if loosely held achenes attach, though *C. stoebe* populations commonly expand through growths of existing stands (Cal-IPC, 2005b).

Chondrilla juncea

Chondrilla juncea (rush skeletonweed or naked weed), is a perennial forb with an extensive, deep root system (USFS, 2013). Chondrilla juncea originated from the Transcaspian region of Eurasia and indiscriminately invades cultivated and disturbed soils, though is commonly thought of as a roadside invader (Cal-IPC, 2005c). *Chondrilla juncea* grows particularly well in well-drained sandy or gravel soils in Mediterranean climates, like those found the Sierra, and has a vast tolerance range of environmental conditions, from 10 in. – 50 in. of rain per year (Cal-IPC, 2005c). Outcompeting native plants for soil N, *C. juncea* significantly reduces soil nutrient availability (Dodd & Panetta, 1987; Liao, Monsen, Anderson, & Shaw, 2000). In 2000, *C. juncea* covered more than 6 million acres of rangeland throughout the Pacific Northwest and California (Liao et al., 2000). Though it had invaded Idaho sagebrush steppe then, it has yet to establish itself in California sagebrush ecosystems.

Chondrilla juncea produces and spreads seed in fascinating quantities. One Australian study found plants to produce more than 27 000 seeds, via vegetative or asexual production, with more than 80% viability (Cal-IPC, 2005c), producing seed longer annually and earlier in life stages (Dodd & Panetta, 1987). The length of seed viability is largely unknown and likely based on local environmental conditions. One Mediterranean study, a region similar to its native habitat, suggest *C. juncea* seed lose viability within a year (Wapshere, Hasan, & Caresche, 1974), while another North American study suggest its seeds are more persistent and able to germinate past one year (Liao et al., 2000). *Chondrilla juncea* frequently contaminates hay in established invaded regions, though seeds are often locally dispersed through wind or fur attachment (Dodd & Panetta, 1987).

Materials

NIS observation data

CalFlora (http://www.calflora.org/), an online plant observation database used by academic institutions, private organizations, public agencies, scientist, and volunteers, was used to collect the number of observed *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* infestation sites within Nevada County, recorded between 2000 and 2014. Observations' geographical coordinates were documented to prevent repeat observations within a one-year period. CalFlora is essentially a collaborative citizen-science, data collection and redistribution, digital library which relies on contributions from its users for the information it provides. CalFlora serves as a repository of readily usable information on California's wild plants, native and non-native species.

Weather data

The National Weather Service (NWS) Cooperative Observer Program (COOP) was used to obtain historical annual climatological summary data, including annual mean maximum temperatures (MMXT), annual precipitation departures from normal (DPNP), and annual total snowfall (TNSW), within the date-range of 2000 to 2014.The primary weather station used in this research was at Boca, CA (COOP: 040931). Boca was chosen as the most ideal weather station for this research because, at 5580 feet above sea level, it is located nearest the median altitude of Nevada County. U.S. Forest Service Ranger Station in Truckee, CA (COOP: 049043) was used as a secondary weather station to fill minor gaps in DPNP data lacking from Boca. Truckee Ranger Station is 6020 feet above sea level.

Pearson's *r*

Pearson Correlation (v1.0.9) in Free Statistics Software (v1.1.23-r7), Office for Research Development and Education, **(**http://www.wessa.net/rwasp_correlation.wasp**)** was used to derive Pearson's product-moment correlation coefficient (*r*), measuring the strength of linear relationships between the number of recorded observations of the three invasive weed species within the date-range and DPNP, MMXT, and TNSW. Pearson's *r* has been used for more than a century, defining correlation as any constant(s) which determine the function of one variable to another (Pearson, 1896). Pearson's *r* assumes a linear relationship between variables and requires their measurement on interval scales (Hauke and Kossowski, 2011). Pearson's *r* has limits of ±1 ($1 \geq r \leq -1$), where 1 implies a perfect positive correlation. Thus for all values *x* increases so too *y* increases. Conversely, -1 implies a perfect negative correlation, where for all values *x* decreases so too *y* increases (or vice versa). And 0 suggest no correlation between variables.

Methods

I conducted an online plant search on CalFlora for each of the three target species within Nevada County between 2000 and 2014, resulting in lists of each of their recorded observations which included a hyperlink unique observation identification number (CalFlora ID), name(s) of individual(s) or group that submitted the observation, a brief description of the location, and date/time. Clicking on the CalFlora ID provided further metadata including specific geographical coordinates of the infestation and GPS device location accuracy (m^2). I collected 674 recorded observations of *Carduus nutans*, *Centaurea stoebe,* and *Chondrilla juncea* infestation sites within Nevada County (540 *Carduus nutans*, 107 *Centaurea stoebe*, and 27 *Chondrilla juncea*).

Annual climate data was taken from the NCDC weather station at Boca, CA to determine all MMXT and TNSW for each calendar year between 2000 and 2014. Similarly, Boca, CA was used to calculate DPNP for each calendar year except 2007 and 2001, where data was insufficient for those calculations. Instead, data was taken from Truckee Ranger Station, CA to determine DPNP for 2007 and 2001.

Each independent variable, DPNP, MMXT, and TNSW was correlated individually with the number of observations of each *Carduus nutans*, *Chondrilla juncea*, and *Centaurea stoebe* for each year between 2000 and 2014, using *r*:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x^2) - (\sum x)^2]\,[n(\sum y^2) - (\sum y)^2]}}$$

The numbers of recorded observations of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* were individually, and collectively, input into Pearson Correlation (v1.0.9) in Free Statistics Software (v1.1.23-r7) as *x* data with DPNP, MMXT, and TNSW which were separately input as *y* data, in inches, degrees Fahrenheit, and inches, respectively. The software output scatter plots, Pearson's *r*, covariance, determination, and correlation t-test, with Jarque-Bera and Anderson-Darling normality tests applied to both variables.

IV. RESULTS

The results found positive correlations between MMXT and observed infestation sites of each *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*. As MMXT increased so too did observations of the three NIS. Negative correlations were found between DPNP and TNSW. Observations of these NIS increased as DPNP and TNSW decreased. All of these results were enhanced significantly when *r* values were established for each of the three species (individually and collectively) over a span of the last six years, 2009 – 2014, using the same independent variables (MMXT-6, DPNP-6, and TNSW-6), versus 15-year data. A significant majority, 74%, of the total observed infestations sites were reported between 2009 and 2014.

15-year *r*-values

Using observation and climatic data from 2000-2014, I found the strongest positive correlation between *Chondrilla juncea* and MMXT (*r* = 0.499). *Centaurea stoebe* and *Carduus nutans* similarly showed strong, positive correlations with MMXT (*r* = 0.447 and *r* = 0.424, respectively). Combined, using the 674 observed NIS infestation sites, these three NIS species showed an overall strong, positive correlation with MMXT (*r* = 0.455).

Negative correlations were discovered between both DPNP and TNSW and each invasive species.

Correlations with TNSW were all negative, but strength of correlation varied by species. *Chondrilla juncea* had the weakest negative correlation with TNSW (*r* = -0.235). *Carduus nutans* also showed a moderate, negative correlation with TNSW (*r* = -0.294), but *Centaurea stoebe* showed a strong, negative correlation (*r* = -0.561). Overall, there was a moderate, negative correlation between the observed NIS infestation sites and TNSW (*r* = -0.383).

Carduus nutans had the weakest negative correlation with DPNP (*r* = -0.134), almost no relationship whatsoever. *Centaurea stoebe* and *Chondrilla juncea* showed moderate, negative correlations with DPNP (*r* = -0.321 and *r* = -0.340, respectively). There was an overall weak, negative correlation between the observed NIS infestation sites and DPNP (*r* = -0.202).

6-year *r*-values

Using observation and climatic data from 2009-2014 showed drastically more robust correlations between each variable, DPNP-6, MMXT-6, and TNSW-6. The strongest positive correlation was found using MMXT-6 with *Centaurea stoebe* (*r* = 0.973), a nearly perfect positive correlation. *Carduus nutans* and *Chondrilla juncea* similarly showed strong, positive correlations with MMXT-6 (*r* = 0.791 and *r* = 0.580, respectively). Combined, using the 499 observed NIS infestation sites between 2009 and 2014, these species showed a strong, positive correlation with MMXT-6 (*r* = 0.878), almost double that of the 15-year MMXT covariance.

Negative correlations between observed invasive species sites were also more pronounced using DPNP-6 and TNSW-6, compared to 15-year data.

Correlations between NIS and TNSW-6 were all strong, negative. Each was significantly stronger than 15-year data. *Centaurea stoebe* had the strongest negative correlation with TNSW-6 (*r* = -0.881). *Chondrilla juncea* also showed a strong, negative correlation with TNSW-6 (*r* = -0.745), and *Carduus nutans* showed strong, negative correlation (*r* = -0.693). Overall, the three species showed a strong, negative correlation with TNSW-6 (*r* = -0.788).

Chondrilla juncea showed the strongest negative correlation with DPNP-6 (*r* = -0.672). *Centaurea stoebe* and *Carduus nutans* similarly showed strong, negative correlations with

DPNP-6 (r = -0.627 and r = -0.598, respectively). There is an overall strong, negative correlation between the observed NIS infestation sites and DPNP-6 (r = -0.623).

Summary

The results of this simple correlative analysis do not provide assumptions of cause-and-effect relationships between the number of observed NIS infestation sites and DPNP (-6), MMTX (-6), or TNSW (-6); rather the results quantify the covariance between *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*, and these independent variables. These correlations however, allow us to draw some conclusions about the relationships between drought conditions and the potential increased presence of these NIS in northern Sierra Nevada.

V. DISCUSSION

The weeds are winning the battle throughout the greater northern Sierra Nevada ecoregion. These NIS are aided in their efforts by climatic conditions which are proving conducive to their expansion by providing opportunistic advantages over native-plant species. This simple correlative analysis showed increased temperatures, decreased rain and snow correlate with increased observations of *Carduus nutans*, *Centaurea stoebe* and *Chondrilla juncea* throughout northern Sierra Nevada. These correlations are greatly enhanced with the more robust datasets found in more recent years, which more clearly reveal the damage caused by the quiet ecological explosion of NIS throughout the region.

The strong, positive correlations found in both the 15-year and 6-year data between each of these invasive species and MMXT help to convey the expectance of the increased presence of NIS throughout northern Sierra Nevada during years of warmer temperatures, consistent with seasons of drought. Similarly, the strong negative correlations found between each of the invasive species and DPNP and TNSW during those same years reinforce the hypothesis that observations of NIS increases with drought conditions. If the recent extraordinary drought trends continue throughout northern Sierra Nevada, there is a high expectation, and probability, of seeing increased observations and range expansions of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*, and similar NIS, throughout the region.

Observations

The raw data of observed NIS infestation sites during the larger overall drought trend, between 2000 and 2014, when 11 of those 15 years saw negative DPNP and warmer MMXT, shows significant increases in recorded observations of these NIS on the CalFlora website in more recent years and as trending drought conditions persist. For example, in 2000 there were no recorded observations of *Carduus nutans, Centaurea stoebe,* or *Chondilla juncea* documented in Nevada County, while in 2014 there was a total of 162 observations of these three NIS collected. This lack of historical observation data in earlier years coupled with steadily increasing observations in more recent years, in effect, skews *r* in the 15-year analyses to show weaker correlations between drought conditions and the presence of NIS than the 6-year analyses, a timeframe where a significant portion of observational data is concentrated. The notable increase in collections of observational data sets in more recent years (2009-2014) represents a richer sampling of these NIS throughout Nevada County, and allows for stronger and more meaningful correlations to be established. This phenomenon of increased observational reporting clearly allows for a greater sampling of observed NIS to be utilized in correlative analyses, and consequently a more realistic representation of the scope of infestations throughout the region. Similarly, the lack of historical data hampers the ability to conduct any comparatively long-term analyses, and stymies the ability for any relative historical conclusions to be drawn about the correlations between these species and drought conditions in northern Sierra Nevada right now. Moving forward however, with increased observations on publicly available references like CalFlora, the ability to conduct further research involving greater historical correlative analyses of NIS throughout the region will be made possible, and warranted.

Drought-NIS relationships

The results of this simple correlative analysis show there are indeed relationships between *Carduus nutans*, *Centaurea stoebe*, *Chondrilla juncea*, and increasing temperatures and decreasing precipitation. In the past six years, 2009 – 2014, there has been a 65% increase in the reported observations of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*, in Nevada County compared to the nine years prior, 2000 – 2008. These increased observations coincide with some of the hottest, driest years on record in the region. Annual rainfall totals in northern Sierra Nevada have departed from normal precipitation rates in 11 of the last 15 years. Total snowfall has decreased during the past six years by more than 75%, and 2014 saw the lowest snowfall totals in more than 500 years. Non-native invasive weed species are expanding their range throughout northern Sierra Nevada at unprecedented rates, and these NIS range expansions are coinciding with recent exceptional drought conditions in the region. The covariance of the increased NIS observations during this period of extreme drought in Sierra Nevada indicates the climatic conditions are ripe for these three NIS, *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*.

The consistency and strength of their *r*-values discovered in this study, both positive and negative, particularly the more robust six-year *r*, indicate these recent drought conditions are at related to the increased invasibility of the region. Climatic changes create environments which are susceptible to *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* invasions. A prime example of how the recent drought conditions in the Sierra Nevada drought are increasing invasibility throughout the region is witnessed at Boca Reservoir and Prosser Creek Reservoir, both located in eastern Nevada County. These man-made lakes require spring runoff of winter snows. Since snowfall totals have been so low for consecutive years, Boca and Prosser Creek Reservoirs' water levels have decreased by amounts never before seen in their histories, and flows from their dams into the Truckee River were cut-off at unprecedentedly early dates in 2015 due to the lack of water. Their basins now serve off-highway vehicle recreationist with myriad of trails, and fertile areas for NIS invasions for which there is relatively little native-plant community to defend against such an attack. *Carduus nutans* and *Centaurea stoebe* have been observed in these lake basins, in areas which were underwater two years ago.

While the results of this correlative analysis certainly show increasing temperatures, decreased precipitation, and reductions in snowfall, alone and collectively, significantly correlate with increased observations of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* in Nevada County, and the greater northern Sierra Nevada bioregion, these climatic alterations cannot be solely indicted as the culprit(s) of NIS invasions. There are other considerable environmental and socioeconomic aspects which play an intricate role in the transport and spread of NIS.

The ecological and economic impacts of these NIS range expansions have yet to be fully realized. Similarly, a cohesive scientific understanding of the pathways and factors that work in concert with these exceptional drought conditions to increase the invasibility of the northern Sierra Nevada region is in an infantile state. These drought-NIS relationships are complex, as plants often respond unpredictably to numerous environmental components (Bradley et al., 2009). Changing climatic conditions are just one, and perhaps the most unpredictable and uncontrollable, of the growing list of pathways and factors which induce opportunistic conditions for invasive explosions, leading to the increased invasability of ecosystem regions. Understanding the relationships between NIS and environmental changes that may influence the risk of invasion is crucial for implementing effective NIS management programs and policies (Bradley et al., 2009). Drought conditions in northern Sierra Nevada are providing NIS with a competitive edge over native species (Caziarc, 2012). Nonetheless, these results serve to improve our current knowledge of the relationships between *Carduus nutans*, *Centaurea stoebe*, *Chondrilla juncea*, and drought conditions in northern Sierra Nevada.

Citizen-science models

The increase in observations on CalFlora's website during more recent years, namely 2009 – 2014, is likely attributed to an increase in the number of users and increased knowledge and ability of the CalFlora-user interface. Technological advance in CalFlora's usability in recent years, such as intuitive and user-friendly web pages and phone apps, has improved CalFlora users' ability to upload and share observational plant data. Additionally, knowledge and awareness of the potential impacts of NIS has undoubtedly expanded from scientist and stakeholders to a growing interest by the general public who wish to contribute to building information resources, biodiversity conservation, and education. Nonetheless, contributions from an increasing number of CalFlora users improved this correlation analysis by providing congruent and data-rich observations of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*.

Citizen-science models used to detect and report invasive weed species like CalFlora are becoming ever more popular in the 21st century and are providing particularly useful data for researchers, scientists, and land managers alike (Gallo & Waitt, 2011). These citizen-scientists contributions made freely and readily available online allow for the effective collections of significant amounts of specific long-term plant data across vast regions, from New England (Invasive Plant Atlas of New England – IPANE) to the MidSouth (Invasive Plant Atlas of the MidSouth – IPAMS) and Texas (Invaders of Texas), and are helping to detect introductions and dispersals of NIS throughout local areas (Gallo & Waitt, 2011). Between 2005 and 2009, Invaders of Texas citizen-scientists submitted over 9000 species observations across the great state, and Gallo and Waitt (2009) found those observations helped reveal significantly increased distribution of *Arundo donax* (giant reed), when compared to previously recorded data.

The scope and scale of the battlefield is incredibly vast and expanding exponentially as native flora and wildlife habitats are continually lost to NIS. Traditional scientists and researchers generally cannot, without the contributions of collaborations of concerned citizens and other agencies conducting reconnaissance operations, effectively nor efficiently conduct meaningful target acquisition of the enemy, NIS. As more people engage in collecting observations of invasive species data, and have access to forums which share and distribute that data (i.e. CalFlora, Invaders of Texas, IPAMS, IPANE, etc.), the entire knowledge base about NIS grows. This growth of general and scientific knowledge allows researchers to conduct more meaningful data-rich studies. And resource managers are afforded the opportunity to more effectively implement NIS management strategies.

Invasive-Plant Management

An effective NIS management plan is essential for the protection of vital ecological and economic systems against the negative impacts of NIS attacks. Without any form of NIS management, native ecosystems, wildlands, forests and grasslands, as well as agricultural, pastoral, and rangeland are entirely vulnerable to NIS invasions, which can undoubtedly have crippling and irreversible effects. The results of this correlative analysis provide important data for governmental, non-governmental land-managers, and other stakeholders to consider when deciding to implement NIS management strategies.

Guiding principles

In 2002, the Convention on Biological Diversity set forth guiding principles for NIS management which includes a three-stage hierarchical strategy; prevention of introduction, early-detection and rapid response for eradication, and long-term containment. This hierarchical strategy is widely accepted as the most adequate and comprehensive management plan to combat NIS which threaten ecosystems, habitats, or other species.

Prevention

Blockading NIS and preventing initial encroachment of NIS into foreign plant communities is certainly the most effective tactic to combat invasions, avert their negative impacts on ecosystems, and preserve ecological resiliency. This entails the daunting task of preventing the anthropogenic movement of invasive plant species, namely via trade and transport. While optimal, thwarting entry of non-native invaders and ultimately inhibiting their establishment is largely economically and technologically impractical for most ecoregions (Working Group on Invasive Species and Climate Change, 2014). Prevention includes stopping all introductions of NIS, including agricultural or nursery contamination, timber harvest, or vehicle and machinery hitchhikers, to name a few. Prevention is different than eradication and control measures, or restoration efforts, in that it is anticipatory and proactive. While more cost-effective and environmentally desirable than reactive secondary measures, prevention requires dedication and continued monitoring which can pose challenges depending on specific conservation goals and available resources. Nonetheless prevention is the most effective tool for land managers and decision-makers.

Eradication

Following the commonly accepted hierarchy of NIS management, the second line of defense, where prevention either failed or was never attempted and when an invasive species is established and an attack is underway, is early detection and eradication which can significantly mitigate detrimental ecological or economic impacts (Wittenberg and Cock, 2001). Early detection is the catalyst which often leads to successful eradication of NIS due to the competitive nature and efficient reproductive capabilities of invaders (Working Group on Invasive Species and Climate Change, 2014). Increasing knowledge of the interactions of NIS with regional climate conditions should assist in addressing early detection and rapid response efforts to proactively defend previously uninvaded ecosystems.

Control

When an invasive species has become well-established beyond the point of feasible eradication, then control becomes the fallback option. Control of NIS usually insinuates a longer-term engagement of the enemy to limit its spread or protect priority resources, which obviously entails greater management overhead costs (Working Group on Invasive Species and Climate Change, 2014). Long-term strategies to control generally include biological treatment (e.g. host-specific parasites), chemical treatment (e.g. herbicides), cultural methods (e.g. grazing, crop rotation, water management, etc.) and/or mechanical treatment (e.g. manual removal, prescribed fire, mow, etc.).

Regional management

The results of this research which show strong correlations between *Carduus nutans*, *Centaurea stoebe*, *Chondrilla juncea* and drought conditions in northern Sierra Nevada provide an impetus for addressing regional NIS management strategies with an emphasis on local climate conditions.

Weed Management Areas (WMA)

Currently, within the state of California, NIS management is predominately organized and carried out through county Agricultural Commissioners' offices. County Commissioners work cooperatively with local stakeholder groups, including private partners, local state, and federal agencies, as well as non-profit organizations, collectively known as Weed Management Areas (WMA). The WMA program was created in California in 1999 (Cal IPC, 2015). These WMA develop individual strategic plans designed to combat regionally identified priority NIS. There are 48 WMA covering all 58 counties in California, whose contracts are administered by CDFA. Weed Management Area strategies have proven particularly effective. California's WMA have contributed to the treatment of 128 421 acres of NIS infested lands, the permanent eradication of 2015 NIS infestation sites, and strengthened partnerships between various agriculturalists, conservationists, landowners, and governmental agencies (Cal IPC, 2015).

Nevada/Placer WMA

The Nevada County works within the Nevada/Placer WMA, though each county's Agricultural Commissioner allocates resources for their particular county to aid the cooperative NIS management effort. Nevada County's NIS management program is seasonal, running from late spring through fall. Generally following the guiding principles of the hierarchical structure of prevention (where feasible), eradication, and control, the Nevada County NIS program is designed to survey, identify, and eradicate priority NIS like *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea*.

Nevada/Placer WMA works in concert with federal and state agencies, non-profit citizen groups, and private landowners to accomplish these goals and protect vital natural resources within the two counties. For example, a large portion of Tahoe National Forest is found within Nevada/Placer WMA, thus the counties NIS programs work with the U.S. Forest Service to protect this national forest from NIS invasions. The same is true for state-owned resources such as protected wildlife management areas and state parks, where the Nevada/Placer WMA NIS program works side-by-side with CDFA and the California Department of Fish and Game to prevent NIS expansions into or spread within these areas. Similarly, the Nevada/Placer WMA NIS program provides support for weed management efforts spearheaded by local non-profit organizations such as the Truckee River Watershed Council, which serve to protect the locally prominent and important watershed. Finally, the Nevada/Placer WMA NIS program engages local private landowners, agricultural businesses such as vineyards and small acreage farms, individuals utilizing rangelands to raise livestock, or residential homeowners, to help prevent, eradicate, and/or control NIS invasions and mitigate their negative ecological and economic impact throughout the county, the WMA, and northern Sierra Nevada.

Recommendations

Non-native invasive weed species are aggressive opportunistic plants which have overcome great geographical barriers, via anthropogenic and natural pathways, to establish themselves and invade environments far away from their native ranges, often where no natural enemies exist to help contain their spread. The range expansions of *Carduus nutans*, *Centaurea stoebe*, and *Chondrilla juncea* into northern Sierra Nevada, and their explosions during opportunistic climate changes in the region of late, serve as prime examples of the advantageous virility with which these, and similar NIS, outcompete native plant communities for available resources like, light, nutrients, and water. These NIS commonly have detrimental ecological and economic effects on invaded ecosystems by decreasing agricultural crop and pasture yields, reducing forage and habitat for various wildlife species, displacing native plant communities, and overall diminishing biodiversity. Invasions of NIS also alter the general aesthetics of a region and inhibit recreation potential for private and public lands and waterways.

The increasing presence of NIS throughout northern Sierra Nevada, their destruction of natural ecosystem structure and function there, and in numerous environments and plant communities worldwide, requires action to mitigate further devastation. The question, then, is not if these NIS should be managed, but how can they most efficiently and effectively be managed. The answer however, is best answered regionally, and must consider physiological plant-community properties and their specific soil nutrient uptake mechanisms, local pathways and factors of NIS invasions including regional climatic changes and local soil disturbances (natural and anthropogenic), and the relative interactions of these environmental causes with specific NIS which may further facilitate invasions and increase an ecosystem's invasibility.

NIS management

Given the results of this correlative analysis which shows significant covariance of *Carduus nutans*, *Centaurea stoebe*, *Chondrilla juncea* and drought conditions in northern Sierra Nevada, it is pertinent that local governmental and non-governmental NIS management strategies consider the effects regional climatic changes, particularly recent drought trends, have on the ability of NIS to expand their ranges into previously uncharted lands.

One simple change regional NIS management programs might entertain, in light of this knowledge of the relationship between perpetually increasing temperatures and decreasing precipitation rates and NIS throughout northern Sierra Nevada, is the idea of beginning survey, identification, and eradication efforts earlier in the season to (1) ascertain the extent of range expansion of NIS, particularly those deemed high-priority which are known to be noxious and economically and ecologically detrimental and that have the greatest reasonable chance of full eradication, and (2) take a more proactive stance against these NIS, that is prevent growth earlier in the growing season in an attempt to stunt flowering, and ultimately seeding. The latter could likely be achieved for most NIS by applying plant-specific pre-emergent herbicides at known NIS sites, when plants are in immature stages of growth. Seasonally warmer temperatures where last frost dates are earlier in the season, and less snowpack exist in higher elevations, like those trends seen in recent years throughout northern Sierra Nevada, indicate NIS growth will follow suit and begin life stages sooner than years of cooler seasons with greater snowfall. Beginning life cycles sooner allow NIS to grow more advantageously and vigorously, outcompeting native plant species and to flower and produce more seed earlier. Likewise, when warmer temperatures extend beyond traditional first-frost dates the use of selective and targeted post-emergent herbicide throughout full leafing and flowering stages as late as possible into specific NIS growth stages should benefit NIS containment.

Prescribed burning has shown to be an effective means of reducing range expansions of some NIS. Where possible, and for species which have proven to respond affirmatively, prescribed burning should be implemented following pre-emergent herbicide application – in a spray, burn, spray cycle; a three-step process to be completed once in a growing season. Further, as part of a more comprehensive NIS management plan, the inclusion of native-seeding tactics designed to restore native-plant communities and establish more competitive ecosystems which are able to efficiently combat NIS invasions. Native-plant seeding would increase sheer native plant numbers and diversity of native species, and provide increased forage and habitat for numerous wildlife species. Monetary and human resource costs are commonly cited as reasons for WMA exclusion of native-seeding tactics, though the long-term investment should be considered when possible.

The task of NIS management is daunting for individual WMA or county agencies. Continued and further growth of cooperative management strategies with state and federal agencies, non-profit organizations, and private landowners to combat NIS invasions for longer durations during the year will create a significant impact on the effectiveness of NIS management by the sheer number of individuals engaging the enemy and allowing for more ground to be covered quicker. At all levels of interagency action, but perhaps most importantly in engagements with private individuals, continued education of specific NIS and best management practices for their regional eradication will foster a more knowledgeable and stronger force to engage NIS. This may include educating agricultural producers and private landowners on the benefits of introducing cultural methods of NIS management, like rotational grazing and field fallowing. Education, of course, requires constant review of recent research and academic literature pertaining to regionally specific NIS, but it also may be as simple as furthering the promotion of participation in citizen-science models, like that of CalFlora, Invaders of Texas, IPAMS, IPANE, and similar educational forums designed to help detect, identify, and precisely map NIS infestations and invasions. These citizen-science contributions are invaluable to researchers and land managers alike.

Future research

The growing general concern and scientific understanding of the ecological and economic impacts of NIS has fostered a landscape of increasingly valuable data and research for implementing practical NIS management strategies. There are some gaps however, which have left some questions about the physiological mechanisms of particular NIS, their interactions with local ecosystems and native plant-communities, and the relationships of NIS with abiotic and biotic factors which facilitate increased susceptibility of differing and specific ecoregions to NIS invasion. Future research should delve into further addressing some of these issues in a manner which allows for broader understandings of these environmental interactions of physiological mechanisms and processes.

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