Role of Soil Disturbances in Determining Post-Harvest Plant Biodiversity and Invasive Weed Distributions

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Abstract - Harvesting for conventional forestry products, bioenergy, or fuels reduction creates varying levels of soil disturbance depending upon the felling and extraction systems used. Site preparation before replanting imposes additional soil disturbances depending on the mix of mechanical, chemical, and fire techniques used These inter-rotation disturbances usually affect subsequent plant diversity in different ways. Although the common assumption is that these impacts are negative, they can be highly positive depending on the type and level of disturbance. The level and direction of impact (negative or positive) of management-related disturbances depend on a number of factors including the severity of the disturbance. One new aspect of environmental concern regarding plant diversity is the potential for harvesting and site preparation soil disturbance to accelerate invasions by noxious weeds. This paper examines how soil disturbances due to harvesting, mechanical site preparation, prescribed fire, and chemical additions as fertilizers or herbicides affect post-harvest plant diversity and noxious weed invasions.

biodiversity / soil disturbance / site preparation / harvesting / invasive weeds

1. INTRODUCTION

Harvesting for conventional forestry products, bioenergy, or fuels reduction creates varying levels of soil disturbance depending upon the felling and extraction systems used. Site preparation before replanting imposes additional soil disturbances depending on the mix of mechanical, chemical, and fire techniques used [25]. These inter-rotation disturbances usually affect subsequent plant diversity in different ways. Although the common assumption is that these diversity impacts are negative, they can be highly positive depending on the type and level of disturbance. In many forest ecosystems, plant diversity increases after disturbance and then declines as one principal component of plant diversity, trees, eventually dominates the site. A new aspect of environmental concern regarding plant diversity is the potential for harvesting and site preparation soil disturbance to accelerate invasions by noxious weeds. Successful establishment of some nonnative plants have the potential to alter the quality of site plant diversity or reduce it significantly.

1.1 Soil Disturbance

Most natural and anthropogenic disturbances produce impacts on forest soils. The level and direction of impacts (negative or positive) from management-related disturbances depend on: (1) the goals and objectives for land management, (2) ecosystem resistance and resilience, (4) disturbance frequency, and (4) the severity of the disturbance. Both frequency and severity are important concepts to consider since they can occur along a spectrum that may or may not involve the same site and the same time period.

Forest harvesting and its associated reforestation activities produce varying types, amounts, and degrees of impact to the soil. Physical soil disturbance produced by harvesting machinery or mechanical site preparation can result in erosion, compaction, plant seedbed preparation, nutrient redistribution, changes in soil moisture, and alteration of biological activity [25]. Chemical soil disturbance from fertilizer additions or herbicide use results in nutrient additions, altered biological activity, and the exclusion of some plant species. Fire produces thermal disturbances that have the potential to combust much of the soil organic matter, produce both nutrient mineralization and depletion, breakdown soil structure, alter biological activity, and alter soil hydrology [6], [33]. Biological disturbances not directly related to harvesting activities include activities such as grazing, animal burrowing, road and trail maintenance, and infrastructure development such as building, pipeline, and powerline construction.

Site preparation disturbances can have variable effects on the forest floor that override those of harvesting [25]. Although logging and mechanical site preparation produce easily visible physical effects, their chemical and biological impacts are more subtle and longer lasting. The same is true of prescribed fire [6]. Even prescribed fires contain a spectrum of low-, medium-, and high-severity soil impacts. Nutrient depletion or availability reduction on a site can then lead to reduced growth by native plants, and colonization opportunities for aggressive invasive weeds [24].

1.2 Invasive Weed Colonization Strategies

Nonnative plants employ a number of strategies to establish a presence on new sites. These include plant height, wind pollination, adaptability to high and low moisture and nutrient sites, and life histories that key into disturbance [31]. Some nonnative weeds are perfectly adept at invading sites in the absence of soil disturbance. *Lonicera tatarica* in the United States [43] and *Hieracium lepidulum* in

New Zealand [41] are good examples of such invasions. Usually invasive plants are given opportunities to invade a new site by the presence of soil disturbance, a change in the frequency of disturbance, or an increase in the severity of disturbance [14]. Other opportunities are provided by soil erosion, soil compaction, habitat structure alteration, human distribution of plant propagules (vehicles, tools, soil hauling, etc.), fire exclusion, and high severity wildfire [26], [32]. The latter three are becoming more noticeable as the frequency, area, and severity of wildfires builds in western North America [26].

1.3 Sustainability

A number of international meetings and conferences have been held to developed management guidelines and criteria to ensure conservation and sustainable management of forests in Europe and North America [13], [23]. The Santiago Declaration, signed at the 2nd Summit of the Americas in 1998, reaffirmed the criteria and indicators for sustainability formulated at the Helsinki Conference and in the Montreal Process.

Sustainability is the stewardship goal of nearly every forester, but its definition and attributes are complex [22]. Allen and Hoekstra [1] discussed the concept of sustainability and the difficulty in defining it. They clearly pointed out that there is no absolute definition of sustainability. It must be viewed within the context of human conceptual frameworks and societal decisions on the type of ecosystem to be sustained, and the spatial and temporal scales over which attainment of sustainability is to be judged. Forest sustainability is also defined in terms of society's needs, the professional frame of reference of foresters, and the ecological models that are used to predict future conditions for natural resources. However, our ability to predict future ecosystem conditions is often assailed by the uncertainties of increasing encounters with extreme events, poorly understood ecological processes and linkages, surprises by the law of unintended consequences, the development of critical thresholds, and chaotic system behavior.

Another approach to the definition of sustainability is to define the conditions that warn of or mark ecosystem deterioration into unsustainability [22]. Although the goals of the Montreal Process and Santiago Declaration are to ensure management of forest lands for sustainability, the Criteria and Indicators are in essence warning flags to obtain the attention of land managers before ecosystems decline into unsustainability.

A key component of the forest sustainability issue is biological diversity. [16]. It is the first criterion addressed by the Montreal Process. The concern over biodiversity is due to the currently high rate of loss of undisturbed native forests and the extinction of species in these forests, and the intensification of management of secondary forests. Man-managed forests have become extremely important to forest biodiversity since they make up a large percentage of the globe's forests. Although the greatest threat to forest biodiversity results from permanent conversion of forest lands to agriculture, urban areas, transportation corridors, water reservoirs, or wastelands, forest management and harvesting also have the potential to change biodiversity. These changes need to be carefully considered. Forest management activities that produce disturbances must be examined within the context of what society deems necessary to maintain forest health and ecosystem integrity. This is not an easy task since, like sustainability, the definitions and attributes of biodiversity are complex and open to considerable interpretation [39], [22].

1.4 Plant Diversity Concerns

Biodiversity in forests is very complex and involves tremendous numbers and types of plant, animal, and micro-biotic species. In order to focus the objectives of this paper, only plant diversity is considered in this analysis. Plant diversity can be measured in terms of organism genetics, species numbers, biomass, and community structure and function. It can also be evaluated at different landscape scales (alpha, beta, and gamma diversity) and in terms of changes over time. As Kimmins [16] clearly pointed out, no clear scientific relationships between biodiversity and ecosystem health, integrity, productivity, and stability have been identified. The Santiago Declaration of 1998 also makes a strong point that no single criterion or indicator stands alone as an indication of sustainability.

It is generally accepted that natural disturbance regimes are necessary to maintain native plant species diversity [42], [14]. Forest management activities such as harvesting have variable effects on plant biodiversity [36], [7], [30]. Decreases in native plant species diversity are generally linked to increases and decreases in disturbance frequency and intensity, specific ecosystem responses, and changes in the type of disturbance, not necessarily the mechanism of disturbance (Figure 1) [5], [14].

Forests are naturally dynamic ecosystems, whose system states ebb and flow in response to physical, chemical, and biological disturbances (Figure 2) [15]. Ecosystems with some measure of resiliency recover to their natural, dynamic state after disturbances providing that the severity and frequency of those disturbances are not high. The concern about forest harvesting and site preparation is that the frequency and severity of disturbance could result in a loss of ecosystem integrity, and push system states, such as plant diversity, permanently into a stable, but disturbed and lower level state.

An example of a resilient forest ecosystem with a rapid recovery is shown in Figure 3 [36], [37]. A *Pinus elliottii* ecosystem in north Florida was clearcut, burned, and prepared for planting with mechanical site preparation. Plant diversity increased in the first four years but then declined to pre-harvesting levels in just over a decade as the second rotation pine stand dominated the site. An example of a decline into a stable, but disturbed lower state is shown in Figure 4. A series of mechanical site preparation disturbances of increasing intensity in the uplands of south Texas permanently shifted the plant community from a species-rich shrub community to a species-poor community dominated by acacias (*Acacia* spp.) and mesquite (*Prosopis* spp.) [9]. Roller chopping and cabling, although intensive site preparation techniques, were not of sufficient severity to push the shrub community into a stable, but lower diversity ecological state.

Forest harvesting and vegetation management are controversial parts of the biodiversity debate because of their potential to change the frequency, intensity, and type of soil disturbance. A new factor in the plant diversity debate is invasive exotic plant species [39]. In the past, exotic species that invaded forests after harvesting were thought to be only reforestation and stand management headaches. With the general acceptance of the Montreal Process criteria as international standards for certification of sustainable forest management [16], the issue of the impact of invasive, exotic weeds on native plant diversity needs to be examined.

There is growing evidence that, in some forest ecosystems, non-native weeds invasions pose a far greater threat to plant diversity than the physical effects of harvesting or site preparation alone or in combination with other vegetation management techniques [38], [40]. In addition, non-native weed exploitation of recent wildfire sites is being recognized as a developing vegetation management problem [12]. Vegetation management techniques for controlling post-harvest and post-wildfire "weed" species may need reexamination in light of the spread of non-native plant species.

This paper examines how soil disturbances related to vegetation management affect post-harvest plant diversity and noxious weed invasions. The special focus of this paper is on the role of fire, both prescribed and wildfire, in affecting the outcome of plant diversity in managed forests. This is not an attempt to link vegetation management-related plant diversity changes with ecosystem integrity, health, or stability, only to examine trends.

2. METHODS

This paper is a review and synthesis of information on soil disturbance after vegetation management and plant diversity. Although different vegetation management techniques (mechanical, fire, and chemical) are discussed, the main emphasis is on fire impacts. Several vegetation management case studies in the Southwest are examined.

Local information was derived from two studies in Arizona on pinyon-juniper (*Pinus edulis* and *Juniperus* spp.) and ponderosa pine (*P. ponderosa*) sites near Flagstaff, Arizona. These represent forests with different productivities, management potentials, and vegetation management approaches.

2.1 Ponderosa Pine

At the ponderosa pine sites in the vicinity of Flagstaff, Arizona, , measurements were taken in 16 pine stands on soils of volcanic parent materials (derived from basalt flows, ash falls, and cinder deposits) with progressively greater degrees of soils disturbance [9], [27]. The treatments and disturbances were: Control - four untreated pine stands with no tree harvesting in past 30 years; Thin Only - four thinned stands, >30% of pine basal area removed between 1987 and 1993; Thin and Burn - four stands thinned as above and broadcast burned within 3-4 years of thinning; and Wildfire - four stands burned by a wildfire in 1996 with >90% of tree basal area killed. The residual impact upon soils, measured in 2000 in a total of 64 plots as percentages of exposed bare soil, reduced litter cover, and vegetation basal area. The data were analyzed by the Kruskal-Wallis 1-way ANOVA test ($p<0.05$. Understory diversity in the above stands was measured in 1999 as both species richness (number of understory plant taxa per plot, including both native and non-native taxa), and evenness (a Braun-Blanquet abundance class was assigned to each understory plant taxon in the plot and summed over all taxa in each plot to yield a plot score).

At the pinyon-juniper site near Heber, Arizona, , a 10 ha opening was created in a pinyon-juniper stand during a fuelwood harvest [2]. The residual slash was lopped and scattered, and left to dry for two years before burning in the spring of 1991. Locations where slash was piled 2-3 m high had the greatest burn severity. Areas between the piles burned at a low severity of not at all. Vegetation reestablishment was measured periodically after the prescribed fire.

3. RESULTS AND DISCUSSION

3.1 Plant Diversity Impacts – Harvesting and Site Preparation

A number of investigators have closely examined the effects of forest harvesting and associated site preparation practices on plant diversity. Most of these studies addressed the effects of harvesting on total plant diversity, not the quality of that diversity. A summary of the results reported by Neary et al. [27] are presented here.

Harvesting Operations and Mechanical Site Preparation

The majority of the research studies dealing mostly with harvesting impacts reported no change or an increase in plant diversity [27] (Figure 5). Of six studies reviewed for this paper that dealt only with harvesting impacts, none reported a long-term decrease in plant diversity, one documented an increase in plant diversity, three measured no changes, and two had mixed results. Halpern and Spies [11] reported a decrease in species richness one year after a Douglas-fir harvesting operation. By 12 and 24 years after harvest, total plant species richness had increased from the pre-harvest condition. However, their study included prescribed fire.

Very few studies have examined mechanical site preparation in the absence of harvesting. Of five papers reviewed by Neary et al. [27] that studied only mechanical site preparation treatment impacts, none reported a long-term decrease in plant diversity, three documented an increase in plant diversity [36], [18], [29], one measured no changes, and one had mixed results. (Figure 5). For the most part, mechanical site preparation has no effect or increases plant diversity. In situations where plant diversity declined the first year after harvesting and site preparation, it either increased or exhibited no change from pre-disturbance conditions over the long-term [36], [37], [20]. A study by Locasio et al. [18] clearly demonstrated the effect of site preparation severity on plant diversity. The most intensive treatment (shear, rake, disk, and fire) was the only one that resulted in a plant diversity decline. The most intensive treatment in the study reported by Swindel et al. [36], [37], and Lewis et al. [17] documented a diversity reduction (plant cover) in the 1st year, but by the 3rd year plant diversity was increased. However after six years, plant diversity indices were trending back towards that of the pre-harvesting and site preparation as a single species (slash pine) began to dominate the site again.

Prescribed Fire

Fire is a useful tool for increasing herbaceous plant diversity at the expense of woody species that are not fire adapted or eliminating some nonnative invasive species [35]. Schimmel and Granstrom [34] demonstrated the effect of high fire severity on reducing plant diversity. Of the plant diversity studies reviewed by Neary et al. [27], almost as many studies reported increases or no effect as mixed results. None of the studies reported only decreases in plant diversity.

Herbicides

Herbicides rarely increase plant diversity in the short-term. Brooks et al. [3] measured short-term increases in herbaceous plant diversity due to a reduction in competing woody species from the use of four different herbicides. Although plant diversity is often reduced in the short-term (1-5 years; [44], it usually recovers in the long-term (>7 years; [21].

3.1 Ponderosa Pine and Fire - Plant Diversity Impacts

Although harvesting and reforestation activities in ponderosa pine forests in the Southwest have historically been low in frequency and intensity relative to other forests in the country, this situation is likely to change in the near future. The need to reduce fuel build-ups in a short time frame will certainly increase the levels of harvesting and extent of soil disturbance to those not seen since the early 20th century [26]. The current experience in ponderosa pine stands in northern Arizona being treated to reduce fuels or subjected to catastrophic wildfire, indicates that harvesting-related soil disturbances invite the establishment of early seral, invasive weeds, and particularly non-native (exotic) weedy species. Harvesting is not the only activity implicated in the invasive weed spread. Wildfires in unthinned stands are also involved in the landscape-level weed invasion. The establishment of these non-native invasive species may pose a far greater risk to plant diversity than harvesting operations.

Exotic plant abundance has not been significantly increased by thinning operations in the ponderosa pine stands of northern Arizona [9], [27] (Figure 6). There was little difference in the amount of bare soil between the untreated, thinned, and thinned and burned plots (8.6 to 9.9 % bare soil). Harvest-related soil impacts such as soil compaction or erosion were not measured, but in any case weedy exotic plants apparently responded similarly to the different stand conditions [9]. The addition of prescribed fire significantly increased the abundance of invasive weeds (Figure 6).

The sites burned by a wildfire in 1996 had the greatest residual impact of invasive plants due to reduced litter cover and much exposed soil (36 %). Plots measured in 2000 from the 1996 wildfire were outside of salvage logging areas and hence had no soil impacts from recent mechanized equipment (although prior to the fire many stands were subject to commercial and non-commercial tree thinning).

Major exotic species found in the post-treatment stands included *Chenopodium album, Salsola australis, Teloxys graveolens, Laennectia schiedeana, Conyza canadensis, Verbascum thapsus, Linaria dalmatica, Pseudognaphalium viscosum* and the grasses, *Bromus tectorum, Poa pratensis, Hordeum leporinum,* and *Bromopsis inermis*. Some of the latter were actually introduced as part of the seed mix in post-disturbance re-seeding efforts. Most of these species are invasive. They have prolific seed or vegetative reproduction, high dispersal capability, and rapidly establish on recent soil disturbances. For many of these species, seeds are abundant and have long viability in the soil. Characteristically, these species form virtual monocultures soon after soil disturbances and ensuing years.

The addition of these exotic species to the understory flora after soil disturbances by recent tree harvests, prescribed fires, and moderate to high severity wildfires changed he patterns of floristic biodiversity. The results were detailed by Griffis et al. [9]. The number of understory plant taxa were not affected by any of the disturbances. Plots without tree harvests in the past 30 year also contained non-native and invasive weedy species, but these were never abundant. The weedy species in these plots probably reflect logging disturbances 30 or more years ago and sustained grazing pressures by wildlife (mainly elk) and domestic cattle.

On the other hand the more severe soil disturbances sharply increase the abundance of weedy and invasive exotic species. The evenness component of diversity [19] increased with tree thinning and prescribed fire and more drastically with stand-replacing wildfire. This highlights the fact that high diversity itself may not be a desired stand condition in ponderosa pine forests, if the content of diversity is an abundance of undesirable weed species.

While many invasive weedy species are palatable to grazing ungulates and may serve in the short term to reduce soil erosion, they also are suspected of increasing fuels continuity and flammability in stands and inhibiting succession by native plants. These possible effects remain to be studied.

3.1 Pinyon-Juniper and Fire - Plant Diversity Impacts

Prescribed fire had a very negative effect on plant diversity at the pinyon-juniper site. Most of the biomass that burned was in slash piles left over from the fuelwood removal. Interval areas did not burn much due to a limitation of woody and herbaceous fuels. The slash pile fires apparently crossed a critical temperature threshold that they burned hot enough to sterilize the soil and kill any residual seeds [6]. Six years after burning most areas where slash piles had burned were still devoid of vegetation (Kruse, personal communication). Other pinyon-juniper areas with the same treatment have been observed to be devoid of vegetation 25 years after burning.

A ring of blue gramma grass (*Bouteloua gracilis*) was found on many plots in a ring around the outer edge of the burned pinyon-juniper slash piles. No other native pioneer grasses or herbaceous species have entered the burned areas at this time. Unlike the ponderosa pine sites, nonnative invasive weeds have also been absent. It is not known if this was due to the lack of a seed source or the high severity of the prescribed fire. While fire is known to enhance the spread of a number of invasive weed species [8], a high frequency of fire can also keep invasives out of sites with thriving, fire-adapted grasses and forbs [35].

Plant diversity on the burned pinyon-juniper sites at Heber has certainly been suffered. By comparison, adjacent areas that were harvested and roller-chopped have responded very well. Fire is known to reduce the shrub and grass component of pinyon-juniper stands while increasing the forb cover [4]. Also, the literature record on the effects of fire on biodiversity is mixed [27]. The critical factor in this situation was probably fire severity [6]. Unless fire severity can be reduced by selecting a time when fire will be less active or by reducing fuel loads, pinyon-juniper sites should not be burned to protect plant diversity.

At another pinyon-juniper site studied by Overby et al. [28], prescribed fire increased the percent cover of perennial grasses, perennial forbs, annuals, and the number of species. Their data indicated that the prescribed fire increased plant diversity (Table I). However, Overby et al. [28] recommended that fire not be used for site preparation due to the high percentage of bare soil and the potential for high loss of total and mineralizable nitrogen on a site that is nitrogen poor. Lopping and scattering or crushing of slash were viewed as less disturbing to potential site productivity. Their conclusions aptly point out that even though plant diversity may be increased on some sites by using fire for site preparation, the loss of critical nutrients during burning and post-fire erosion may offset the ecological advantage gained by burning.

4. SUMMARY AND CONCLUSIONS

A review of literature published mostly in the past decade clearly indicates that soil disturbing activities such as harvesting, mechanical site preparation, and fire do not always directly in themselves produce adverse, long-term changes in plant diversity [27]. In many instances, harvesting increases plant diversity for a period of time since disturbance-dependent native plants thrive in the perturbed soil environment. There is growing evidence that, in some forest ecosystems, noxious weeds invasions after soil disturbance pose a far greater threat to plant diversity than the physical effects of harvesting or site preparation alone or in combination. In some instances fire has increased the abundance of invasive weeds and in others it has had no effect at all. Foresters should be aware of the ecological processes and dynamics of weed species invasion and the species of invasive weeds they need to deal with when planning inter-rotation vegetation management activities.

In ponderosa pine forests in northern Arizona and forests elsewhere, the composition, structure and function of the ecosystem is very sensitive to soil disturbances imposed by various land management treatments, whether they are tree or understory harvests, pesticide applications, fire prescriptions, or manipulations to attain some future stand condition. Ecological "surprises" are hidden and latent in the present stands we manipulate, and these surprises are often triggered by soil disturbances, as our example with pinyon-juniper woodlands suggests. Desired effects of stand and landscape manipulations can be, and more often than not are, offset by less desirable, unforeseen, unwelcome effects such as exotic species weed invasions in either the short- or long-term.

Despite major science advances in the 20th century, we do not understand all the vast complexities of soil physical, chemical, and biological processes. Some of the results of soil disturbances brought about by heavy machinery, soil seed banks dominated by exotic plants, accumulated residues of alien biochemicals, excesses of soil nitrogen fertilization, disruption of soil carbon cycling processes, wildfires, and other human caused effects, can be likened to results of tuning an auto engine with a sledge hammer. The difference, of course, is that evolution proceeds within the unsustainable chaos we leave behind in the forest, whereas the automobile is destroyed. An ignored or forgotten lesson for management is to treat ecosystems with some humility. We should not forge ahead with extensive and intensive forest manipulations until we understand the processes behind the results at finer scales. Otherwise, we may have to deal with the "law of unintended consequences". Major, unforeseen and unwanted results, such as the regionally widespread, overstocked forests in the western United States or widespread nonnative weed plant invasions, are likely to continue to occur.

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REFERENCES

[1] Allen, T.F.H., Hoekstra, T.W. Toward a definition of sustainability. In: Covington, W.W. and DeBano, L.F. (tech. cords.) Sustainable Ecological Systems: Implementing an Ecological Approach to Land Management. USDA Forest Service General Technical Report RM-247 (1994), Pp. 98-107.

[2] Baker, M.B. Jr., Jemison, R.L. Soil loss – key to understanding site productivity. In: Ortega Klett, C.T. (ed.) WRRI Report No. 265, Proceedings of the 36th Annual New Mexico Water Conference, Agencies and Science Working for the Future, New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM, (1992) pp. 71-76.

[3] Brooks, J.J., Johnson, A.S., Miller, KV. Effects of chemical site preparation on wildlife habitat and plant species diversity in the Georgia sandhills. USDA For. Serv., Gen. Tech. Report SO-93. (1993) Pp. 605-612.

[4] Bunting, S.C. Use of prescribed burning in juniper and pinyon woodlands. In: Everett, R.L. (compiler) Proceedings--Pinyon-Juniper Conference, Reno, NV, January 13-16, 1986. USDA For. Serv. Gen. Tech. Rep. INT-215, (1987) Pp. 141-144.

[5] Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs. Science 1999:1302-1310.

[6] DeBano, L.F., Neary, D.G., Ffolliott, P.F. Fire's Effects on Ecosystems. John Wiley and Sons, New York, 1998.

[7] Denslow, J.S. Chapter 17: Disturbance-mediated coexistence of species. Pp. 307-323. In: The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando, FL, 1985.

[8] Grace, J.B., Smith, M.D., Grace, S.L., Collins, S.L., Stohlgren, T.J. Interactions between fire and invasive plants in temperate grasslands of North America. In: Galley, K.E.M., Wilson, T.P. (eds.) Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species, Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11, Tall Timbers Res. Stn., Tallahassee, FL, (2001) Pp. 40-65.

[9] Fulbright, T.E. “Viewpoint”: A theoretical basis for planning woody plant control to maintain species diversity. J. Range Manage. 49 (1996) 554-559.

[10] Griffis, K.L., Crawford, J.A., Wagner, M.R., Moir, W.H. Understory responses to management treatments in northern Arizona ponderosa pine forest. For. Ecol. Manage. (2001)

[11] Halpern, C.B., Spies, T.A. Plant species diversity in natural and managed forests of the pacific northwest. Ecol. Applic. 5(1995):913-934.

[12] Harrod, R.J., Reichard, S. Fire and invasive species within the temperate and boreal coniferous forests of western North America. . In: Galley, K.E.M., Wilson, T.P. (editors) Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species, Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11, Tall Timbers Res. Stn., Tallahassee, FL, (2001) Pp. 95-101.

[13] Helsinki Process. Proceedings of the Ministerial Conferences and Expert Meetings. Liaison Office of the Ministerial Conferences on the Protection of Forests in Europe. FIN-00171, Helsinki, Finland.(1994)

[14] Hobbs, Huenneke, R.J. Disturbance, and invasion: implications for conservation. Conservation Biology 6 (1992):324-337.

[15] Kauffman, J.B., Beschta, R.L., Otting, N., Lytjen, D. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22 (1997):12-24.

[16] Kimmins, R.J. Biodiversity and its relationship to ecosystem health and integrity, The Forestry Chronicle 73 (1996):229-232.

[17] Lewis, C.E., Swindel, B.F., Tanner, G.W. Species diversity and diversity profiles: Concept, measurement, and application to timber and range management. J. Range Manage. 41(1988):466-469.

[18] Locasio, C.G., Lockaby, B.G., Caulfield, J.P., Edwards, M.B., Causey, M.K. Mechanical site preparation effects on understory plant diversity in the Piedmont of the southern U.S.A. New Forests. 4 (1991):261-269.

[19] Magurran, A.E. Ecological Diversity and Its Measurement. Princeton University Press, Princeton, New Jersey, 1988.

[20] Michunas, D.G., Schultz, K.A., Shaw, R.B. Plant community responses to disturbance by mechanized military maneuvers. J. Environ. Qual. 28 (1999):1533-1547.

[21] Miller, J.H., Boyd, R.S., Edwards, M.B. Floristic diversity, stand structure, and composition 11 years after herbicide site preparation. Can. J. For. Res. 29 (1999):1073-1083.

[22] Moir, W.H., Mowrer, H.T. 1995 Unsustainability. For. Ecol. Manage. 73 (1995):239-248.

[23] Montreal Process, Criteria and indicators for the conservation and sustainable management of temperate and boreal forests. Report Fo42-238/199E., Canadian Forest Service. Natural Resources Canada, Hull, Quebec, Canada. (1995)

[24] Morris, L.A., Pritchett, W.L., Swindel, B.F. Displacement of nutrients in windrows during site preparation of a flatfoots forest. Soil Sci. Soc. Amer. J. 47 (1983):591-594.

[25] Neary, D.G.; DeBano, L.F.; Ffolliott, P.F. Fire impacts on forest soils: a comparison to mechanical and chemical site preparation. In: Moser, W.K., Moser, C.F. (eds.) Fire and Forest Ecology: Innovative Silviculture and Vegetation Management. Tall Timbers Ecology Conference Proceedings, No. 21. Tall Timbers Res. Stn., Tallahassee, FL. (2000) Pp. 85-94.

[26] Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffolliott, P.F. Fire effects on belowground sustainability: A review and synthesis. For. Ecol. Manage. 122 (1999):51-71.

[27] Neary, D.G., Moir, W.H., Phillips, B.G. Harvesting-related soil disturbance: Implications for plant biodiversity and invasive weeds. In: Richardson, J., Bjorheden, R., Hakkila, P., Lower, A.T., Smith, C.T. (comps.) Bioenergy From Sustainable Forestry: Principles and Practice. Proceedings of IEA Bioenergy Task 18 Workshop, 16-20 October 2000, Coffs Harbour, New South Wales, Australia, New Zealand Forest Research Institute, Forest Research Bulletin No. 223. (2001) Pp. 17-32.

[28] Overby, S.T., Moir, W.H., Robertson, G.T. Soil and vegetation changes in a Pinyon-Juniper are in Central Arizona after prescribed Fire. USDA For. Serv. Proc. RMRS-13, (2000) Pp. 371-374. .

[29] Peltzer, D.A., Bast, M.L., Wilson, S.D., Gerry, A.K. Plant diversity and tree responses following contrasting disturbances in boreal forest. For. Ecol. Manage. 119 (2000):191-203.

[30] Pimentel, D., Stachow, U., Takacs, D.A., Brubaker, H.W., Dumas, A.R., Meany, J.J., Oneal, J.A., Onsi, D.E., Corzilius, D.B. Conserving biological diversity in agricultural/forestry systems. Bioscience 42 (1992):354-362.

[31] Prach, K., Pylek, P. How do species dominating in succession differ from others? J. Veget. Sci. 10 (1999):383-392.

[32] Reich, P.B., Bakken, P., Carlson, D., Frelich, L.E., Friedman, S.K., Grigal, D.F. Influence of logging, fire, and forest type on biodiversity and productivity in southern boreal forests. Ecology 82 (2001):2731-2748.

[33] Sackett, S.S., Haase, S.M., Harrington, M.G. 1996. Lessons learned from fire use for restoring southwestern ponderosa pine ecosystems. USDA For. Serv. Gen. Tech. Rep. RM-278. (1996) Pp. 54-61.

[34] Schimmel, J.; Granstrom, A. Fire severity and vegetation response in the boreal Swedish forest. Ecology 77 (1996):1436-1450.

[35] Smith, M.D., Knapp, A.K. Exotic species in C4-dominated grassland: Invisibility, disturbance, and community structure. Oecologia 120 (1999): 605-612.

[36] Swindel, B.F., Conde, L.F., Smith, J.E. Plant cover and biomass responses to clear-cutting, site preparation, and planting in *Pinus elliottii* flatwoods. Science 219 (1983):1421-1422.

[37] Swindel, B.F., Conde, L.F., Smith, J.E. Index-free diversity orderings: Concept, measurement, and observed response to clearcutting and site preparation. For. Ecol. Manage. 20 (1987) 195-208.

[38] Vitousek, P.M., Walker, L.R., Whitteaker, L.D., Mueller-Dumbois, D., Matson, P. Biological invasions by Myrica faya alters ecosystem development in Hawaii. Science 238 (1987):802-804.

[39] Westman, W.E. Managing for biodiversity. Bioscience 40 (1990):26-33.

[40] Wilcove, D.S., Rothstein, D.., Dubow, J., Phillips, A., Losos, E. Quantifying threats to imperiled species in the United States. Bioscience 48 (1998):607-615.

[41] Wiser, S.K., Allen, R.B., Clinton, P.W., Plattt, K.H. Community structure and forest invasion by an exotic herb over 23 years. Ecology 79 (1993):2071-2081.

[42] White, P.S., Pickett, S.T.A. Natural disturance and patch dynamics: An introduction. In: Pickett, S.T.A., White, P.S. (eds.) The Ecology of Natural Disturbance and Patch Dynamics, Academic Press, New York , 1985.

[43] Woods, K.D. Effects of invasion by Lonicera tatarica L. on herbs and tree seedlings in four New England forests. Am. Midl. Nat. 130 (1993):62-74.

[44] Zutter, B.R., Zedaker, S.M. 1988. Short-term effects of hexazinone applications on woody species diversity in young loblolly pine (*Pinus taeda*) plantations. For. Ecol. Manage. 24 (1988):183-189.

Figure Legends

Figure 1 Plant diversity levels as a function of disturbance (Adapted from [5] [9])

Figure 2 Changes in the states of ecosystems in response to disturbance (Adapted from [15])

Figure 3 Changes in plant diversity of time in a Pinus elliottii forest after harvesting, prescribed fire, and intensive mechanical site preparation (Adapted from [36] [37])

Figure 4 Alteration in species richness after intensive mechanical site preparation in Texas brushlands (Adpated from [9]).

Figure 5 Literature reports of the effect of harvesting, mechanical site preparation and fire on plant diversity (Adapted from [27]).

Figure 6 Exotic plant abundance in a ponderosa pine ecosystem of northern Arizona after thinning, thinning plus prescribed fire, and wildfire (Adapted from [27]).

Figures

Figure 1

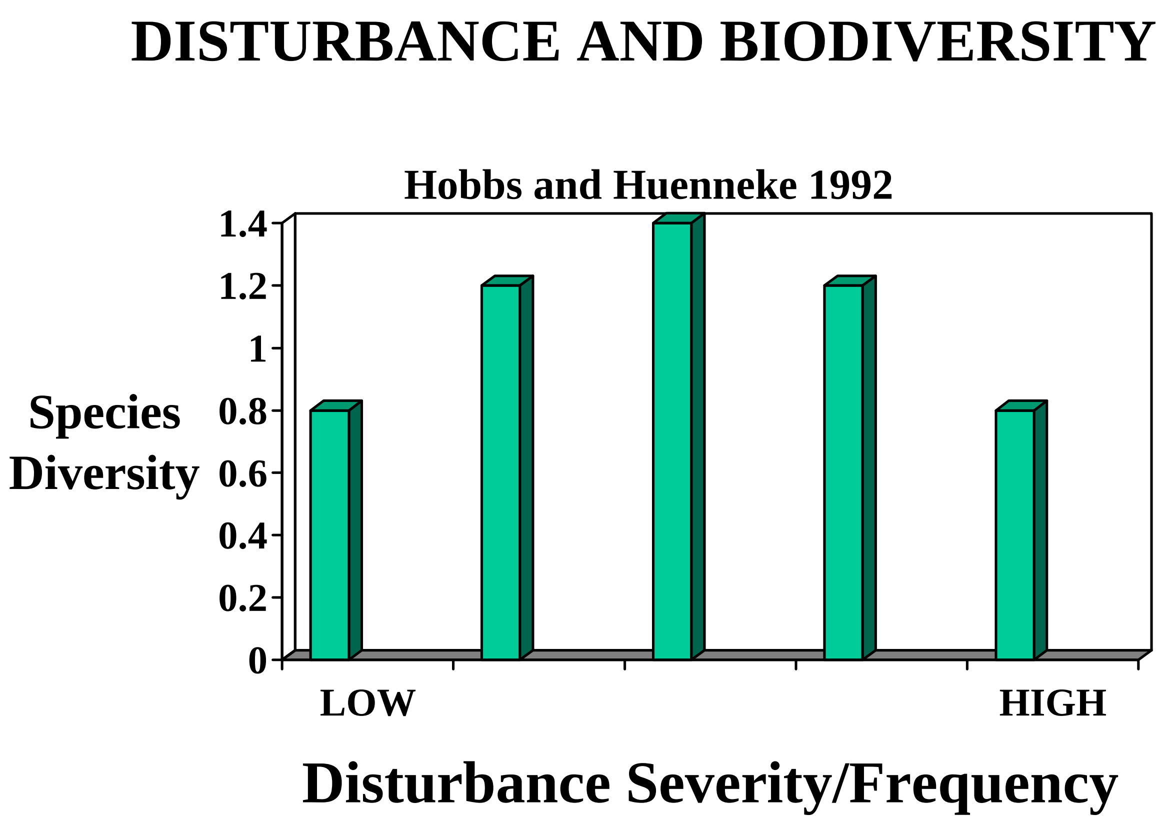

Figure 2

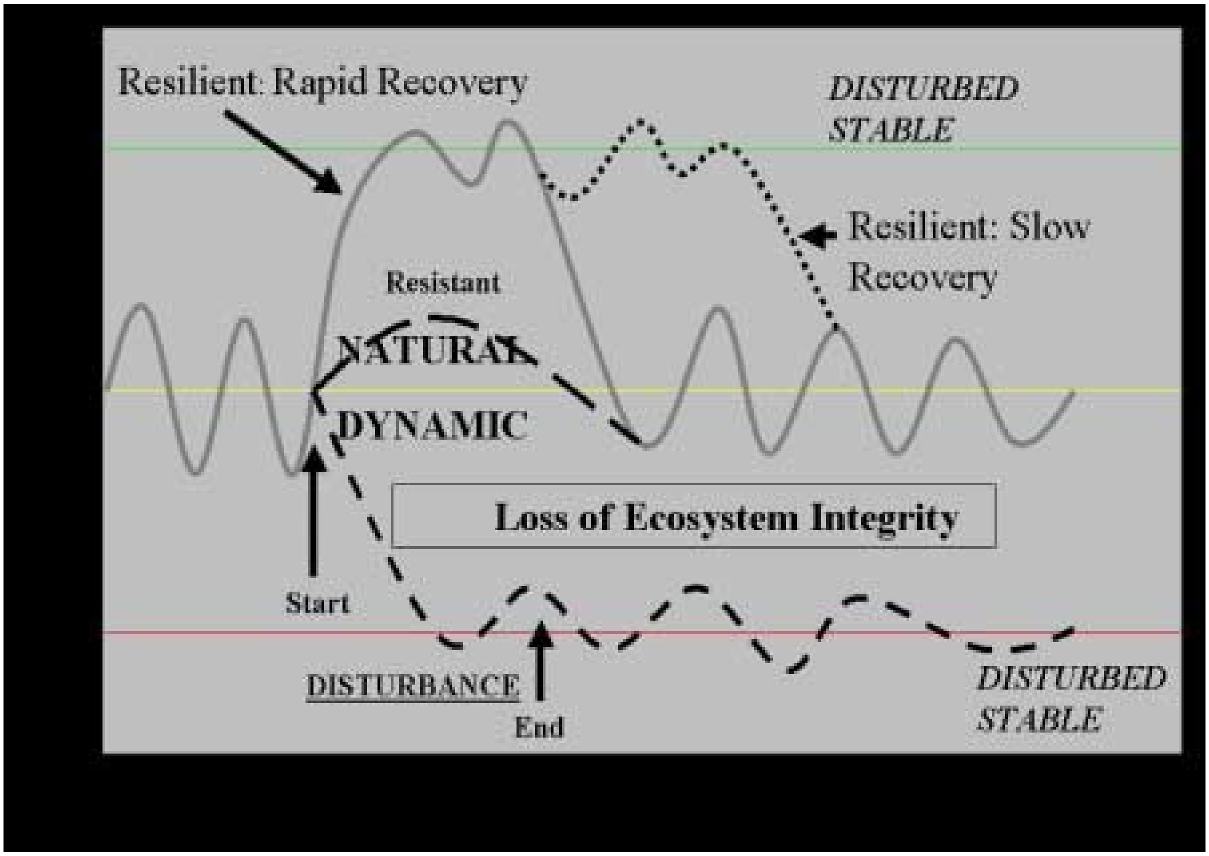

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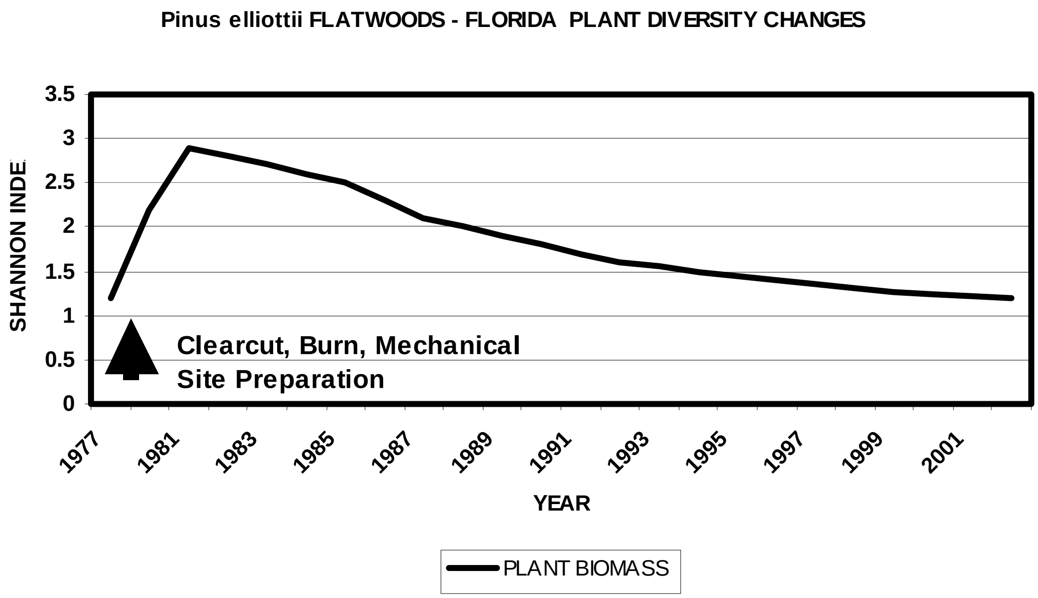
Figure 3



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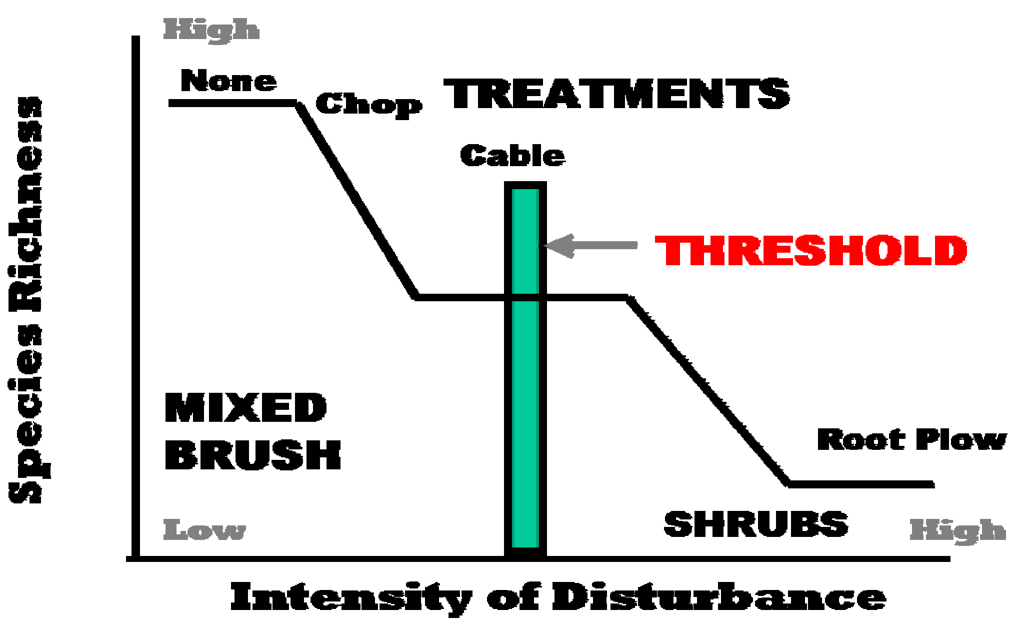


Figure 5

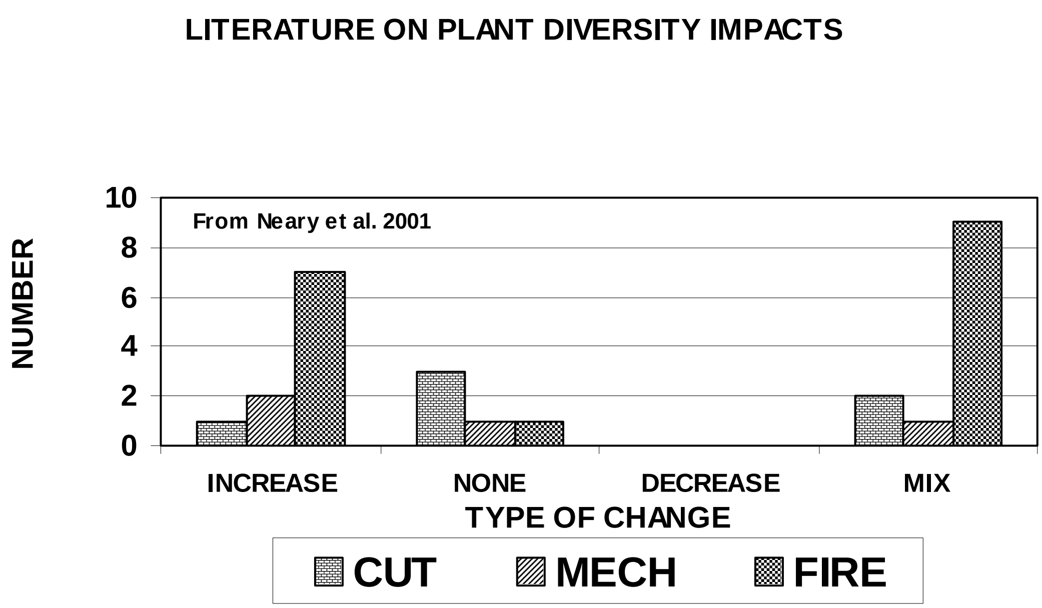
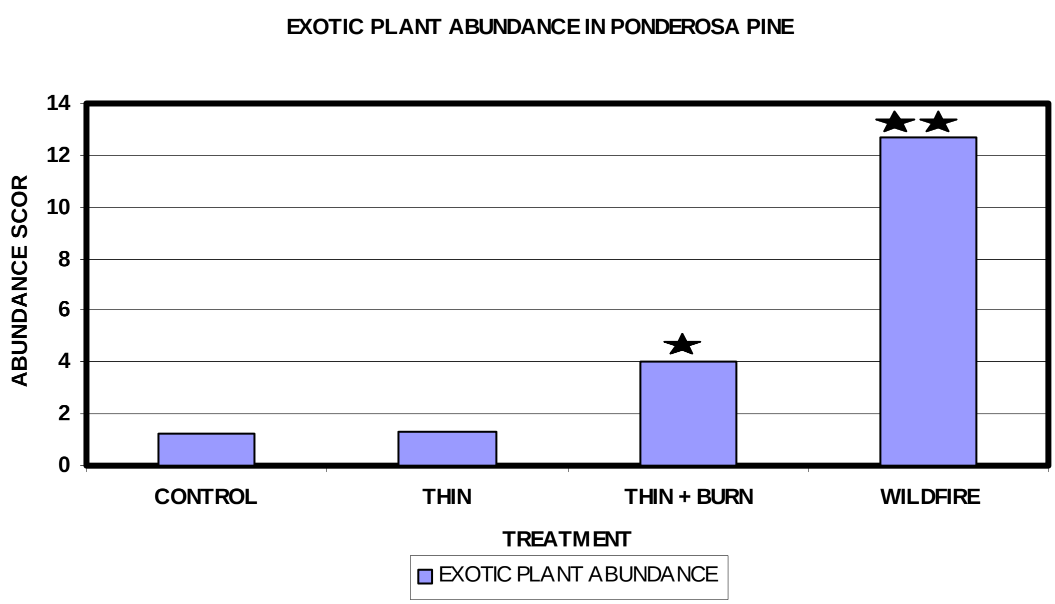


Figure 6



TABLES

Table I. Vegetation and ground cover in 1997, 2 years after a prescribed fire at the Hogg Pasture pinyon-juniper study site, Coconino National Forest, Arizona (Adapted from [28]).

Cover Category	Unburned	Prescribed Fire
Species (Number)	16	24
	……..……………..Percent Cover……………………	
PLANTS		
Perennial Grasses	2.0	6.0
Perennial Forbs	0.03	2.0
Annuals	0.03	12.0
Shrubs	9.0	7.0
Unidentified Herbs	0.05	2.0
GROUND TYPE		
Litter	6.0	10.0
Coarse Woody Debis	1.9	1.4
Rock-Gravel	33.0	38.0
Soil	59.0	49.0