IMPACTS OF SOCIAL TRAILS AROUND OLD-GROWTH REDWOOD TREES IN REDWOOD NATIONAL AND STATE PARKS

By

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A Thesis Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Natural Resources: Environmental and Natural Resource Sciences

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May 2016

ABSTRACT

IMPACTS OF SOCIAL TRAILS AROUND OLD-GROWTH REDWOOD TREES IN REDWOOD NATIONAL AND STATE PARKS

Claudia Voigt

Old-growth coastal redwood stands and the habitat they provide are the conservation target of Redwood National and State Parks (RNSP) in northern California. In recent years there has been greater access to location information about record-sized trees, and visitors have created networks of social trails in redwood groves, including one grove that has no formal access. Coupled with increasing visitor numbers, this has caused an alarming increase in recreational impacts in redwood groves. By providing visitors access to groves, managers accept that there will be ecosystem impacts, but data is needed to evaluate the degree of impact on trees, soil and understory vegetation. I assessed impacts of social trails around old-growth redwood trees in three alluvial flat groves with different use intensities in RNSP. In 2015 I mapped old-growth redwood trees and social trail networks around these trees. I randomly sampled 20 to 30 trees per site and collected baseline data on the spatial extent of disturbance and selected vegetation and soil indicators. Tree size (measured as diameter) proved to be significantly positively related with trampling disturbance around trees in two of the sites, while in the highest-use site, distance from the formal trail was most strongly related with disturbed area. The findings of this study will serve as initial baseline conditions for recreational impacts in these

stands. RNSP can use the study design developed for this thesis to monitor changes in trail-related visitor impacts in old-growth redwood stands of management concern.

ACKNOWLEDGEMENTS

This project would not have been possible without the support of many people. First off, I would like to thank my field assistants Ian McCowen, Garrett LaRue, Ross Greenlee and Garrett Jaquysh who spent countless hours in the field with me. And Kenny Sauve who did a spectacular job assisting with mapping and digitizing trees before the field season and digitizing trails and disturbed areas after. Ian McCowen additionally did a substantial part of the data entry. To the undergraduate students who assisted with digitizing trails and disturbed areas: Trevor Denson and Taylor Jenson. To George Pease for his help with all the equipment I used from the Forestry Stockroom.

Special thanks to Carol Wilson and Joe Seney who were my main contacts at Redwood National and State Parks and have provided invaluable information and counsel throughout this project. To Jeff Bomke, who suggested this topic to become a master's thesis, Amber Transou, Jay Harris and Lathrop Leonard who supported the project, helped with tricky field method questions and the setup of trail cameras, Josh van Buskirk who mapped trails with me and to the many other people at the parks who shared their knowledge and opinions. To Emily Burns, the scientific director of Save the Redwoods League for her support.

Thank you to my committee members Yvonne Everett, Erik Jules and Jeff Dunk who provided guidance throughout this project. And to Mark Rizzardi for his advice on statistical analyses. Finally, to my advisor, Steven Martin, for his support, guidance, and patience throughout the past two years.

Save the Redwoods League provided funding for this study.

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INTRODUCTION

In every national and state park, trails exist to provide access, offer recreational opportunities, and protect park resources by concentrating visitor impacts to designated trails with durable tread surfaces (Leung & Marion 1999, Pettebone et al. 2009). As a core component of the recreation infrastructure for protected areas, many trail networks must accommodate a growing number and diversity of recreational visitors, and with them, increasing impacts that threaten the integrity of park resources and the quality of the visitor experience (Marion & Leung 2001). Marion et al. (1993) surveyed 93 National Park Service managers regarding visitor-related backcountry management problems, and found that degrading trail conditions and resulting soil erosion were reported as a problem by almost half of the managers.

Formally designed and designated trails rarely provide access to all locations that visitors want to see, so visitors sometimes create informal or social trails: visually discernible pathways, which become unplanned and unmaintained trail networks (Marion et al. 2006). Although some degree of impact by visitors is inevitable, limiting its negative effects on park ecosystems is essential to ensuring ecological integrity, enhancing visitor satisfaction, and maintaining continued support for protected areas (Lynn & Brown 2003). Resource management requires objective and timely information about formal and social trail conditions, resource impacts, and appropriate mitigation measures. Monitoring programs are explicitly mandated in section 4.1 of the NPS Management Policies (NPS 2006):

> "Natural systems in the national park system, and the human influences upon them, will be monitored to detect change. … The Service will use the results of monitoring and research to understand the detected change and to develop appropriate management actions."

In the past 50 years numerous studies have been published on recreational impacts that affect ecological conditions and processes. Vegetation and soil responses to trampling on trails and recreation sites have been most systematically evaluated, as they are the most visible form of disturbance from outdoor recreation activities (Monz et al. 2010). Most trail studies have focused on mountainous areas, as steep trail grades are most susceptible to degradation (e.g., Leung et al. 2011b) and on open landscapes, more susceptible to social trail proliferation due to low vegetation density and high visibility (Walden-Schreiner & Leung 2013).

In past decades, most research has focused on formal trails, resulting in the development of well-tested impact indicators (Leung & Marion 2000, Cole 2004). One finding is that unsurfaced recreational trails are more subject to degradation induced by natural processes and recreational use than are surfaced trails (Marion & Leung 2001). In recent years, more research effort has been devoted to informal trails (Marion et al. 2006, Leung et al. 2011b, Wimpey & Marion 2011). The impact of informal trails to protected area resources is substantially greater than that of formal trails due to their lack of professional design, construction, and maintenance (Monz et al. 2010). Informal trail networks may penetrate into protected habitats, threatening ecological integrity, aesthetics, and visitor experiences (Leung et al. 2011b).

Fragmentation effects include altered soil moisture regimes, increased barriers of movement for soil invertebrates, and reduced habitat quality in smaller patches (Forman

1995, Knight 2000). The disturbed area is further extended by visitors creating duplicative routes in close proximity to one another (Wimpey & Marion 2011).

Figure 1 summarizes direct and indirect trail impacts and their interrelation: exposed soil, caused by loss of vegetation and organic litter, can lead to soil compaction, muddiness, erosion and trail widening (Hammit et al. 2015, Manning & Anderson 2012). Soil compaction decreases soil pore space and water infiltration, which in turn increases muddiness, water runoff, soil erosion and inhibits plant growth (Coder 2000). Compaction also causes less stable moisture conditions in the surface layers where fine roots grow (Settergren & Cole 1970). Recovery of organic litter levels may take even longer than compaction levels take to get back to before-use levels. In Sequoia Kings Canyon NP, organic litter depth on campsites closed for 15 years had not returned to the depth of control sites (Parsons & DeBenedetti 1979). The erosion along trails exposes rocks and plant roots, creating a rutted, uneven tread surface and sediments may smother vegetation. Visitors seeking to circumvent muddy or badly eroded sections contribute to tread widening and creation of multiple treads (Leung & Marion 1999).

Trampling can alter the appearance and composition of trailside vegetation by reducing vegetation height and favoring trampling resistant species (Cole 1995, Hartley 1999). Visitors can also introduce and transport exotic plant species along trail corridors, some of which may replace native vegetation, use trails as further conduits, and migrate away from trails (Cole 1987, Forman 1995).

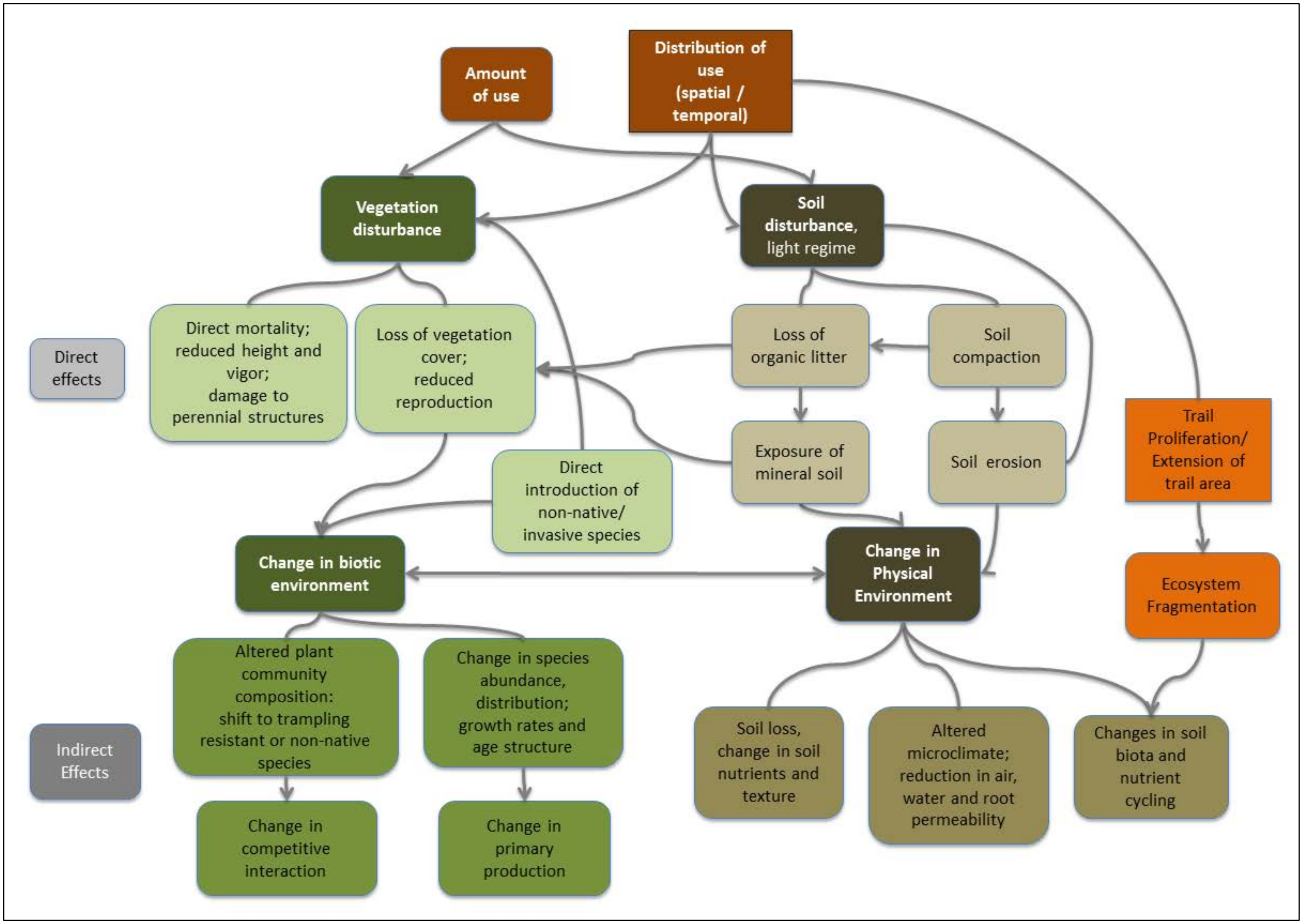

Figure 1. Common trampling impacts on vegetation and soil in parks (adapted from Hammit et al. 2015)

Social trails are often created with motivations such as avoidance, exploration, access to places of interest and shortcuts (Turner and LaPage 2002; Bradford and McIntyre 2007). Once created, social trails are difficult to disguise and slow to recover because of the associated vegetation loss. Frequently used trails become more attractive due to the ease of using already cleared paths (Helbing et al. 1997). They act as a 'releasor cue' that draws even more visitors off formal trails (Roggenbuck 1992) who through trampling, make the trails more prominent and inviting to future visitors and the trails come to be more and more permanent. Trampling studies suggest that this process occurs quite rapidly: In different ecosystems, the relationship between frequency of use and the intensity of impact to vegetation and soil has been found to be asymptotic and curvilinear (**Figure 2a**): Noticeable degradation of organic litter and vegetation resulting

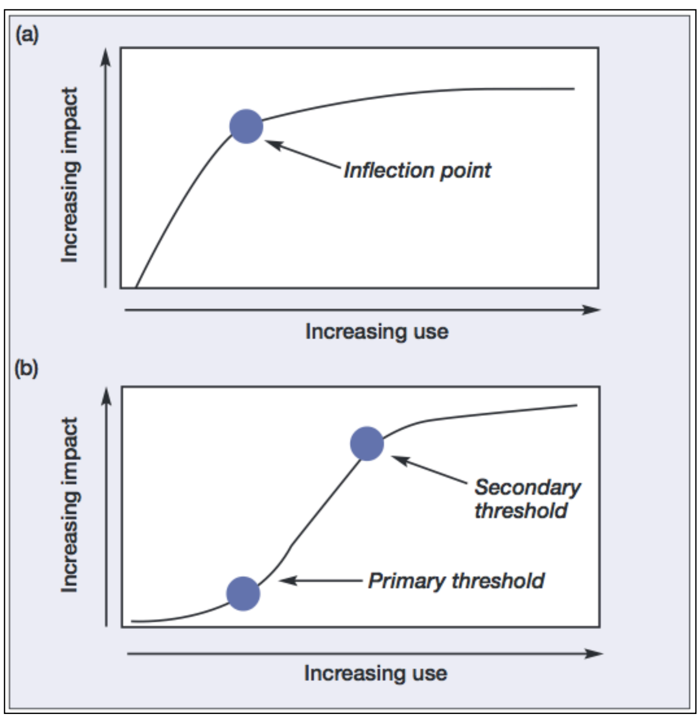

Figure 2. Use-impact relationship (Monz et al. 2013). **(a)** Common model for the relationship between use and impact on vegetation and soil (Cole (1982); Hammitt & Cole (1998)), **(b)** Alternative model for areas with dispersed low levels of use. (Liddle (1975); Cole & Monz (2004); Growcock (2005))

in visually evident paths occur rapidly after trails are first used (Cole 2004). This model of the relationship between use and impact indicates that on previously undisturbed sites, even small increases in the amount of initial use result in substantial increases in impacts (Cole 1982, Thurston & Reader 2001, Hill & Pickering 2009). Consequently, where use is light, sites that receive even small differences in amount of use can have substantial differences in impact levels. Where trail use is heavy, sites that receive substantially different amounts of use may have similar impact levels and additional use causes proportionally less impact (Monz et al. 2010). As an alternative, a sigmoidal response to use (**Figure 2b**) has been suggested for areas with dispersed low levels of use, particularly on trampling-resistant vegetation (Cole & Monz 2004; Growcock 2005).

Informal trail indicators

Agencies have increasingly turned to indicator-based management frameworks to address visitor-related resource impacts (Manning 2007). Limits of Acceptable Change (LAC) and U.S. National Park Service's Visitor Experience and Resource Protection (VERP) define management objectives and desired conditions, designed to monitor established indicators and implement management actions if monitoring indicates a deviation from standards of quality (Manning 2012).

Due to their ecological and social significance, social trails are increasingly recognized as an indicator of resource degradation in the VERP management framework and in the Vital Signs natural resource monitoring program (Monz & Leung 2006; Marion et al. 2006). As part of a VERP planning effort, indicators related to social trail impacts were first used in Arches NP (Belnap 1998), and have now been successfully integrated into the annual VERP monitoring in the Merced and Tuolumne River Corridors in Yosemite NP for 10 years (NPS 2009; Leung et al. 2011b) and in Mt. Rainier NP (Rochefort & Swinney 2000, Moskal & Halabisky 2010), where a 10-year monitoring of social trails had already been started in 1986.

A variety of methods for evaluating trail impacts have been described in the literature, as reviewed by Cole (1983), Leung and Marion (2000) and Marion and Leung (2011). There are two categories of indicators in assessing informal trails: spatial and resource condition attributes. Analogous to indicators developed for formal trails, spatial impact indicators based on GIS trail mapping include the location, arrangement, number, width and lineal extent of social trails, and the area of disturbance (Cole et al. 1997, Marion & Leung 2011, Rochefort & Swinney 2000, Wimpey & Marion 2011). Line feature assessments provide more comprehensive information on the spatial distribution and lineal extent of informal trail networks than point-based assessment methods.

Other advantages of these census surveys include the ability to produce maps showing the location and spatial arrangements of informal trail networks, perform GIS analyses to investigate proximity to rare flora or fauna or sensitive environments, evaluate habitat fragmentation indices, and perform other relational analyses. Repeated measures of trail width provide data on trail widening. Commonly used resource condition indicators include degradation of vegetation, organic litter, and soils and change in ground cover along informal trails (Leung et al. 2011b; Marion et al. 2006; Newsome et al. 2001). For measuring vegetation indicators, transects can be spaced in accordance with various strata such as level of use or vegetation type (Hall & Kuss 1989). Additionally, some studies have used evaluations of condition class ratings to describe varying levels of resource impact (Cole et al 1997, Leung et al. 2002, Leung et al. 2011b, Marion & Leung 2011, **Table 1**). These qualitative ratings provide a useful summary of resource conditions but their application can be subjective.

Trail impacts to forest vegetation

To date, there have been few studies on trail impacts to forest vegetation. Different vegetation layers and different species within a forest show different levels of resistance (ability to withstand impact) and resilience (ability to recover) to impacts on trails. For herbaceous vegetation, plant vigor and reproductive capacity are reduced by breakage and bruising and as a result of soil changes (Hammitt et al. 2015). Severe trampling kills such ground cover plants and tree seedlings directly. Cole's (1995) experimental study in five subalpine and montane forest regions of the US showed that grasses and sedges exhibited the greatest tolerance to trampling, and deciduous ferns and erect broad-leaved forbs exhibited the least. Relative cover of the ferns was only 33% after just 25 passes and only 2% cover survived after 500 passes. Forest herbs and tree seedlings growing in the shade are particularly intolerant of trampling because of their shade-adapted large, thin leaves and tall stems. Low shrubs and other plants that have low growth rates are relatively resistant to trampling, but once damaged they recover much more slowly than grassland species (Cole 1995). In addition to different unassisted recovery rates among species and life forms, research has shown that the spatial zones along a trail recover at different rates (Stohlgren & Parsons 1986). La Page's study (1967) in Pennsylvania campgrounds documented the resulting change in species composition. After heavy loss of vegetation cover during the first year of campsite use, in subsequent years there was an influx of *Poa* and *Juncus* species more resistant to trampling.

Shrubs and saplings in trail corridors are removed as part of a park maintenance effort to clear trailsides. In combination with trampling and outcompeting of tree seedlings by more trampling resistant vegetation those maintenance efforts can greatly hinder tree regeneration. The loss of tree and shrub cover over trails can increase light exposure, which promotes further changes in composition by favoring shade-intolerant plant species (Hammitt et al. 2015).

In general, visible impacts to mature trees on more developed sites result from mechanical damage. Bark erosion occurs below breast height, where the probability of decay is particularly high. Once weakening occurs, trees along formal trails are often rated as hazard trees and must be removed by management (Hammitt et al. 2015). Exposure of tree roots is a common occurrence on and around trails and can make trees more prone to wind throw. A study by Cole (1982) conducted in subalpine campgrounds in Oregon indicated though that more than six decades of recreational use did not cause recreation-related mortality or even loss of vigor in mature subalpine coniferous trees. Pelfini and Santilli (2006) studied the effects of root exposure on conifers along two trails in the Italian Alps and found no significant variations in growth increments. Hartesveldt (1962) conducted a study of visitor impacts on the coast redwoods closest relative, the

Giant sequoia, in Yosemite NP. He found no significant correlation between annual growth increments and soil compaction or loss of vegetation cover. He suggested, however, that the slight decline in growth could just be an early stage in a trend and might lead to significant decline if compaction is not relieved. He concluded that the greatest concern is that trampling weakens the Giant sequoia's stability, since overturning has been the main cause of old-growth sequoia death in past decades. Other studies suggest that recreation-caused loss of vigor and increased tree mortality occur where soils are thin and droughty or where trees are thin-barked and particularly susceptible to decay. Merriam and Peterson (1983) found that, on average 40% of aspen and birch had died 14 years after campsite use began. Tree damage of all types is cumulative. Damage to new (understory or regeneration) trees is not offset by recovery of other trees (Cole & Hall 1992).

Recreational impacts on coast redwood

Coast redwoods (*Sequoia sempervirens*) are a unique and impressive tree species, found only in a narrow strip of land along the coast from southern Monterey County in California to the southwestern tip of Oregon. Today, only five percent of the original old-growth redwood forest remains (Emily Burns, Save the Redwoods League 2015, unpublished data). Forty-five percent of all old-growth redwood forest remaining in California is protected in RNSP, managed cooperatively by the National Park Service and the California Department of Parks and Recreation (California State Parks 2014). While the "crown jewels" of old-growth redwood are situated in the State Parks, which were set aside in the 1920s, the National Park Service acquired adjacent land with remaining old-growth redwood and founded Redwood National Park in 1968.

There have been only seven studies on recreational impacts on coast redwood forests. They found either no empirical evidence of trampling effects on the long-term growth and vigor of mature redwoods or results were inconclusive. Potential visitor impacts on old-growth redwood trees in California parks were a concern since the first redwood parks were established. In 1928, at the request of the Deputy State Forester, Meinecke (1928) investigated the effects of recreational trampling on old-growth redwoods in ten areas in California Redwood State Parks (SP). Coast redwoods are shallow rooted, with a majority of their feeder roots lying in the top 15 cm of soil. Meinecke's (1928) samples, taken from soil trenches dug in compacted areas and in neighboring undisturbed areas, showed that fine feeder roots in the upper 15 cm of soil were essentially absent in the areas compacted by camping, but were dense and healthy in undisturbed soil. For remaining feeder roots of trees growing in compacted soil he found a reduction in their size and health.

The other studies investigating trampling impacts on redwoods confirmed that soil compaction results in increased soil density, reduced macro porosity, reduced feeder root density, reduced water infiltration, and ultimately reduced ability of redwoods to absorb moisture and nutrients from soil (Zinke 1962, Sturgeon 1964, Standish 1972, Krenzelok 1974, and McBride & Jacobs 1978). The three studies from the 1970s were conducted at the southern end of the redwood range in more densely populated areas. Standish (1972) studied a heavily used picnic area in Portola SP in the southern Bay Area. Krenzelok

(1974) and McBride & Jacobs (1978) studied trampling in alluvial flats of Muir Woods National Monument (just north of San Francisco) where heavy visitor use had occurred for 70 years. All three studies found significantly higher soil bulk density on heavily trampled plots. Krenzelok (1974) also demonstrated a significant correlation between soil compaction and the loss in vigor, distribution and abundance of herbaceous species in Muir Woods.

Sturgeon (1964) suggested that in redwood parks intensive foot traffic in the summer season drastically wears down the ground vegetation and decreases shrub growth to some extent, but the long rainy season from October to May provided time for plants to revegetate. However, in heavily-used shaded areas no understory or ground cover developed. In parks with rotation of use areas it took annual plants and shrubs 5 to 10 years to regrow in set aside areas. Sturgeon’s study was based on interviews with park staff, managers and foresters and on personal observations throughout Humboldt and Del Norte Counties.

Standish (1972) and McBride & Jacobs (1978) did not find a significant difference between growth rings of redwood trees with and without recreation impacts. A more recent study conducted in Big Basin Redwoods SP (Martin et al. 2004) also found no significant difference in crown sparseness between mature redwoods in a campground used for more than 70 years and those in an untrampled control site. The paucity of knowledge of direct impacts on long-lived mature trees is based, in part, on the relatively short span of time in which studies have been conducted.

My study provides baseline data for a social trail inventory and monitoring protocol to regularly reassess visitor impacts in old-growth redwood stands in Redwood National and State Parks (RNSP). Given that these trees were the very reason for the establishment of the parks, understanding visitor impacts of and around them is of great importance. RNSP managers are challenged with providing visitor access to some of the old-growth redwood stands, while at the same time assuring that the remaining parcels of old-growth forest are not impaired by overuse and that they maintain their ecosystem processes and functions, including their habitat value for wildlife.

Limitations in staff and funding frequently constrain parks from obtaining information about visitor impacts (Marion & Leung 2001). Due to a combination of limited funds and the assumption that visitor use has been below the carrying capacity of the parks, RNSP management have so far not assessed the extent, distribution, or intensity of social trail impacts on trees, soil or surrounding understory vegetation.

In recent years there has been greater access to location information about the largest trees in the world, and visitors have created networks of social trails also in redwood groves that previously had not been accessed. Modern technology via global positioning systems (GPS) and social media likely contribute to these new impacts. Coupled with multiplying visitor numbers, this has caused an increase in recreational impacts in redwood groves.

The study objectives were to:

1) Develop and test a method to map and quantify the extent and distribution of social trails around old-growth redwood trees at two spatial scales: in sample plots and

study sites. Compare the extent and distribution of trampling disturbance among sites with different use levels.

- How does the extent of social trails in Grove of Titans compare to an established high-use and low-use site?
- Does trampling disturbance around a tree increase with a tree's size and decrease with its distance from a formal trail?
- Is disturbance in a subplot facing the trail significantly higher than in a subplot facing away from the trail? Are subplots close to the tree significantly more trampled than subplots further away from the tree?

2) Develop resource condition indicators that characterize potential off-trail hiking impacts on understory vegetation and soil in old-growth redwood stands; and test the indicators on sample plots around trees with varying degrees of impact. Determine the relationship between trampled area and selected soil and vegetation indicators in sample plots with varying degrees of disturbance.

- Is percent vegetation cover lower in subplots facing the trail?
- Are exposed soil and exposed roots significant parts of percent trampled area in old-growth redwood forests? Are species richness, number of sprouts, seedlings and saplings, and mean litter depth significantly lower for highly trampled plots than for plots with little to no disturbance?
- Are soil compaction measurements above growth-limiting thresholds on social trails?

3) Use the results to refine or verify trail condition classes for a social trail monitoring protocol in RNSP.

4) Provide an overview of lessons learned from studies on education campaigns for park visitors and best practices in restoration projects and relate them to the specific impact results from my study sites in RNSP.

STUDY SITES

All three study sites were situated in Redwood National and State Parks in northern California (**Figure 3**). They were chosen in concert with park staff based on visitor use levels and social trail concerns: the Grove of Titans is a site of particular management concern, and I have chosen Stout Grove and Tall Trees Grove to compare to the Grove of Titans because of their different use intensities and different visitor management strategies used there. At the time of data collection, there were no interpretive signs to inform visitors of the relationship between trampling and vegetation damage or to stress staying on formal surfaces in any of the three sites. All sites are part of the northern redwood forest ecosystems as described by Noss (2000) and located in alluvial flats. Most redwood parks are centered around an alluvial flat that originally inspired the creation of the park because the largest trees are often found in the flat bottoms of creek valleys, where the soil moisture is the highest. The two sites in Jedediah Smith Redwoods SP receive much higher annual precipitation and their moderately well-drained soils retain soil moisture for longer, resulting in denser understory vegetation cover than in the well-drained Tall Trees Grove. The sandy loam soils in these alluvial flats are part of the Bigriver and Battery series and the Bigtree-Mystery complex as described in the Soil Survey of Redwood National and State Parks (Natural Resources Conservation Service 2008). Fire scars on many trees in all study sites bear testimony to frequent fire events, however there is no fire history for the study areas. Before fires were largely excluded from old-growth redwoods, the fire return interval in the northern part of the range is thought to have been less than 25 years (Lorimer et al. 2009). During the 1964 floods between 15 and 90 cm of sediment were deposited on part of the Tall Trees Grove and Stout Grove fluvial terraces (Joe Seney, Redwood NP, personal communication). The sediment loads resulted in a new, higher elevation soil surface, which reset existing impacts by allowing renewed understory vegetation and soil development there. In the flooded portions, the O-horizon is thinner and less developed than in the other parts of the study sites, where O- and A-horizon may have developed over hundreds of years.

The alluvial flats are sharply separated by slopes from the adjacent upland areas. In Stout Grove and Tall Trees Grove, I originally included all trees that were situated on the alluvial flat for defining study site boundaries, and later extended study area boundaries to include social trails in the peripheries of these trees. In Grove of Titans I defined the study area to include all social trails that were created in search and exploration of the “Titans” on either side of Mill Creek.

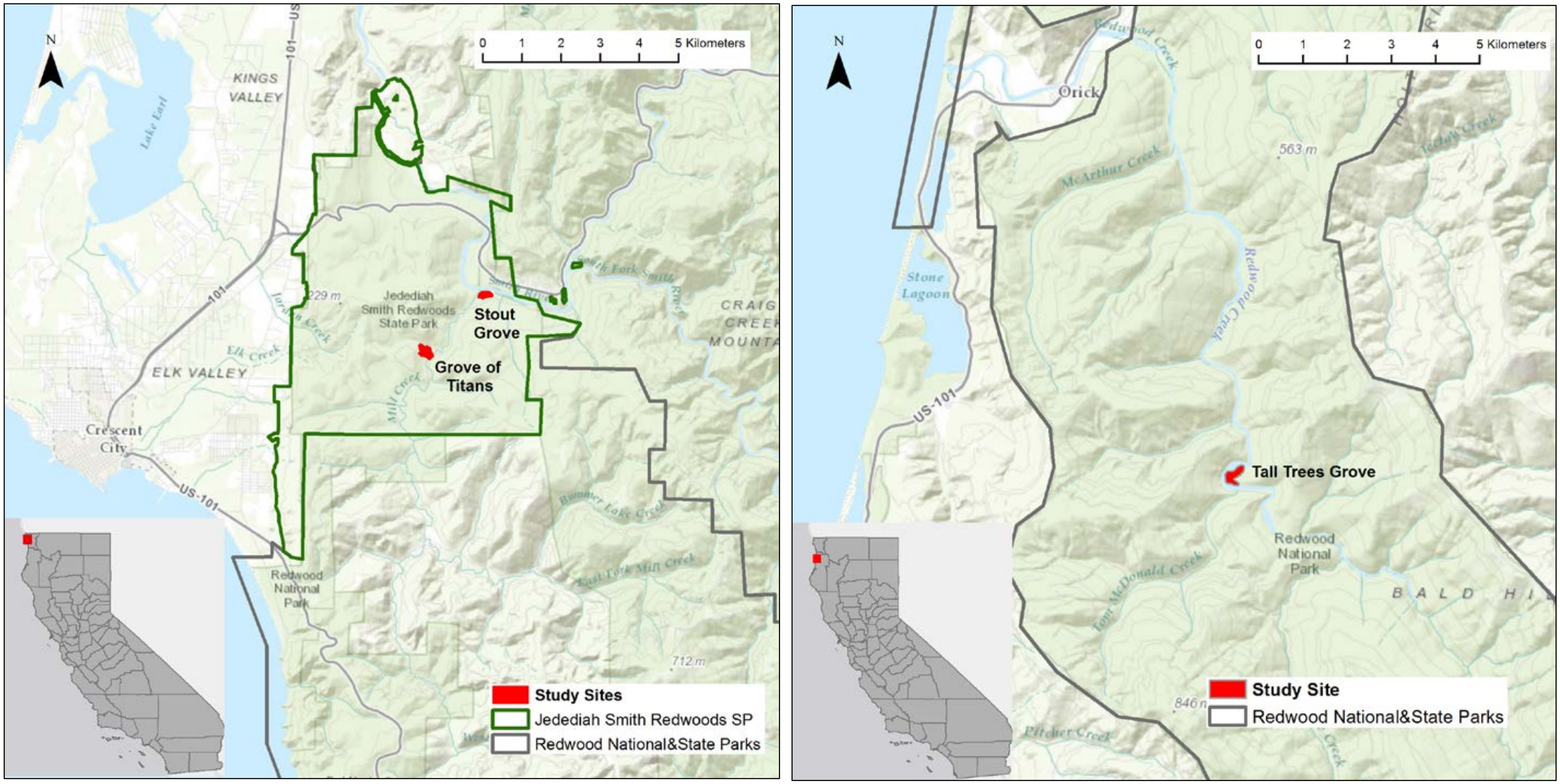

Figure 3a. Study sites in Jedediah Smith Redwoods State Park: Stout Grove and Grove of Titans. 3**b.** Study site in Redwood National Park: Tall Trees Grove.

Stout Grove

Stout Grove is considered to be the heart of Jedediah Smith Redwoods SP, which was established around this grove in 1929 (NPS 2014). This is a traditional high use site where park management tries to concentrate use to limit impact to a certain area (Manning 2012). Located on a small floodplain at the confluence of Mill Creek and the Smith River, the 5.6 ha Stout Grove is accessible by a 700 m loop trail (**Figure 4**). Trail surfaces have been armored with gravel to increase the resistance of park resources to recreational impacts and facilitate access. The trail from the main parking lot runs down a slope and is paved until it reaches the alluvial flat. There are three main access points: the parking lot is reached via the South Fork of the Smith or via the other end of Howland Hill Road (8 km dirt road) and for six weeks in summer a foot bridge connects Stout Grove to the park's campground. Former signs with tree names and heights were removed, since it was assumed that they encouraged people to go off-trail and damage the trees. Fences that used to surround parts of the trail were also removed. The most famous and heavily impacted tree in the grove is the Stout Tree. Since this is a younger grove than the other two, the stand is still denser, especially at the west end of the grove. Floodwater inhibits the growth of understory trees and plants seen in other groves (Baselt 2007).

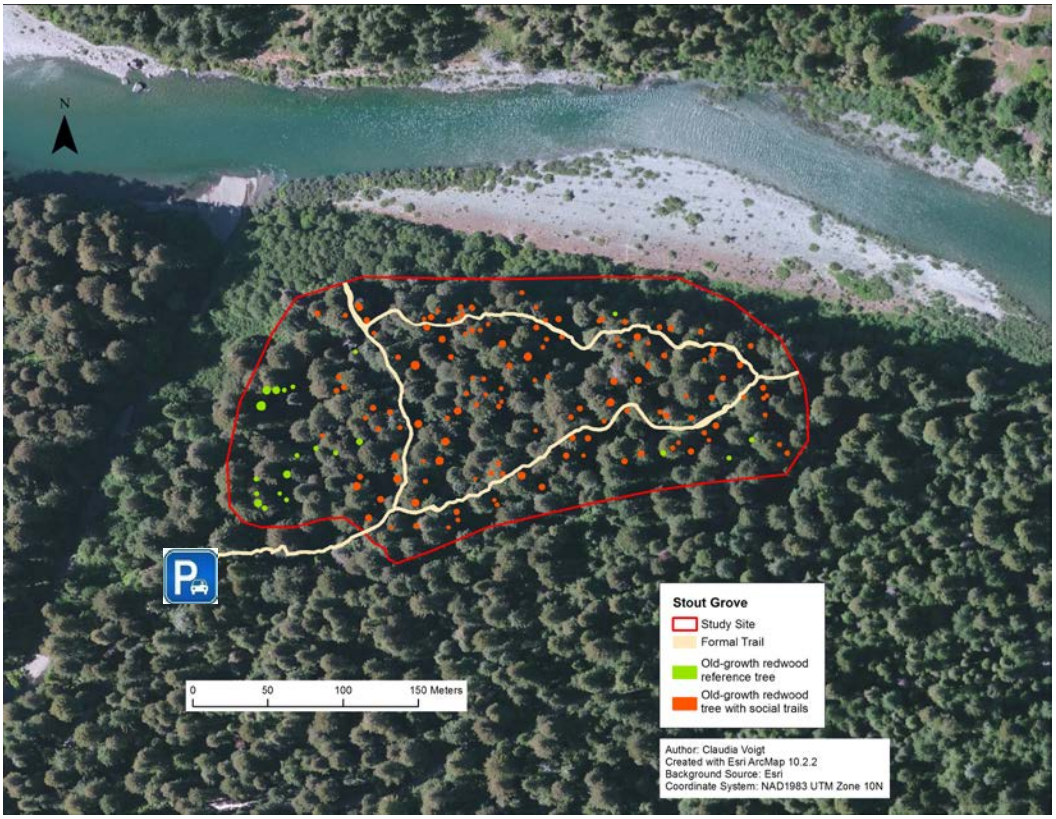

Figure 4. Stout Grove overview map.

Tall Trees Grove

Tall Trees Grove is a popular destination for visitors to Redwood National Park and is highly recommended by guidebooks, but because of its distance from the road it gets lighter recreational use compared to other destinations in the park, such as the heavily trafficked Lady Bird Johnson Grove. Redwood NP allows only 50 daily permits for the main access point to Tall Trees Grove, placing an overall limit on all recreational use there. To reach this trailhead, visitors have to drive down an 11 km unpaved road off Bald Hills Road. The Tall Trees Trail is a 6.5 km round trip hike with 200 m of elevation change, and the Tall Trees Grove Loop, the centerpiece of this hike, begins 2 km from the parking area. The grove itself is located on a thin strip of alluvial flat alongside Redwood Creek. This is the largest of the three study sites, with about 10.8 ha it is almost double the size of Stout Grove. Visitors can explore along a 1,400 m loop trail plus 217 m of other formal trail within the study area. Only half of the loop leads visitors through old-growth redwood (**Figure 5**).

Human impacts on the Tall Trees Grove trail long predate the creation of Redwood National Park. Native Americans had created a trail heading up the coast, turning inland and crossing Redwood Creek at Tall Trees Grove. It became part of the Trinidad Trail in 1850, a supply route between the town of Trinidad and the mines on the Klamath River (Bearrs 1982). The section of trail including Tall Trees Grove was abandoned after construction of the Bald Hills Road at the end of the 19th century. The trail was re-opened by Arcata Redwood Company in the mid-1960s following the 1963 discovery of what at the time was the world’s tallest tree (NPS 2011). The tree known as the Tall Tree or Libby Tree in part spurred the creation of the National Park in 1968. With the 1978 legislation expanding Redwood National Park, the foot trail access to Tall Trees Grove on the east side of Redwood Creek was developed (NPS 2011). The Tall Tree held its “title” and attracted visitors until 1994 when the top died back.

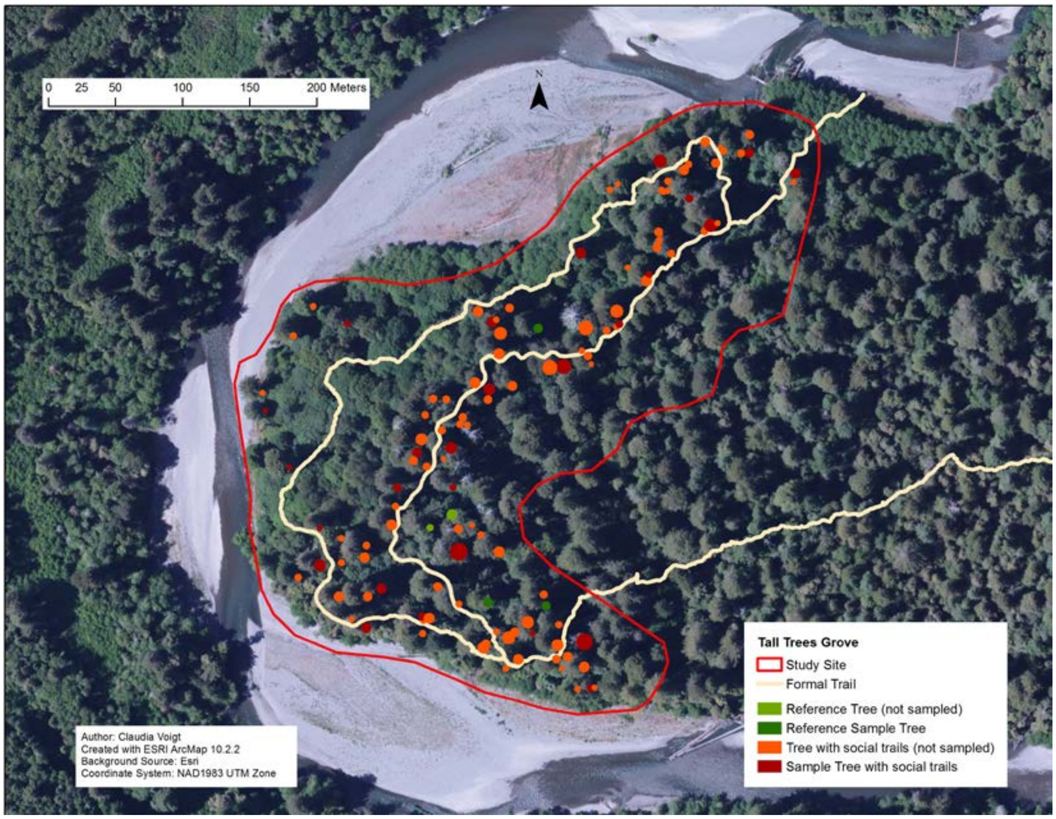

Figure 5. Tall Trees Grove overview map.

Grove of Titans

Grove of Titans (unofficially named) was “discovered” in 1998 by Stephen Sillett and Michael Taylor in Jedediah Smith Redwoods SP. Though not actually a grove, it is a number of unusually large redwoods dispersed over an area almost the same size as Tall Trees Grove (9.8 ha). According to a number of publications, some of the current “record trees” are found in the Grove of Titans (the largest known coastal redwood by volume and the largest known single stem coastal redwood (Noss 2000, Preston 2007, Vaden 2014), which has attracted visitors who look for these specific trees. According to park staff and scientists, before 1998 the Grove of Titans was untrampled by park visitors even though some of its trees are located close to the formal trail. The trees had undoubtedly been looked at occasionally by visitors hiking off-trail, earlier by timber cruisers and before that by Native Americans hunting for elk and nearby homesteaders, but nobody had reported their enormous size. A number of trails were surveyed and constructed inside Jedediah Smith SP during the 1930s by State Parks, but none of the trails entered the Grove of Titans. Park management has not disclosed the location of the grove to the general public, but visitors find it on Google maps, Wikipedia, and numerous other websites provide information on the individual trees in the groves and show pictures of the trees.

On the eastern side of the study site, separated from the other side by Mill Creek, there is only one tree that has been considered a “giant” but because of its significance to the parks and its popularity it was included in the study site (**Figure 6**).

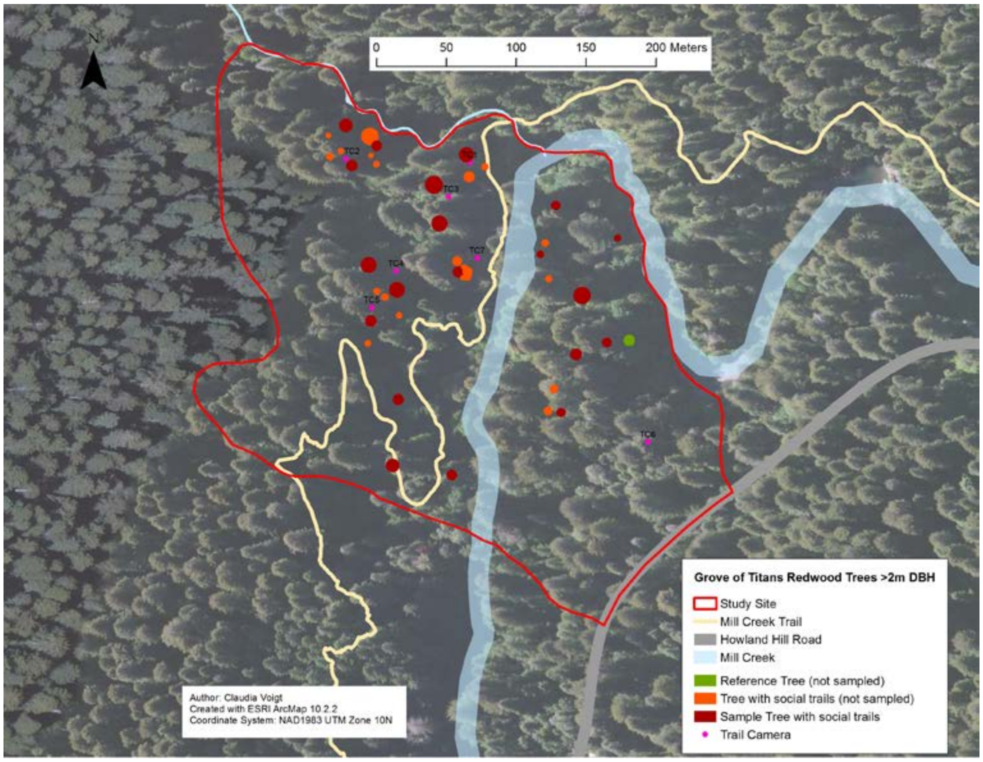

Figure 6. Grove of Titans overview map.

METHODS

Visitor numbers

Since 2013, visitor numbers for Redwood National and State Parks have been increasing. Redwood NP had a 23% increase in visitors from 2014 to 2015 (NPS 2015a). With a total number of recreation visitors of 527,143, 2015 is the first year since 1995 where over half a million visitors came to Redwood NP. Since the park opened in 1968, there have been eight years with such high visitations. For the Redwood State Parks the most recent published numbers are from 2013-2014. In Jedediah Smith Redwoods SP, visitor numbers increased 12 % from 2013 to 2014 (total number was 137,044, California State Parks (2015)). For State Parks, no site-specific park records exist, so there are no visitor estimates for Stout Grove and Grove of Titans, which are necessary to characterize use patterns associated with trampling impacts.

For all three study sites I estimated visitor numbers for the main visitor season of Memorial Day (May 25th) to Labor Day (September 7th). For Tall Trees Grove, the number of users was estimated from daily National Park Service records for permits given out at the four visitor centers. I also counted visitors in Tall Trees Grove on nine days between June 10th and June 26th during the field season and compared my tallies to the permit numbers to see how the two measures related to one another. On each day, all visitors visible from the study plots (close to the formal trail) were tallied for about 7 hours and an hourly visitor number calculated. Visitor days in Tall Trees Grove are shorter than for easy access locations, since there is an hour hike in and hour hike out. To calculate daily visitor estimates, I assumed a visitor day in early summer to be nine hours long.

In Stout Grove, visitors were counted on 10 days between May 25th and June 4th and an hourly visitor number was calculated. Because of the short walk from the parking lot, I assumed a visitor day in early summer to be ten hours long. In Grove of Titans, I installed seven motion-activated trail cameras at the entrances to social trails and in the grove itself from April 4th to August 22nd 2015 (see **Appendix A** for the location of cameras). Once triggered, the cameras took three pictures in a row with a 1 second recovery time before the next three pictures would be taken. Trigger speed and recovery time of the trail camera are essential for a correct visitor estimate. For quite a few pictures the motion trigger was activated but people passed through too quickly to be captured. On others the group size is not correct, because the recovery time of the camera was too slow to capture the people following the person who initially triggered the camera. When positioning the cameras I had hoped the photos would reveal if people who entered the social trails actually reached the Grove of Titans or turned back to the formal trail, but because of the technical limitations this could not be analyzed. I analyzed the 22,000 collected pictures to get an estimate of how many people use the social trails per day and where visitor use was concentrated. People that appeared on more than one camera where included only once in the daily numbers.

Mapping and sampling study trees

Between February and May 2015, I mapped old-growth redwood trees with a diameter at breast height (DBH) of over 2 m in all three sites. I didn't create a complete inventory since I did not map every tree in little disturbed or undisturbed areas on the western side of Stout Grove and the eastern side of Grove of Titans. Tree coordinates were digitized from LiDAR derived canopy height models (CHM) provided by the parks to create field maps and to compare with GPS collected tree positions (**Figure 7**).

Trees were grouped into two categories: Trees with social trails leading up to them and currently undisturbed reference trees. Around reference trees, the understory vegetation and organic litter showed no sign of recent trampling disturbance and there were no social trails present in an area of at least 10 m around the tree. For trees with social trails, the tree coordinates were recorded standing as close as possible to the tree with a Trimble Geoexplorer 6000 XH. Distance and azimuth to each tree were measured at the intersection of the formal trail and the most prominent social trail.

Even though I used this high accuracy GPS unit, much of the data could not be used: GPS signals have a low signal to noise ratio - they are low strength and the dense canopy with a high water content causes the signal to be attenuated. Also, the GPS signal is reflected when it hits a physical barrier like a tree trunk and the enormous redwood trees caused more multipath than other forest environments. The GPS antenna has to determine which is the real GPS signal, and which the "echo". The multipath effect is

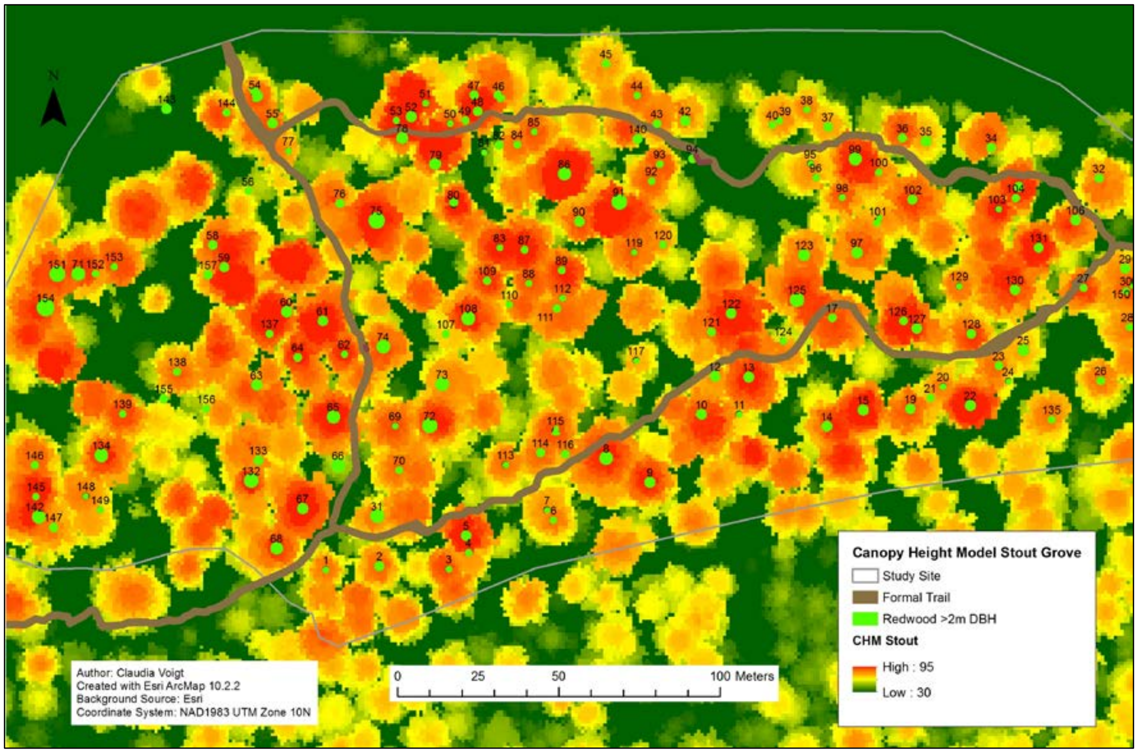

Figure 7. LiDAR derived canopy height model for Stout Grove, with trees between 30 and 95 meters of height. The lowest heights are in green colour and the highest points are in orange.

even worse when tree trunks and branches are wet. Furthermore, under the dense redwood canopy the view to the sky changes frequently, resulting in constantly changing satellite constellations. This means different satellites are used in computing positions, causing a different bias in the data points, resulting in inconsistent data with poor relative accuracy (McLachlan 2002, Lucas 2007, Bastos & Hasegawa 2013). I decided to create a reference layer and recorded the formal trails in all three sites with a Trimble Geo 7x with external antenna. Then I calculated the position of the trees by measuring their distance and azimuth to a reference point. I post-processed all GPS data using Trimble's Pathfinder Office and base station data from the five nearest available Continuously Operating Reference Stations (CORS).

Prominent features (e.g. burls, multiple stems, reiterations, goose pens) of all mapped trees were recorded and their DBH was measured. Trees that were accessible were measured with a DBH tape, according to forestry standards at a height of 1.30 m on the highest point of the tree's circumference. For trees with multiple stems that were not round, trees with a lot of sprouts around them and reference trees, the DBH was too large to be estimated with a relascope. I used an adapted version of the Biltmore stick to estimate the DBH of these trees.

In Stout Grove, I mapped 151 old-growth redwood trees with a DBH over 2 m. Of these, 131 had social trails leading up to them (see stem map in **Figure 8**). In Tall Trees Grove, 116 of the 121 mapped old-growth redwood trees had social trails leading up to them and only 5 trees had no trampling disturbance (**Figure 9**). At the time of mapping, six of 42 trees in Grove of Titans showed no evidence of trampling, but four month later, in the field season, only one of 42 mapped trees remained with no trampling around it (**Figure 10**).

The stem maps were used to represent populations of trees from which I sampled 20-30 study trees per site. Using the ArcGIS Fishnet tool I divided each study site into equally-sized rectangular cells to stratify the sampling. With the r.sample tool in the Geospatial Modelling Environment (Beyer 2014), I randomly sampled one tree per cell. Distance from formal trail was calculated using the ArcGIS Near Tool. As a result of the random sampling, for Tall Trees Grove 13 of 30, for Stout Grove 12 of 27, and for Grove of Titans 2 of 20 trees were closer than 10m to the formal trail (plots overlapped the trail). I also assessed trees that were not visible from the formal trails and only accessed by social trails. In Stout Grove, tree 142 was closest to the paved access leading down into Stout Grove. However, a steep drop separated the tree from this path so I used the distance from the Loop-Trail instead.

Plot design

Around each sample tree, a circular plot was created by establishing eight transects in the cardinal and sub-cardinal directions (**Figure 11**). Transects were 10 m long, measured with a laser range finder from the edge of the plot to the tree's bole. On each transect I recorded the distance from the point that was established as the end of the tree skirt to the 10m mark. The sub-cardinal transects divided the plots into four quadrants (each cardinal quadrant is bounded by its closest sub-cardinal direction transects).

Photographs taken at 28 photo points in and around each plot help to illustrate the plot layout for each sample tree and to track changes in disturbed areas for later monitoring. An overview picture of each study tree facilitates identifying the trees (examples of photo charts can be found in **Appendix D**).

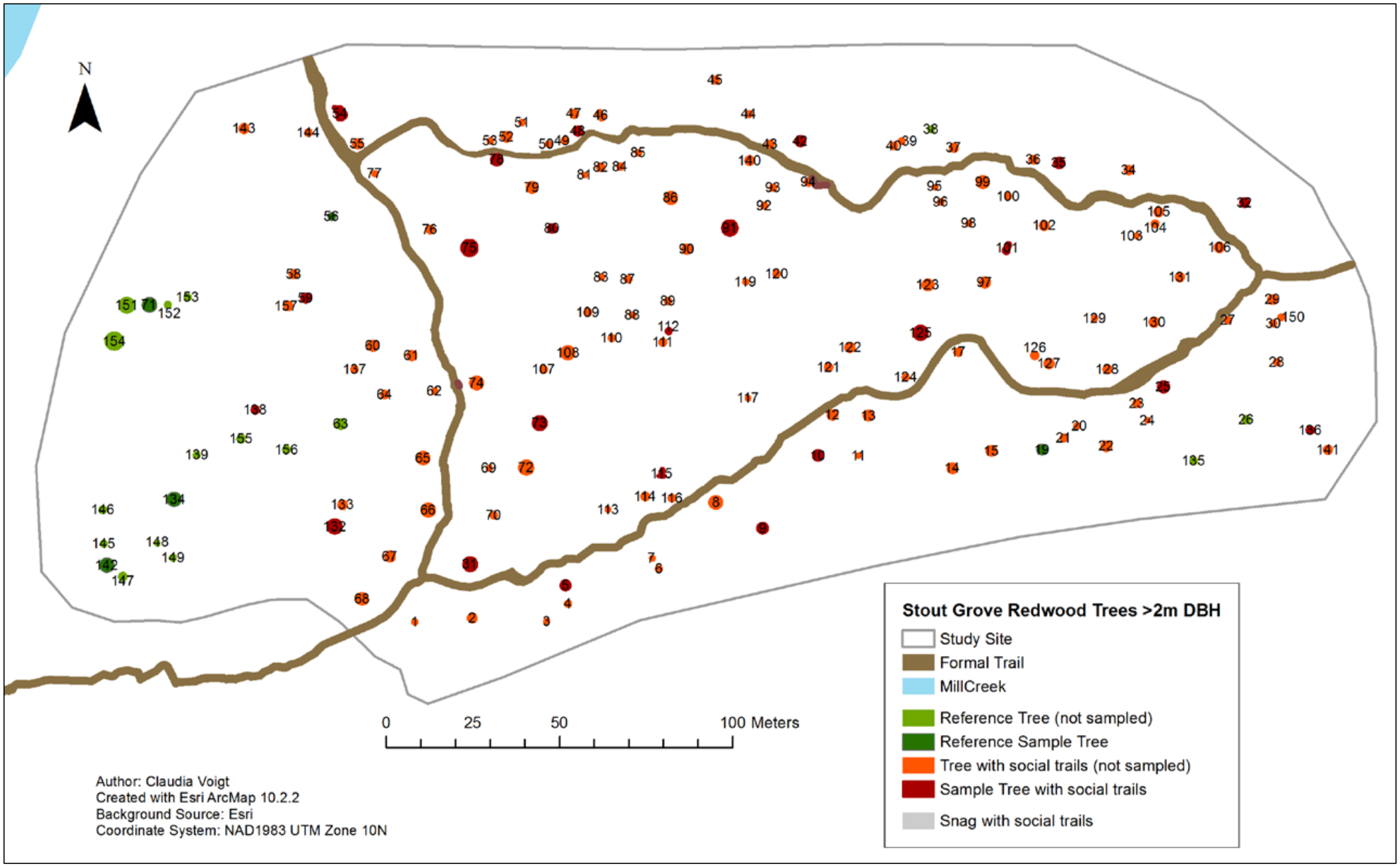

Figure 8. Stem map for Stout Grove including 151 redwood trees with >2m DBH. This is not a complete inventory since I did not map every tree in very little disturbed or undisturbed areas on the western side of Stout Grove. Some snags with a DBH >2m are included as structures in the stem map but were not in the sampling. 131 trees had social trails leading up to them. Of the 20 reference trees (currently no social trails) most are on the Western side of the grove, outside of the Stout Grove Loop Trail.

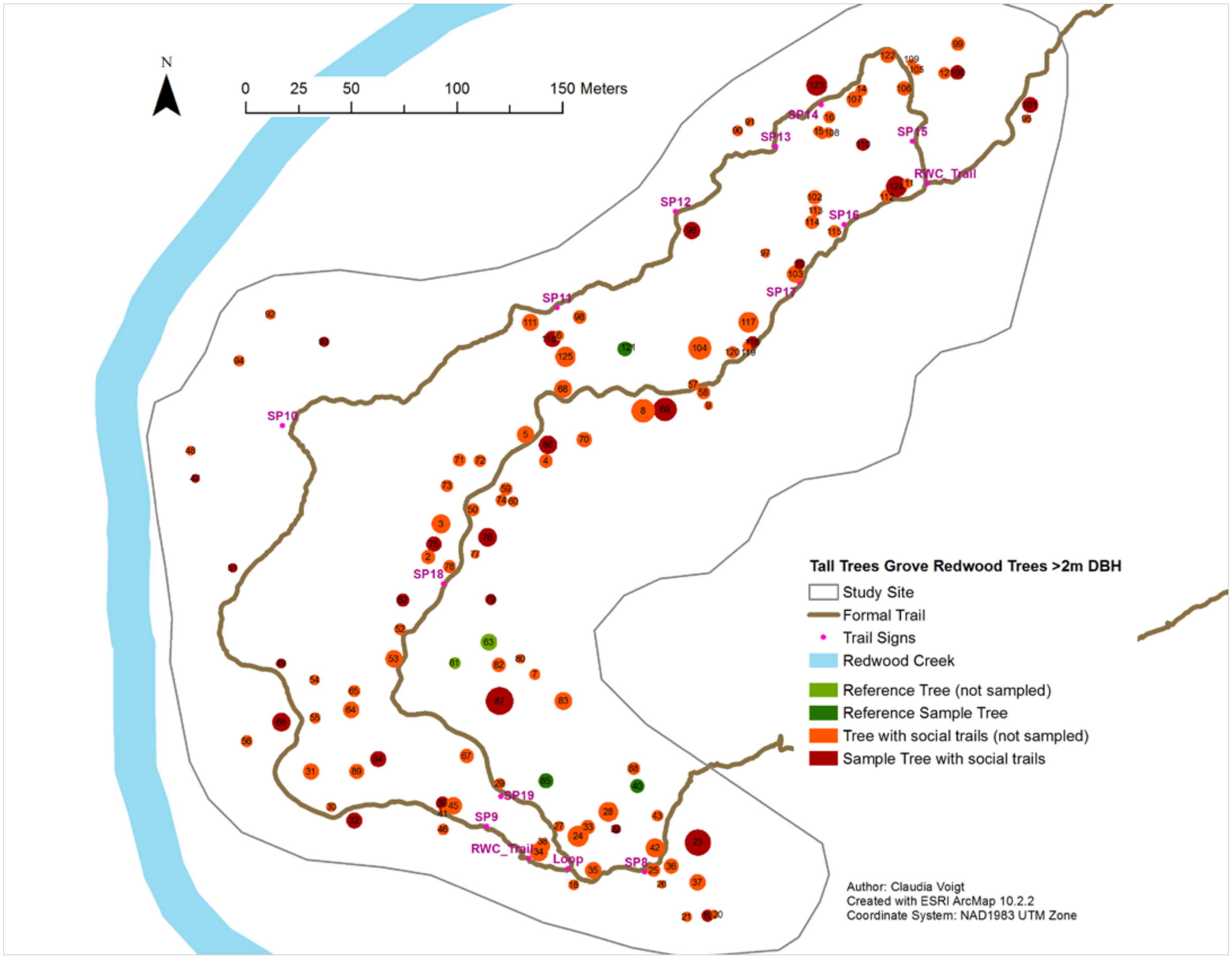

Figure 9. Stem map of Tall Trees Grove with 121 old-growth redwood trees with a DBH > 2m. 116 trees had social trails leading up to them, only 5 trees (reference trees) had currently no trampling disturbance. The DBH buffer was doubled to adjust for the scale of the map.

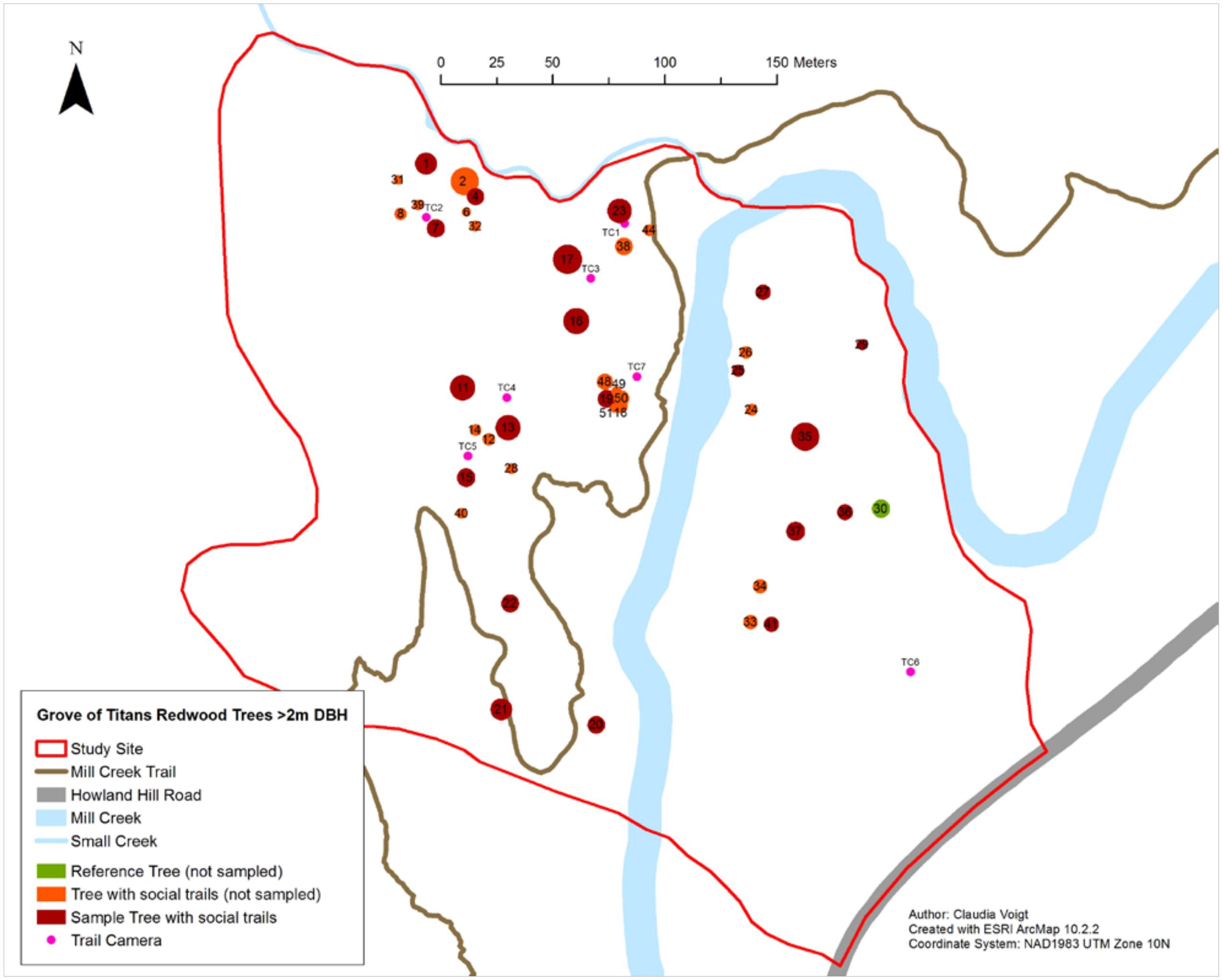

Figure 10. Stem map of Grove of Titans with 42 old-growth redwood trees with a DBH > 2m. This is not a complete inventory, on the Western side of Mill Creek all trees on flat ground were mapped, in little trampled or untrampled areas on the Eastern side only a few trees were mapped as reference. 41 trees had social trails leading up to them, only one tree had currently no trampling disturbance. The DBH buffer was doubled to adjust for the scale of the map.

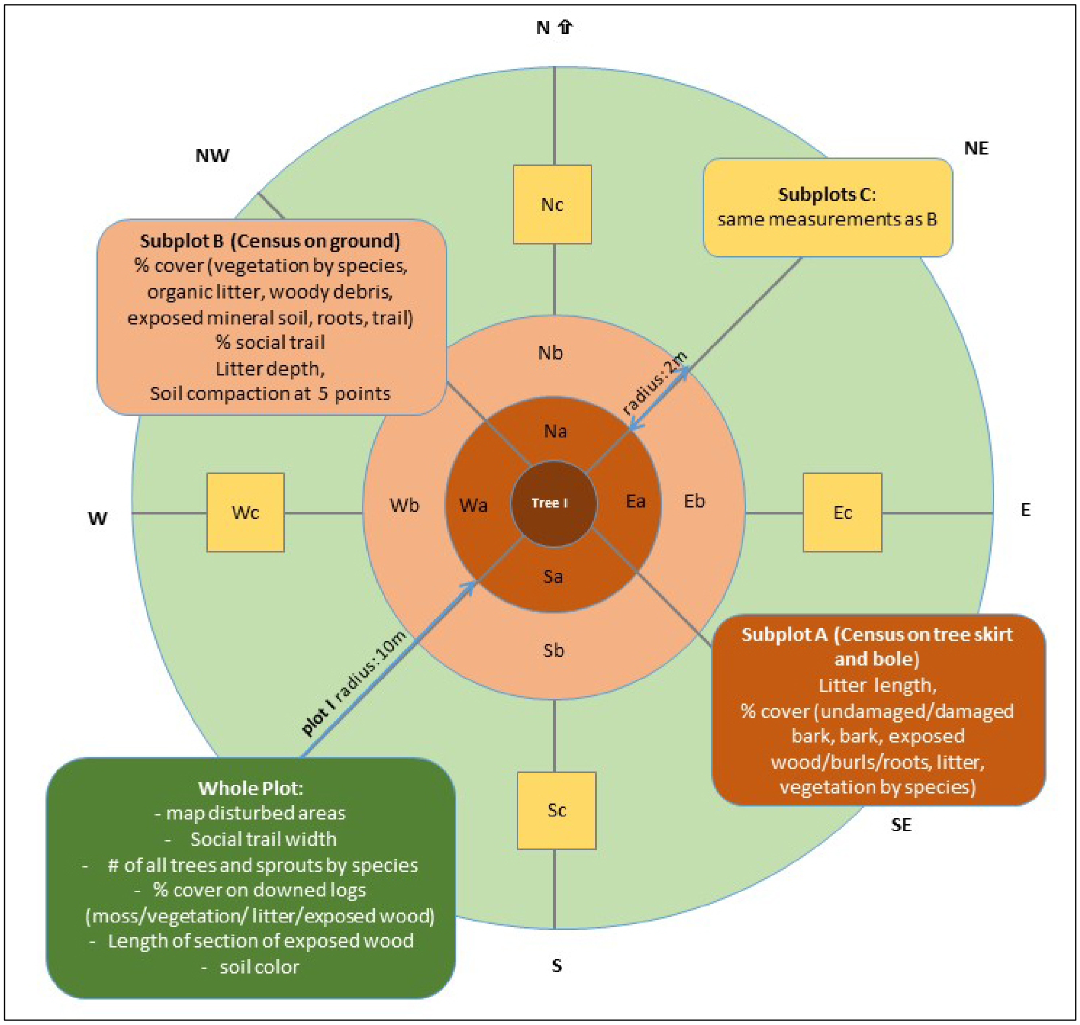

Figure 11. Plot design for 10m radius tree plot with 12 subplots.

Mapping informal trails

In a first trial, social trail segments were recorded with the GPS device as line features. For the above-mentioned reasons, the GPS signal was not accurate enough to determine to which or around which tree an individual trail would lead. As an alternative, I mapped social trails at two different scales: within the plots, social trails were inventoried in detail by drawing trampled areas into plot maps to quantify the extent and distribution of trail segments and disturbed areas. On the last field days in each study site, trails were roughly inventoried for the whole site by drawing them into the stem maps. Many visitors walk on downed logs, so that some of these logs have become part of the social trail network and logs that have been walked on are often devoid of organic litter and vegetation. For these reasons, I have included trails on downed logs into the mapping. For the plot drawings, I created diagrams in ArcGIS that included a DBH buffer of the sample tree, the eight transects, the 2 m and 10 m buffer and the formal trail buffer (Appendix B). Trail width was measured at points of obvious change. Trails and disturbed areas were classified among five condition classes with increasing values being associated with greater impacts. Condition classes were adapted from three other studies assessing social trail impacts (**Table 1**).

Table 1. Comparison of trail condition class descriptions for Marion&Leung (2011), Leung et al. (2002) and this study in old-growth redwood forest

Condition class	Marion & Leung (2011) Assessment of Informal Trails in Great Falls Park (Virginia)	Leung et al. (2002) Social Trails in Boston Harbor Islands and Cole et al. (1997) in high-use wilderness areas in the Cascade Mountains of western Oregon and Washington)	**Description for this study**
1	*Trail distinguishable; slight loss of vegetation cover and /or minimal disturbance of organic litter.*	*Trails are disturbed but not well established. They retain at least 20% of vegetation cover on the treads. The boundaries between trail treads and off-trail areas are often unclear.*	Social trail(s) (just) distinguishable, the boundaries between trail treads and off-trail areas are often unclear; slight loss of vegetation cover and minimal disturbance of organic litter.
2	*Trail obvious; vegetation cover lost and/or organic litter pulverized in primary use areas.*	*Trails are well established. They retain less than 20% of vegetation cover on the treads. These trails are less than 0.3 m wide. The boundaries between trail treads and off-trail areas are often discernible.*	Social trail obvious, but maybe not used recently, on trail vegetation cover lost and/or litter diminished in primary use areas. Trails are less than 0.4 m wide.
3	*Vegetation cover lost and/or organic litter pulverized within the center of the tread, some bare soil exposed.*	*Trails are well established. They retain less than 20% of vegetation cover on the treads and are between 0.3 and 0.6 m wide. The boundaries between trail treads and off-trail areas are usually discernible.*	Social trail well used, vegetation cover lost and/or organic litter pulverized within the center of the tread, some bare soil exposed. Trail treads are between 0.4 and 0.8 m wide.
4	*Nearly complete or total loss of vegetation cover and organic litter within the tread, bare soil widespread.*	*Trails are well established. They retain less than 20% of vegetation cover on the treads and are more than 0.6 m wide. The boundaries between trail treads and off-trail areas are usually discernible.*	Social trail(s) are hard to distinguish from formal trail (have similar appearance and width). Nearly complete or total loss of vegetation cover and organic litter pulverized within the tread, bare soil widespread.
5	*Soil erosion obvious, as indicated by exposed roots and rocks and/or gullying.*		Disturbance spread over big area, no boundaries to identify trail tread, nearly complete or total loss of vegetation cover and organic litter pulverized in the whole area, bare soil widespread

Vegetation and soil measurements

In the plot quadrants, tree regeneration was counted in two categories: less than 1.86 m tall and between 1.86 m and 5 m tall (USDA Forest Service 2014).

In each plot, 12 nested subplots were established along the transects (**Figure 11**). In two pilot studies conducted in November 2014 and March 2015, I tested two different designs for the subplots and compared the time it took to collect data, the feasibility of data collection, and the differences between the collected data. It turned out to be more informative and less damaging to understory vegetation to use a census method rather than a fixed frame quadrat for eight of these subplots.

A-Subplots were used for measurements on the tree skirt and bole. These subplots started where I defined the lowest points of the tree skirt and marked them on the transects with eight pin flags. From there, they went up to a height of 2 m. All measurements for the four subplots add up to a census around the whole tree. I divided these subplots into a percentage of skirt area and a percentage of bark area. Then I recorded the percentage of disturbed area and of the cover elements (e.g. bark, soil, litter; see **Table 2)** using ocular estimates.

B-Subplots were used for measurements on the ground. These subplots were established by measuring 2 m outwards along the transects starting at the first pin flag on the tree skirt. In these subplots, the percentage of ground cover elements was also determined with ocular estimates (**Table 2**). Vegetation cover estimates were recorded by species. Cover was defined as the portion of ground covered by the vertical

Table 2. Description of elements for cover estimates in subplots

	Mutually exclusive set of categories, which add up to 100%	**Description**
Cover Elements used in A-Subplots	Undamaged bark	Bark that has neither been burnt nor damanged
	Burnt bark	Bark that has been burnt in forest fires
	Damaged bark[a]	Bark likely damaged by people walking on the tree skirt and holding onto the tree (often of a redder color than weathered undamaged bark, sometimes polished)
	Exposed wood[a]	Wood showing where bark has been completely removed from tree or a burl
Cover Elements used in A-, B-and C-Subplots	Exposed roots, burl or woody debris[a]	Roots or burl with damaged or removed bark. Woody debris damaged by trampling
	Exposed soil[a]	Litter layer is completely removed. Depending on the depth of O-horizon either black, well decomposed soil or mineral soil of gray color is visible
	Organic litter	Dead plant material, e.g. twigs, bark, needles, and leaves, that have fallen to the ground and have not yet been incorporated into the decomposed top humus layer. Litter that has been pulverized by trampling is not included and is classified as bare soil.
	Woody debris	Woody material, slash and debris, fallen dead trees and the remains of branches on the ground (>50mm width)
	Vegetation	Including trees, shrubs, ferns, forbs, graminoids
	Additional set of categories, also adds up to 100%[a]	
	Disturbed area (social trails present	Area affected by trampling and covered in social trails
	Undisturbed area (social trails absent)	Area without visible disturbance and without discernible social trails

[a]only relevant on impacted trees

projection of the vegetation onto a horizontal plane. Soil compaction was measured as penetration resistance at the mineral soil surface at five evenly spaced points within each subplot (at 5 and 10 cm depths) with a ring penetrometer. For each measurement point I noted if it was taken on a social trail or in an untrampled area. Litter and duff depth (surface to A horizon) was measured at 1 m and 2 m along the transects with a trowel and measuring tape.

C-Subplots were established on the ground, starting at 5 m from the first pin flag along the cardinal transects. A fixed 2 m x 2 m frame defined the C-Subplots because at 5m away from the tree their area would be too big to get reliable ocular estimates using a census method. In the C-subplots the same measurements were taken as in the B-subplots.

To establish if there was a difference between subplots facing the trail and subplots facing away from the trail, I assigned each quadrant a code 0, 1, 2 or 3. A subplot was coded as “0” when it (at least partially) overlapped the formal trail. It was coded as “1” (facing the trail), if the area within a 15 degree angle of the cardinal transect was less than 25 m away from a formal trail or a class 4 social trail. It was coded as “2” if it was neighboring a subplot that had been coded as “1”. A subplot was coded as “3” if it was neither close to a formal trail or class 4 social nor neighboring a quadrant that was. **Figure 12** shows an example coding for the Stout Tree.

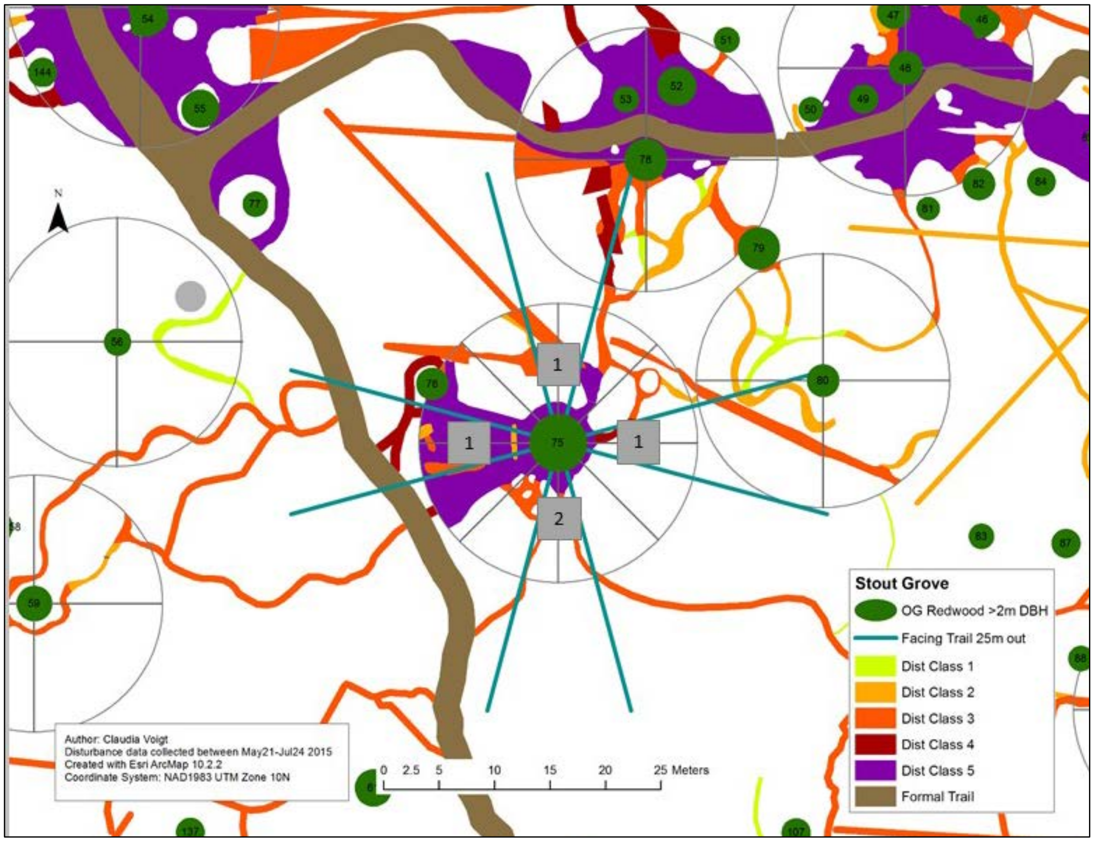

Figure 12. Coding of the variable "Facing Trail" for subplots around the Stout Tree: Subplots in the West were facing the formal trail (coded as "1"), in the North and East facing a class 4 social trail (coded as "1"), and in the South neighboring quadrants that are facing the trail (coded as "2"). Blue lines enclose the area that determined the coding.

Analysis

For spatial analysis, I used the stem maps and hand-drawn plot and trail maps to create maps of social trail networks. All 78 hand-drawn plot maps and six site maps (two for each site) were scanned and georeferenced. The disturbed areas in sample plots were digitized from the plot maps as polygons. From the site maps, trails outside the plots were digitized as polylines. Measurements of trail width and mean trail width were used to buffer social trail polyline data. The GIS data were used to calculate aggregate area of disturbance and lineal extent of trails. The density of informal trails was determined as the aggregate length in m/ ha and total number of informal trails per ha. In all three sites, cover analysis was done with ArcGIS for each tree plot to calculate the size of the disturbed area. Total trampled area within a study site was calculated as the sum of trampled area within all sample plots plus the buffer area of social trails and formal trails outside the plots minus the DBH buffer area of all mapped trees, with results in square meters.

To assess the relationship of DBH, prominent features and distance from formal trail to percent plot disturbance, I performed a linear regression analysis using R (R Core Team 2015). All data were tested for normality and heteroscedasticity of residuals. In the past, percent data and proportions were often square root or arcsine square root transformed. I explored these transformations for percent plot disturbance but neither of them significantly improved the homoscedasticity or linearity of the data. For the relation with distance from formal trail, the proportion of disturbed area was log transformed (1/6 was added to all values to allow the transformation of 0 values (Mosteller & Tukey 1977). The number of prominent features was not independent of the DBH of the trees in Stout Grove and Grove of Titans. In a linear regression, prominent features were used to predict DBH, and trees with more prominent features had on average a higher DBH (Stout Grove R^2=0.34, P=0.04; Grove of Titans R^2=0.53, P=0.02), so I used only DBH in the regression since it is a more objective measure. In Tall Trees Grove, prominent features were not significantly associated with DBH (R^2=0.09, P=0.67). Here, prominent features were not significant in predicting disturbance, independent of whether DBH had been accounted for ($F_{4,24}$=1.30, P=0.30) or if prominent features were used as the only predictor ($F_{4,25}$=0.56, P=0.70).

By definition, percent disturbed area within the subplots is confounded with percent of the five cover elements; I did not describe a correlation between these variables but plotted the raw data to visualize differences and similarities between the sites. To test for differences in mean trampled area and cover between B-plots (close to tree) and C-Plots (further away from tree) I used pairwise t-tests and adjusted the P-values for multiple comparisons using Holm's method. For testing mean differences between subplots facing the trail, adjacent to subplots facing the trail and subplots facing away from the trail I used Games-Howell multiple comparisons (for non-uniform sample size and heterogeneous variance). To avoid confounding disturbance on the formal trail with disturbance caused by visitors walking off-trail, subplots that overlapped the formal trail were excluded from analyses (10 of 312 B-Plots and 22 of 312 C-Plots were removed). Since I was only interested in differences in group means I used all four subplots of a tree in the multiple comparisons to differentiate between plots facing the trail and facing away. To account for having multiple measurements per tree, I included the tree as a random effect in linear mixed effects models and tested whether facing trail and other fixed effects (distance from trail, DBH) significantly improved the fit of the model in the different study sites. Models were compared using Aikaike's Information Criterion corrected for small sample size (AICc). For assessment of the models' goodness of fit, I also calculated the marginal r^2 for the fixed effects and the conditional r^2 for fixed effects and random effects combined (Nakagawa & Schielzeth 2013).

I used the Spearman rank correlation to test if the number of sprouts and saplings per plot or the species richness decrease with increasing trampling disturbance.

To evaluate and compare soil compaction measurements within and between sites, I first needed to establish which root growth limiting threshold values to use. Several researchers defined bulk density and soil strength threshold values for different soil types and textures in agricultural, construction and timber harvest settings. They found that light soil compaction increases the water holding capacity and plant available water in fine loamy sands, so threshold values are higher than on finer soils. In Tokunaga's (2006) review of values for soil strength for different crops on fine sandy loam, the same and slightly higher thresholds were found than the ones reported in a USDA Forest Service study (2005) testing different penetrometers. I compared the number of measurement points that were above the threshold at which root growth of most plants is inhibited (15 kg/cm^2) and above the threshold at which the roots of many plants quit growing (25 kg/cm^2, USDA Forest Service 2005) in undisturbed and trampled areas in B- and C-plots. I used linear regression to determine how much of the variance in the compaction and litter depth data could be explained by trampling disturbance and compared mean differences in plant species richness between B- and C-plots and differences between trampled and untrampled litter depth with *t*-tests, adjusting P-values when necessary.

RESULTS

Visitor numbers

Stout Grove

The 10 days when I counted visitors in Stout Grove were at the very beginning of the tourist season (between May 25th and June 4th) and all were weekdays, so they are not representative for the whole range of visitor use. In May, visitor numbers fluctuated by 100%, from 18 to 36 visitors per hour, and an estimated 183 to 362 visitors per day with a mean of 244 visitors per day. The parking lot was often at capacity but not overflowing. Starting on June 1st Howland Hill Road was graded for a week and access to Stout Grove was very limited. Visitor numbers dropped to 8 to 19 visitors per day during that time (**Figure 13**). According to rangers and maintenance staff, visitor numbers in Jedediah Smith Redwoods SP were at a record level in the summer of 2015. In response, a traffic counter was installed at Breen Bridge on Howland Hill Road in mid-July. It recorded a monthly vehicle number between 8,000 and 10,000. It is not possible to use the traffic counter to calculate a site specific visitor estimate for Stout Grove. An anecdotal indicator of the exceptionally high visitor numbers later in the season was the number of cars that sometimes parked all the way out to Howland Hill Road when I drove by the Stout Grove access road on my way to the Grove of Titans in July 2015.

Tall Trees Grove

For nine observation days in June I calculated a mean of 47 visitor, a fifth of that in Stout Grove. Even though all days were weekdays, the fluctuation here was even higher. I counted between 1 and 13 visitors per hour and calculated between 11 and 118 visitors per day. There was a discrepancy between counted visitors and visitor numbers obtained from park permits (**Figure 14**, a detail of **Figure 13**). There are several possible explanations for this discrepancy: Visitors who want to use other trails along Redwood Creek (e.g. Emerald Ridge Trail) also need a permit for the Tall Trees Grove access road, but will use a different trail from the parking lot. Not all visitors who obtain a (free) permit actually come to Tall Trees Grove.

Based on the permits given out between June 1st and Sept 30th, visitor numbers were highest on the July 4th weekend (139 visitors on a single day and 335 for the whole weekend), in the late July heat wave on July 28th (137 visitors on a single day, 350 in three days), and Labor Day weekend (125 visitors on a single day and 304 for the whole weekend). After the middle of September visitor numbers dropped drastically. No visitors came to Tall Trees Grove on weekdays, while on weekends visitor numbers were only slightly below average.Tall Trees Grove had a 32% increase in visitor numbers (NPS 2015b) from 2014 to 2015.

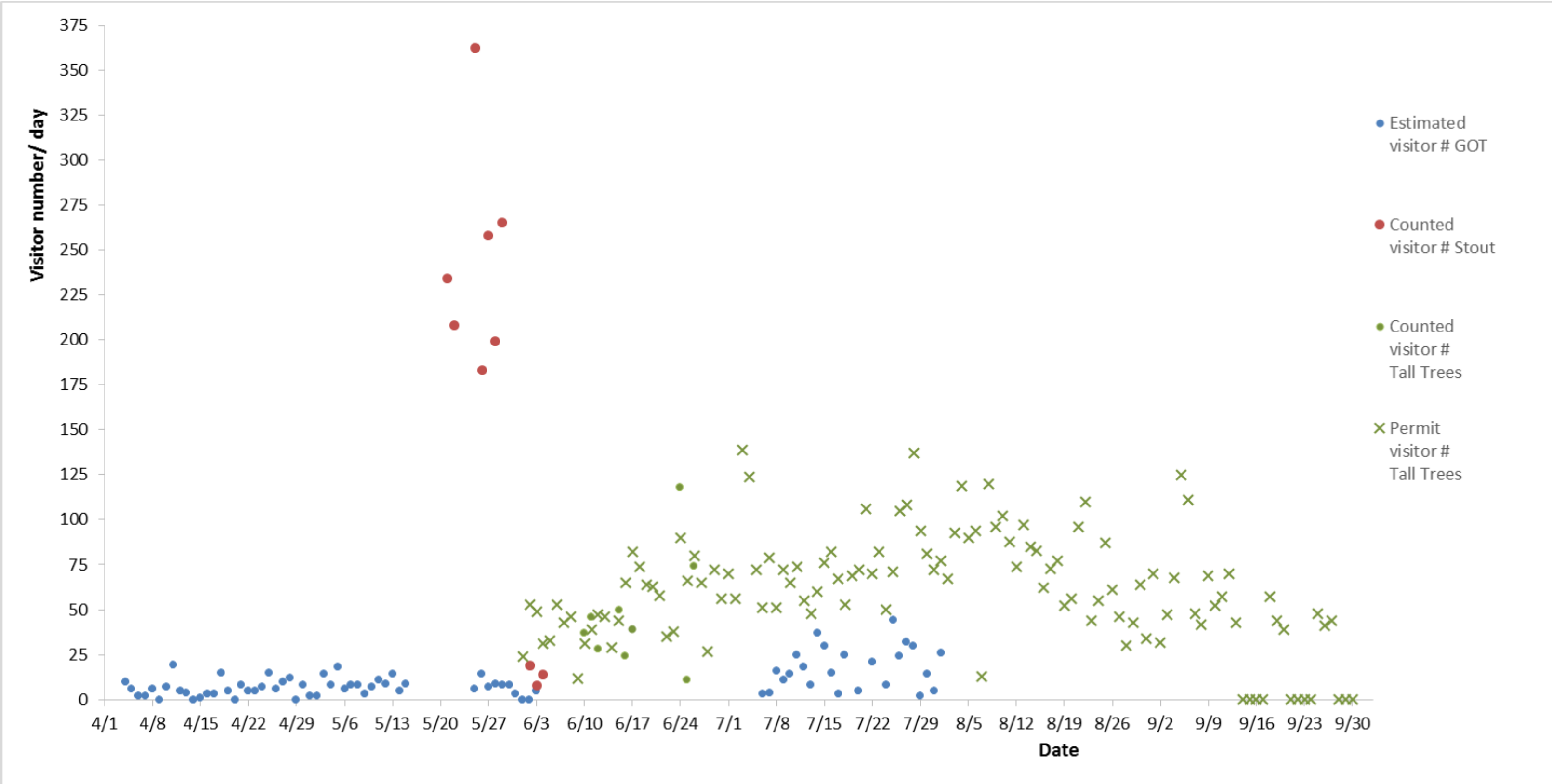

Figure 13. Estimated visitor numbers for all three study sites: Highest use in Stout Grove, where numbers were counted on 10 days in the beginning of the season. For Tall Trees Grove numbers counted on 9 days are compared to numbers obtained from park permits (see 10b). For Grove of Titans (GOT) numbers were tallied from trail camera pictures set up in the grove from Apr 4th to Aug 1st 2015.

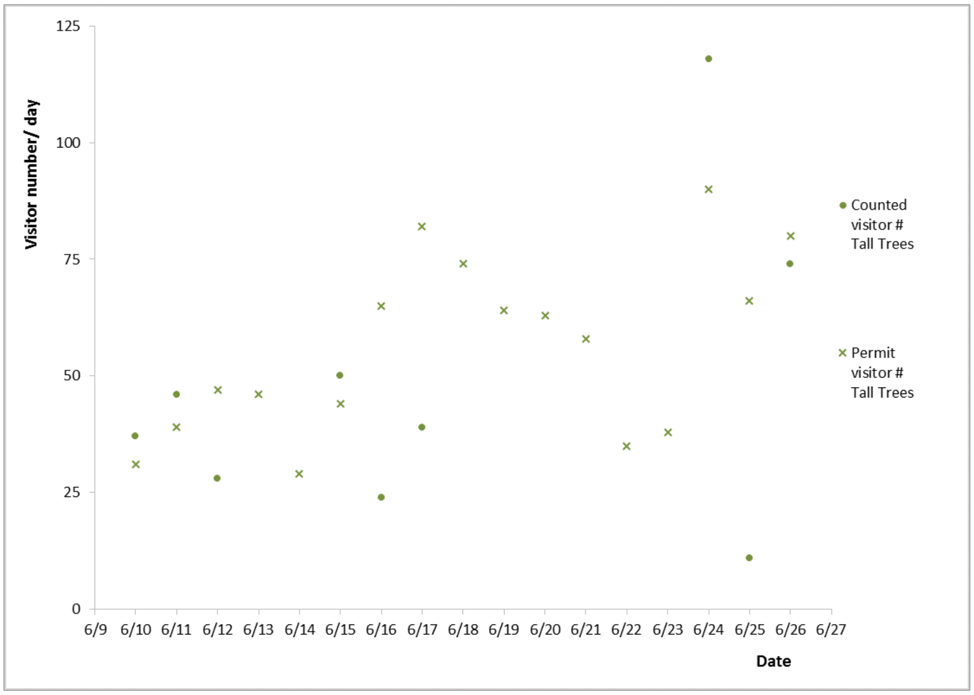

Figure 14. Estimated visitor numbers for Tall Trees Grove. Visitors were counted on nine days in June 2015 and compared to numbers obtained from park permits.

<u>Grove of Titans</u>

I analyzed pictures for 76 of the 141 days between April 4th to August 22th 2015 from seven trail cameras and counted a total of 768 visitors. The mean number of daily visitors was 10, with only six days where no visitors were recorded. In this site, the high visitation seemed unrelated to holiday weekends: On July 14^{th} 2015 37 people and on July 25^{th} 44 people walked into Grove of Titans. In the 234 groups, group size ranged from 1 to 14 people, with an average of 3 people. A group of scientists who did daily fish surveys between mid-March and mid-June and used a trail on the eastern side of Mill Creek (camera 6, see **Appendix A** for a map with the position of the cameras) were not counted as visitors.

Many visitors did not just take pictures and pass through the Grove of Titans but stayed for extended amounts of time, some of them returning multiple times to the same spot within the course of hours. Visitor use was most concentrated in the area around trail camera 2 (293 visitors, **Figure 15**). Camera 7 was installed later (on May 25th), so it was only included on 30 of the days I analyzed. Half of the 234 groups only appeared on one camera, a quarter of them (59 of 234) appeared on two cameras, and the remaining quarter appeared on ≥ three cameras. Only five groups crossed the creek, appearing on camera 6 and at least one camera on the western side of the creek. The trail entrance upslope from Tree 13 seemed to be effectively closed with woody debris, since only 34 people appeared on trail camera 5 and – where it was possible to tell - all of them seemed to be coming from Tree 13.

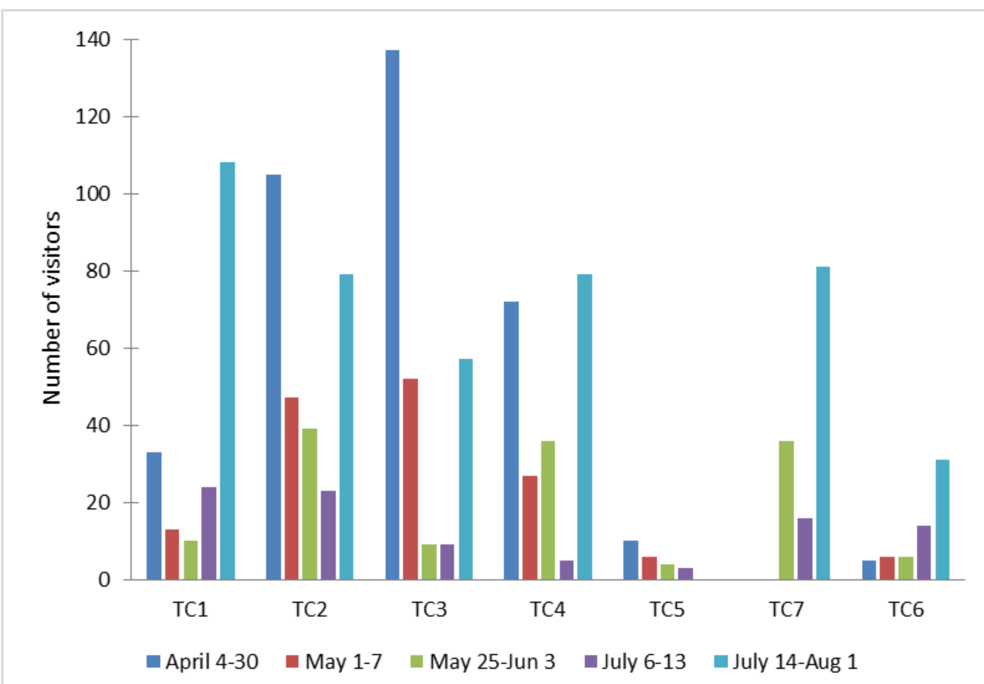

Figure 15. Distribution of visitors to the Grove of Titans over seven trail cameras (TC1-TC7) for five time periods between April 4 and Aug 1 2015.

Spatial Distribution of Trampling Disturbance

Overall degree of disturbance within the study sites

Stout Grove

In Stout Grove, trampling disturbance was concentrated around trees, snags and logs that were close to the formal trails and easily accessible but trampling was also quite evenly spread on the inside of the loop (**Figure 16**). Most of the 20 reference trees (which had no social trails at the time of mapping) were on the western side of the grove, outside of the Stout Grove Loop Trail. The trampled area adds up to 10.4% of the total area within the study site, making it the most disturbed and the most severely disturbed (class 5) of the three sites (**Table 3**). Almost all class 5 trampled areas, completely barren or only covered with pulverized litter and small woody debris, were adjacent to the formal trail. Relative to the size of the study sites, Stout Grove had nine times more class 5 trampled area than Tall Trees Grove or Grove of Titans.

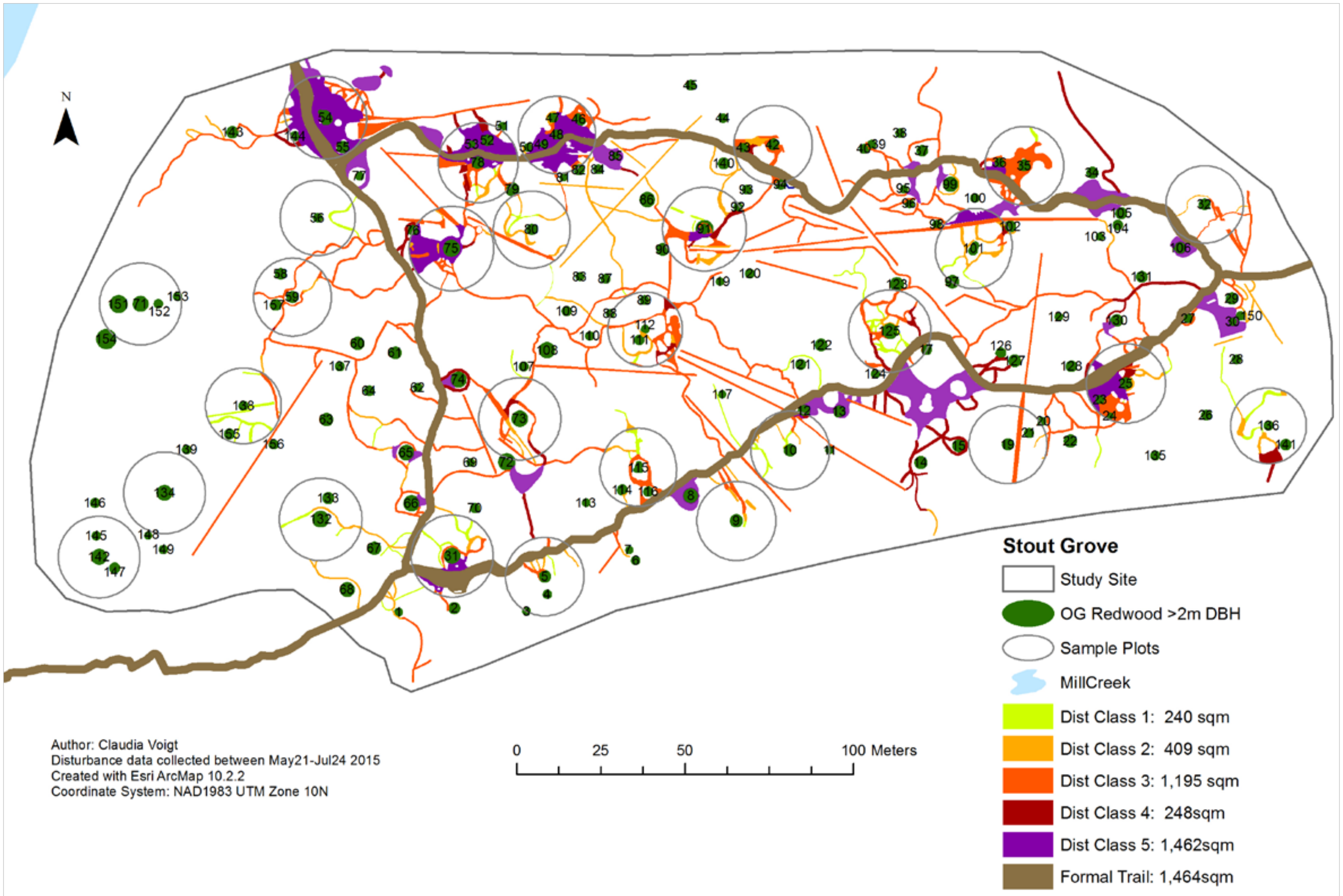

Figure 16. Stout Grove social trail network and areas disturbed by trampling, including trampling on downed logs (visible as straight lines). Disturbance is concentrated around trees that are close to the formal trails and easily accessible but also quite evenly spread on the inside of the loop. The trampled area adds up to 10.4% (5,632m^2) of the total area within the study site, making it the most disturbed of the 3 study sites. The highest trampling disturbance does not occur in the plot around the Stout tree but in a plot on the intersection with the Hiouchi Trail.

Table 3. Spatial measures of social trails for three study sites with 2015 data. Overall amount of trampling disturbance in Tall Trees Grove is similar to Stout Grove, but much less severe (less class 5, more class 2 disturbance, pink shading). Overall trampled area in Grove of Titans is a third of that in Stout Grove, but trail density is half as high as in Stout Grove (59%, yellow shading).

		Stout Grove	**Tall Trees Grove**	**Grove Of Titans**
Size of study site		55,116 m^2	107,510 m^2	94,026m^2
Disturbed area as % of study site	**Total**	**10.4% (5,632 m^2)**	**7.6% (8,027 m^2)**	**3.7% (3,317 m^2)**
	Condition class 1	0.4% (240 m^2)	0.5% (540 m^2)	0.3% (305 m^2)
	class 2	0.8% (406 m^2)	1.3% (1,398 m^2)	0.6% 570 m^2)
	class 3	2.2% (1,191 m^2)	2.0% (2,149 m^2)	0.9% (817 m^2)
	class 4	0.5% (248 m^2)	0.9% (969m^2)	0.8% (677 m^2)
	class 5	2.7% (1,462 m^2)	0.3% (347m^2)	0.3% (244m2)
	Formal Trail	3.8% (2,07 8m^2)	2.4% (2,612 m^2)	0.8% (705 m^2)
Trail length	Formal Trails Total	844 m	1,617 m	705 m
	Social Trails Total (incl. trails on downed logs)	**4,362 m** (5,409 m)	**6,420 m** (7,080 m)	**4.597 m** (4,831 m)
Trail density	Social Trails (incl. trails on downed logs)	**791 m/ha** (981 m/ha)	**597 m/ha** (659 m/ha)	**489 m/ha** (514 m/ha)
# of trails	Social Trails Total	207 trails plus 31 trails on downed logs	280 trails plus 30 trails on downed logs	227 trails plus 29 trails on downed logs
Trail Extent (not incl. trails on logs)	Social Trails/ ha	37	**26**	**23**

<u>Tall Trees Grove</u>

In Tall Trees Grove, trampling disturbance was more difficult to classify for two reasons. There is naturally less vegetation cover (see cover and vegetation metrics) than in the other two, moister, sites, which meant that social trail boundaries and also formal trail boundaries were less defined. Additionally, elk and deer had created many game trails, which were hard to distinguish from the lightly used social trails. Only 5 of 121 mapped old-growth redwood trees had no trampling disturbance. In my pilot study, conducted in November 2014, there was a dense fern forest in the southern quadrant of tree plot 79 (**Figure 17**). When I collected the field data in June 2015, browsing damage was evident on many sword ferns (young shoots and frond tips were eaten) and the trampling disturbance I recorded there did not connect to the formal trail.

Figure 17. Southern quadrant of tree 79 in Tall Trees Grove; left: dense fern forest with no browsing damage in Nov 2014, right: browsing damage on many sword ferns and trampling that didn’t connect to formal trail in June 2015.

The overall amount of trampling disturbance in Tall Trees Grove (7.6% of the total area) was similar to Stout Grove, but the disturbance was less severe. There was much less area in condition class 5 (0.3%), and as a result of the light use and the many game trails, there was more class 1 and 2 disturbance here than in the other two groves (**Table 3**, **Figure 18**). Of the 30 sample plots, the four plots with the most trampled areas (~ 50% disturbance) were relatively close to the entrance of the loop trail. Mean trail width for trail condition classes 1-4 (which were used to buffer the digitized line features) differed between the study sites (**Table 4**). In Tall Trees Grove the less defined trail boundaries resulted in wider trails.

Table 4. Comparison of mean social trail width for trail condition classes 1-4 and formal trail width in all 3 study sites (Stout Grove *n* = 49 measurements (class 1), 50 (class 2), 52 (class 3), 12 (class 4); Grove of Titans *n* = 10, 41, 78, 42; Tall Trees Grove *n* = 12, 19, 41, 15).

Condition class	Stout Grove	Grove of Titans	Tall Trees Grove
1	0.40 m	0.35 m	0.45 m
2	0.45 m	0.40 m	0.50 m
3	0.65 m	0.55 m	0.70 m
4	1.00 m	0.75 m	0.90 m
Formal Trail	2.40 m	1.00 m	1.60 m

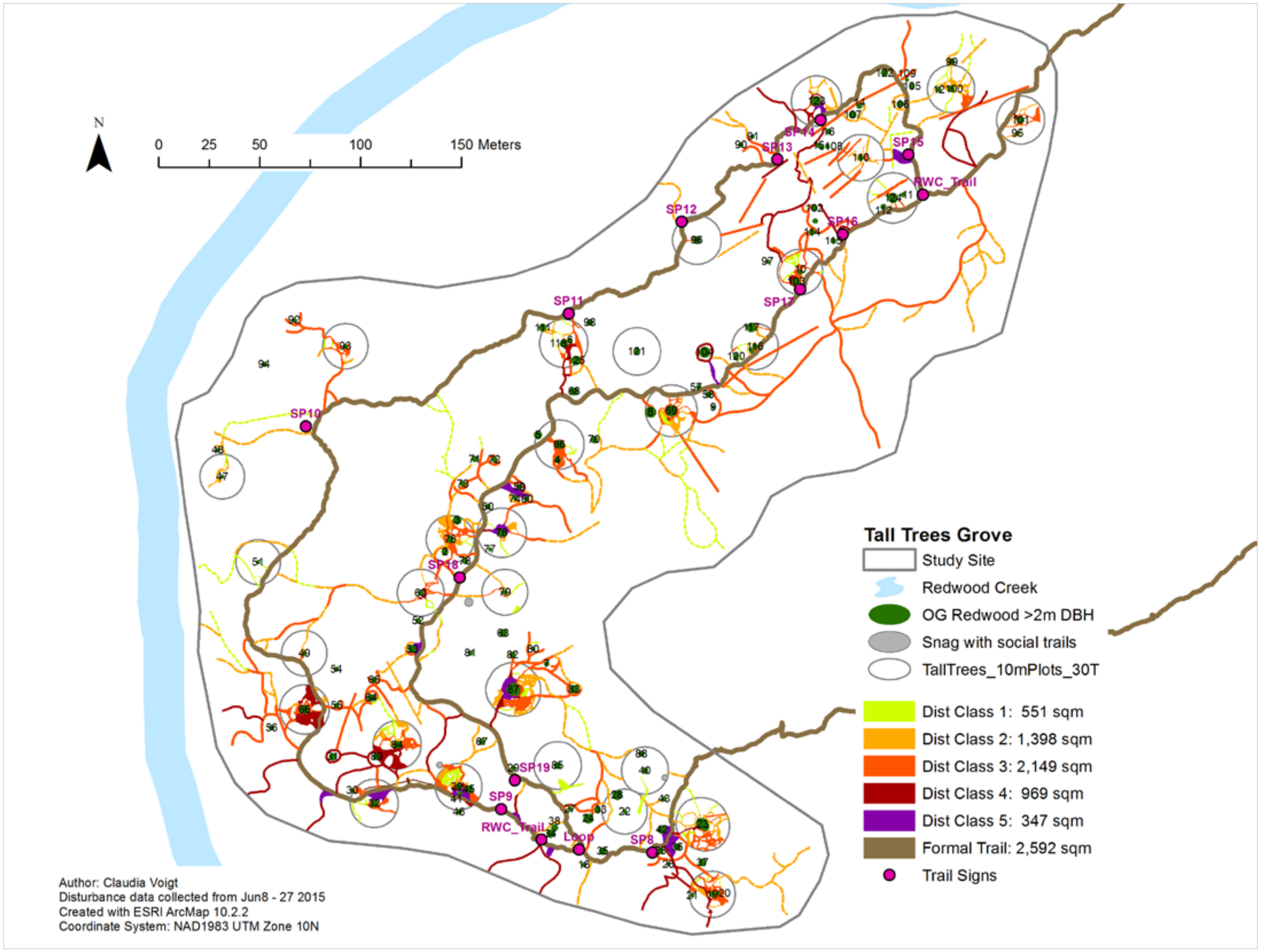

Figure 18. Tall Trees Grove social trail network and areas disturbed by trampling, including trampling on downed logs. The 4 plots with the biggest trampled areas (around 50 % disturbance) were relatively close to the entrance of the loop trail. The trampled area adds up to 7.6% (8,027 m^2) of the total area within the study site.

Grove of Titans

In Grove of Titans, disturbance was quite evenly spread throughout the study site and not as concentrated around individual trees as in the other two sites (**Figure 19**). The trees with the smallest DBH and low trampling disturbance were on the overall less trampled eastern side of Mill Creek. Total disturbed area in Grove of Titans was one third of that in Stout Grove (3.7% of the total area within the study site), but with 489 m of social trail per ha, trail density was almost two thirds of that calculated for Stout Grove (791m/ha) and the number of social trails per ha was almost as high as in Tall Trees Grove (23 vs. 26 trails/ ha, **Table 3**).

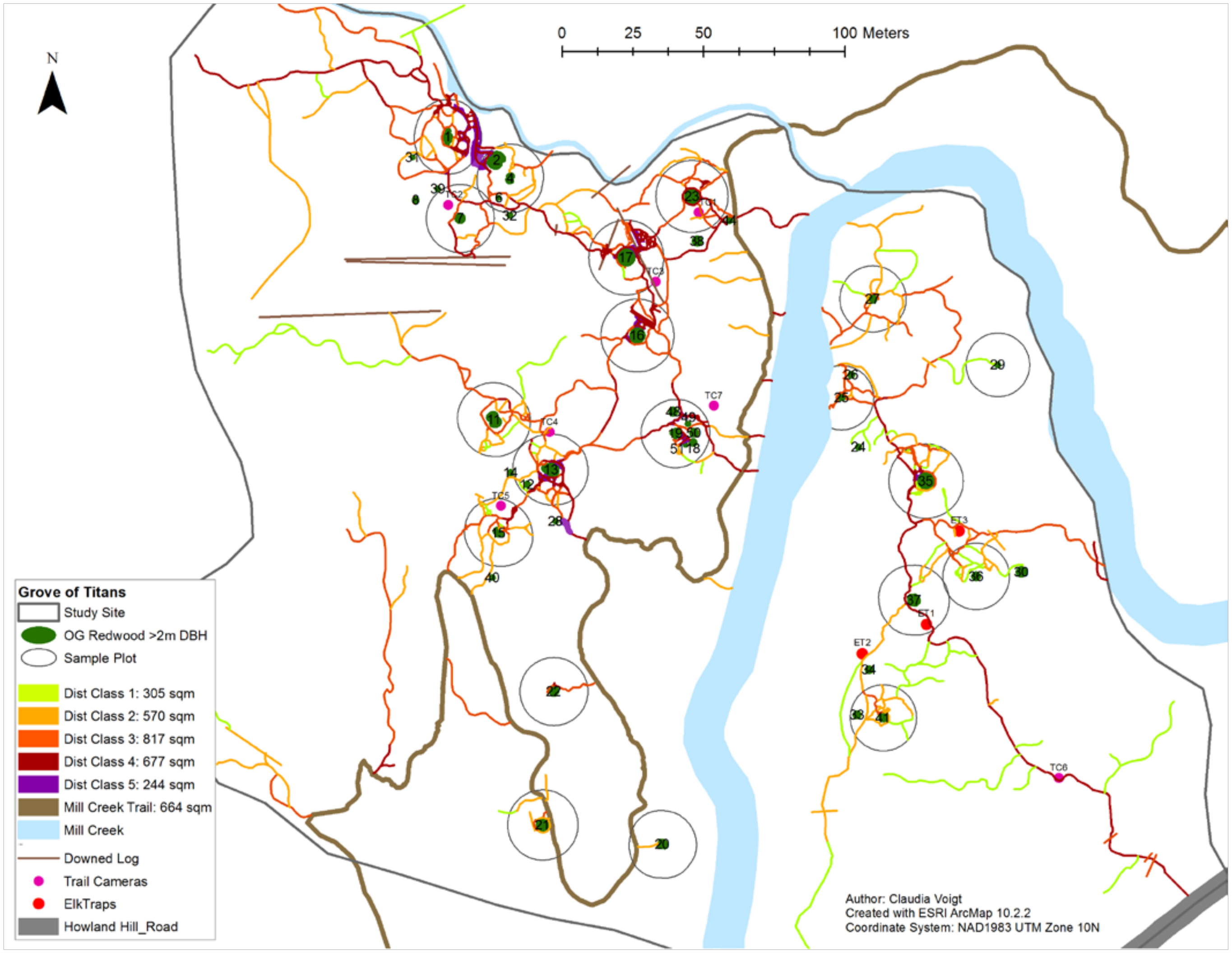

Figure 19. Grove of Titans social trail network and areas disturbed by trampling, including trampling on downed logs. Disturbance is quite evenly spread throughout the study site and not as concentrated around individual trees as in the other two sites. The trees with the smallest DBH and low trampling disturbance within the plot were on the overall less trampled eastern side of Mill Creek.

Trampling disturbance on the plot level

The role that tree size and distance from the formal trail play in explaining variation in trampling disturbance was different in the different sites. Linear regression analysis revealed that for sample plots in Stout Grove, percent trampled area was not significantly related to the size of the trees ($r^2 = 0.01$, df=26, $P = 0.55$). The three undisturbed trees were all bigger than the tree with highest amount of disturbance (**Figure 20**). The distance of the sample trees from the formal trail, however, explained 61% of the variation in trampling disturbance ($r^2 = 0.61$, df=26, $P < 0.001$, for log transformed data). The three most disturbed plots were closest to the trail (**Figure 21**). According to the regression model, for every meter further away from the trail, the estimated mean disturbance decreased by six percent (95% CI: 4.2% to 7.8% decrease).

In both Tall Trees Grove and Grove of Titans, however, percent plot disturbance was positively related to DBH (**Figure 22** and **Figure 24**). In Tall Trees Grove the percentage of variance explained was relatively low ($r^2 = 0.22$, df=28, $P = 0.009$). According to the model for each 50cm increase in DBH, the estimated mean disturbance increased by 3.2 percentage points (95% CI: 1.0 to 5.4 increase). For Grove of Titans an outlier was removed to meet the assumption of residual normality. Tree size explained 46% of the variation in trampling ($r^2 = 0.46$, df=17, $P = 0.001$). For each 50cm increase in DBH, the estimated mean disturbance increased by 1.7 percentage points (95% CI: 0.9 to 2.6 increase).

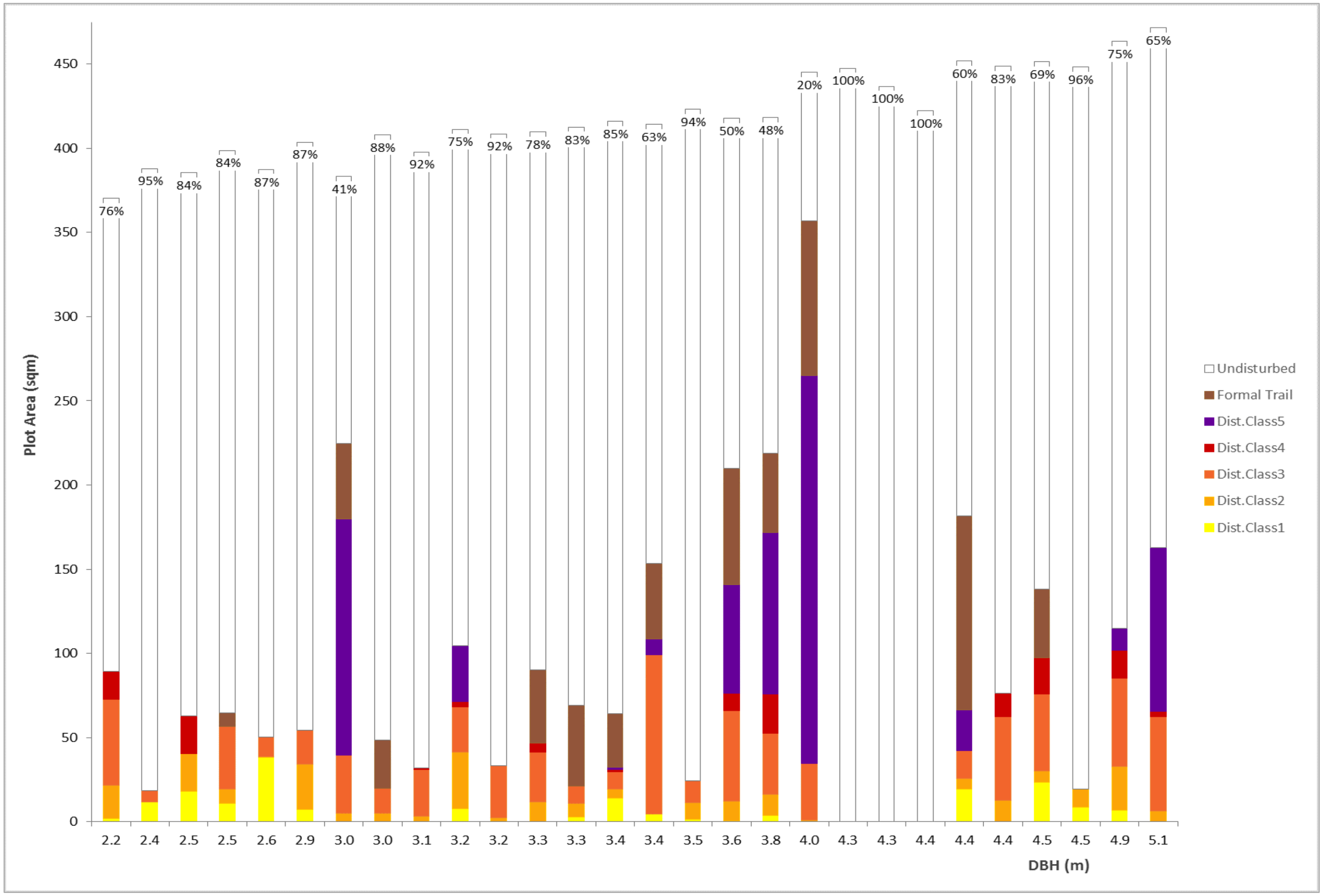

Figure 20. Stout Grove: Relation between a trees' DBH and the area (m^2) in sample tree plots (n=28) taken up by social trail condition classes 1-5, formal trail and untrampled area. Percentage at the top of each column represents the amount of undisturbed area per plot. For this sample, percent disturbed plot area is not significantly related to the size of the trees (e.g. for 3 tree plots without trampling trees are bigger than tree with highest trampling disturbance, (r^2 = 0.01, df=26, P = 0.55).

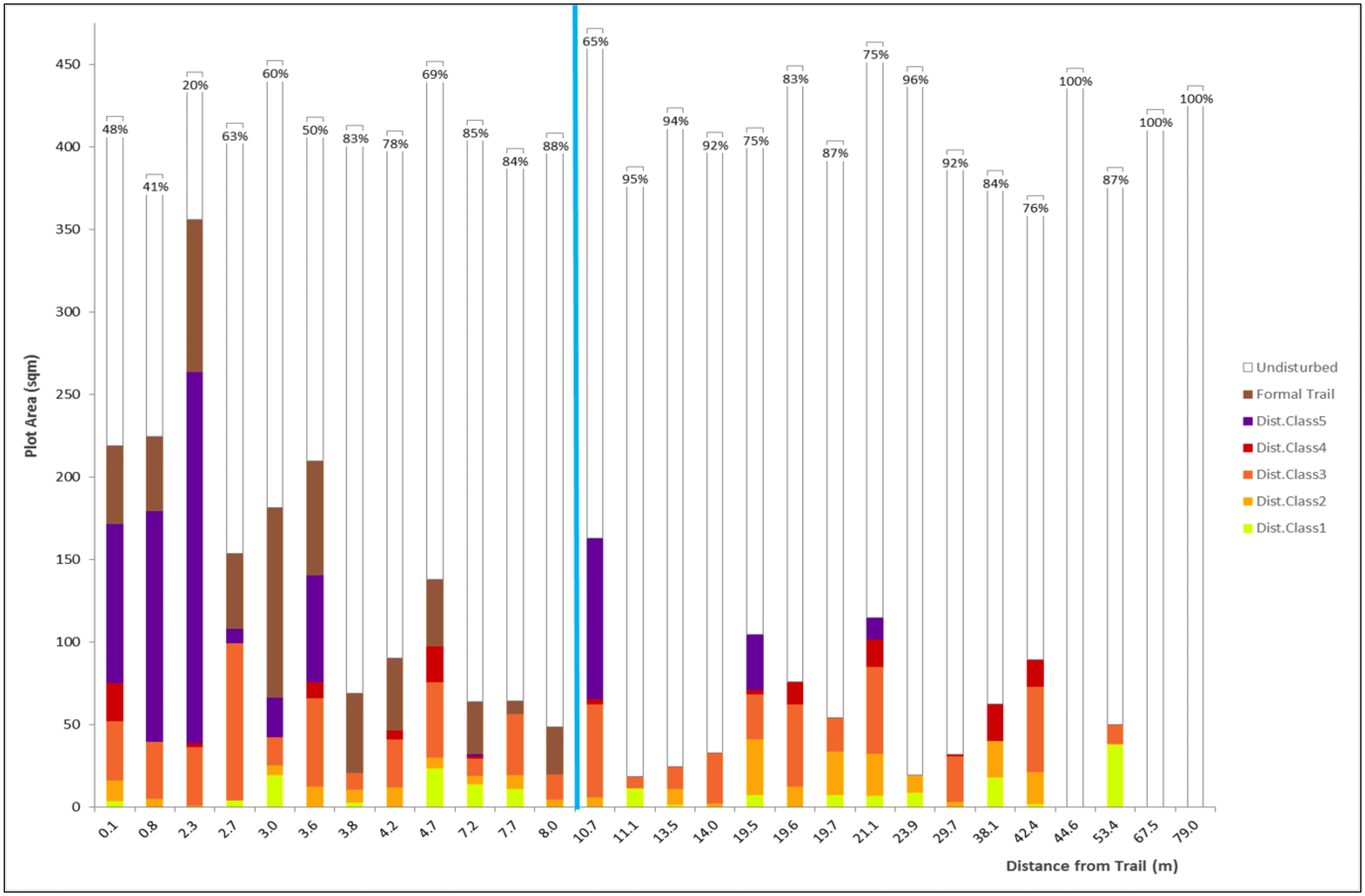

Figure 21. Stout Grove: Relation between a tree's distance from the formal trail and the area (m^2) in sample tree plots (*n*=28) taken up by social trail condition classes 1-5, formal trail and untrampled area. Percentage at the top of each column represents the amount of untrampled area per plot. Trees to left of blue line were less than 10m away from formal trail so their plots overlapped the trail. Percent trampled plot area is negatively related to distance from trail (r^2 = 0.61, df=26, P < 0.001, for log transformed trampling data). The three most disturbed plots (blue circle) are closest to the trail.

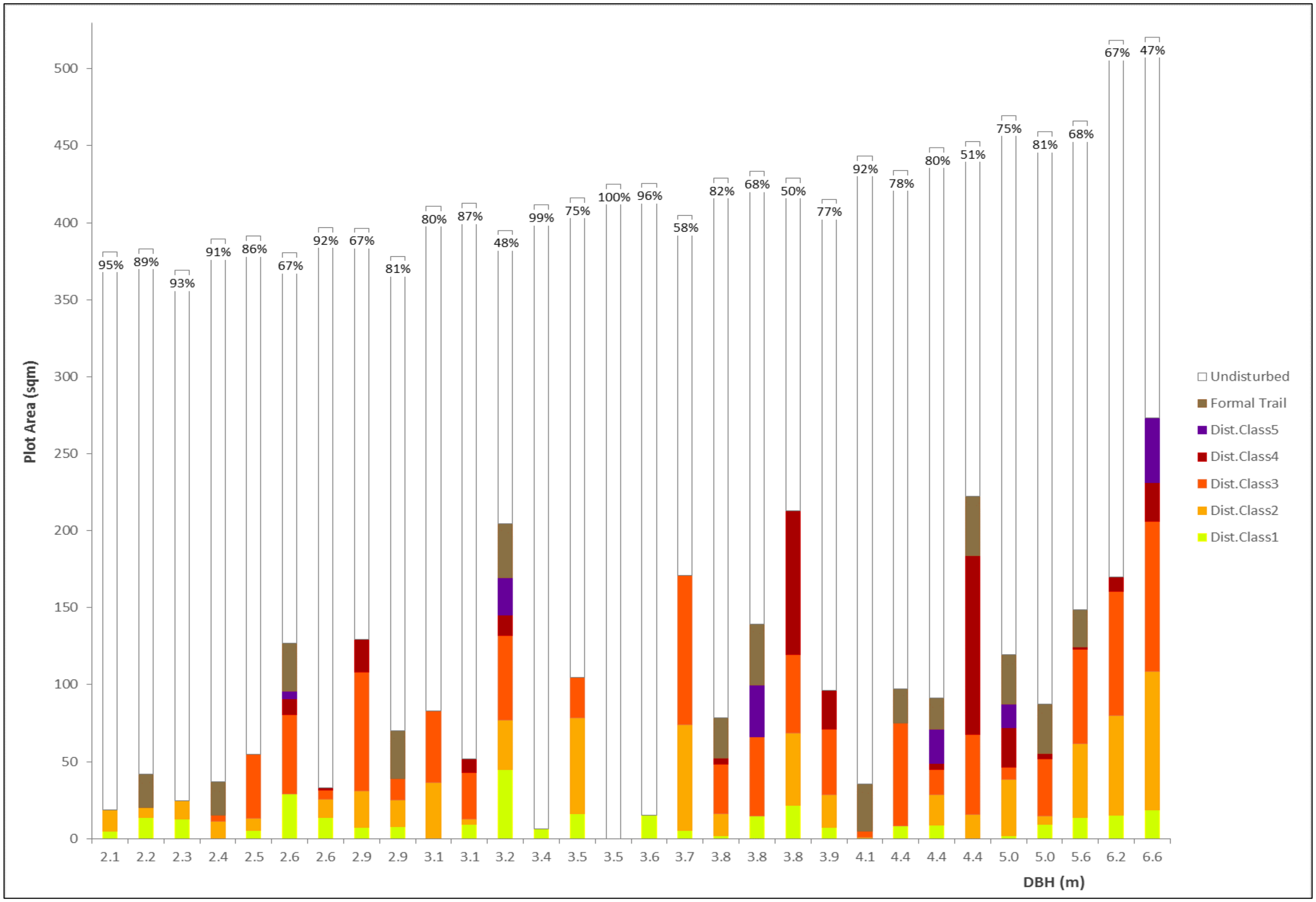

Figure 22. Tall Trees Grove: Relation between a tree's DBH and the area (m^2) in sample tree plots (n=30) taken up by social trail condition classes 1-5, formal trail and untrampled area. Percentage at the top of each column represents the amount of undisturbed area per plot. For this sample, percent disturbed plot area is positively related to DBH of the trees (r^2 = 0.22, df=28, P = 0.009).

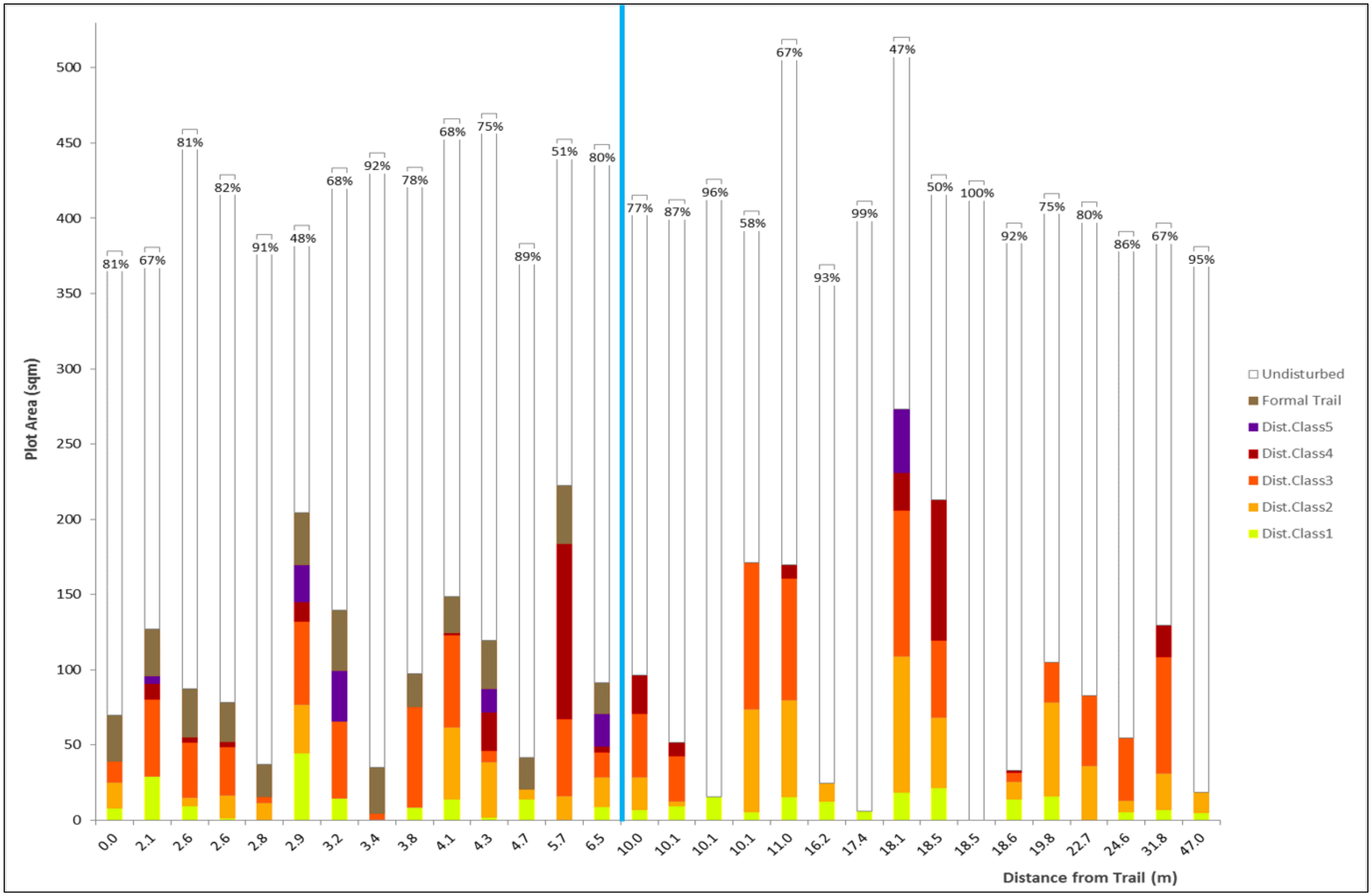

Figure 23. Tall Trees Grove: Relation between a tree's distance from the formal trail and the area (m^2) in sample tree plots (n=30) taken up by social trail condition classes 1-5, formal trail and untrampled area. Percentage at the top of each column represents the amount of untrampled area per plot. Trees to left of blue line were less than 10m away from formal trail so their plots overlapped the trail. In this grove, plot disturbance was not significantly related to distance from trail (r^2 = 0.06, df=28, P = 0.18, for log transformed trampling data).

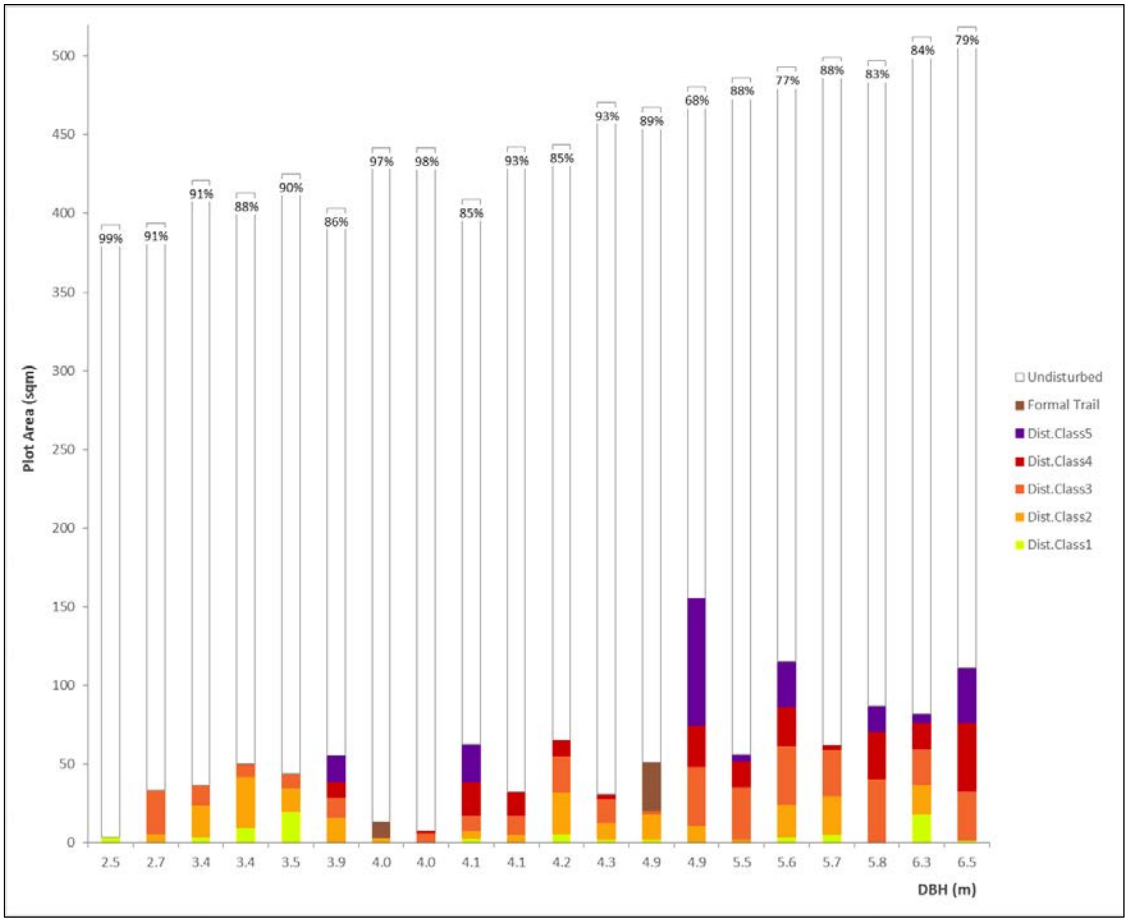

Figure 24. Grove of Titans: Relation between a tree's DBH and the area (m^2) in sample tree plots (*n*=20) taken up by social trail condition classes 1-5, formal trail and untrampled area. Percentage at the top of each column represents the amount of untrampled area per plot. For this sample, percent disturbed plot area is positively related to DBH of the trees ($r^2 = 0.46$, df=17, $P = 0.001$).

For the sample plots in Tall Trees Grove, percent trampled area was not significantly related to distance from formal trail ($r^2 = 0.06$, df=28, $P = 0.18$, for log transformed trampling data, **Figure 23**).

The highest trampling disturbance in Stout Grove (80% of 445 m^2) did not occur in the plot around the Stout Tree but in a plot at the intersection of the Loop Trail and the Hiouchi Trail, in the northwest corner of the study site (**Figure 25**).

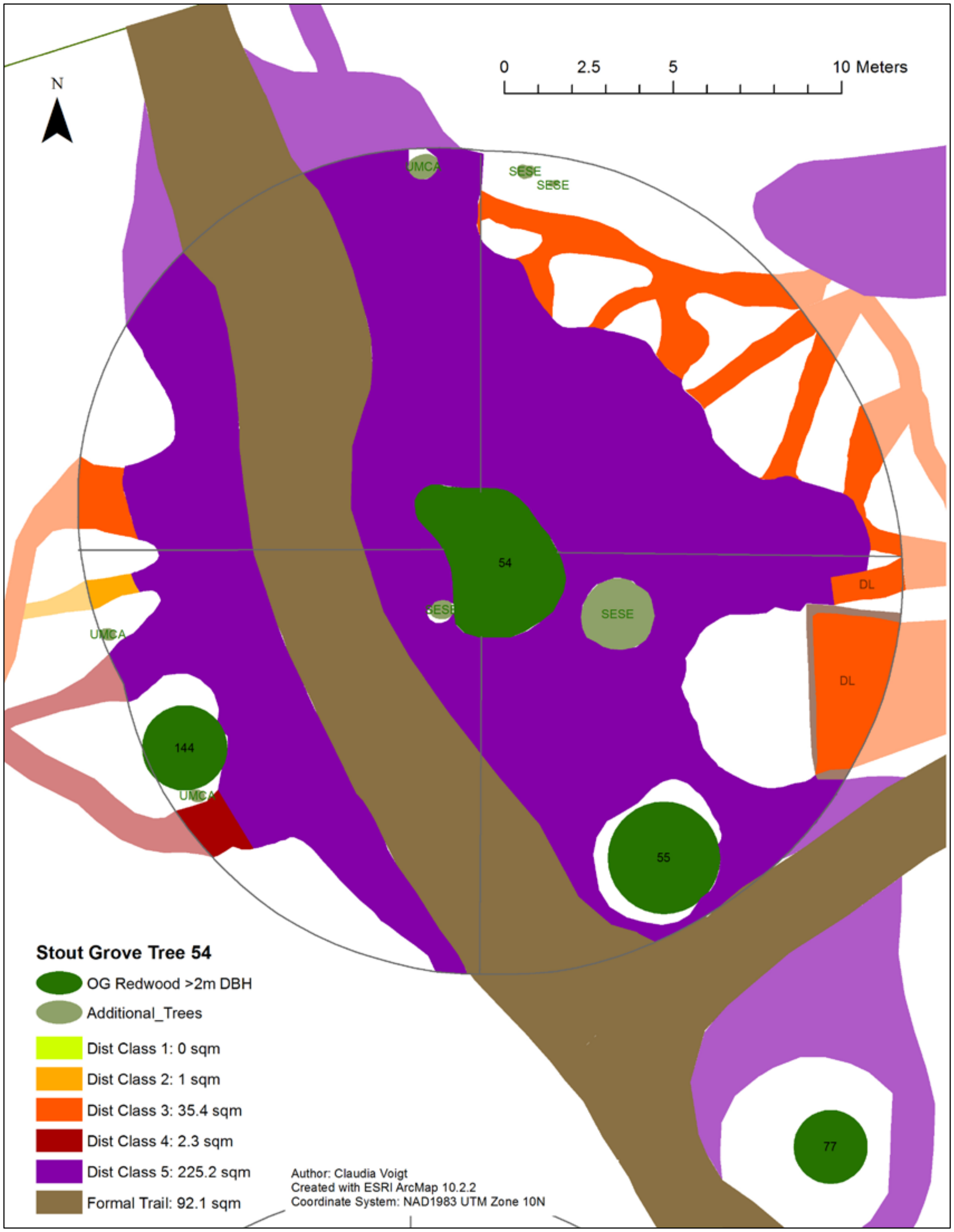

Figure 25. Plot diagram for tree 54, the tree plot with the largest trampled area (80% of 445 m^2) in **Stout Grove.** The plot is located on the intersection with the Hiouchi trail around a tree with many prominent features: three twisted stems with braided bark and a reiteration.

That tree has many prominent features; its three twisted stems are covered in braided bark and an interesting reiteration is visible from the trail (**Appendix D**). **Figure 26** shows the plot diagram of one of the three tree plots in Stout Grove with 0% trampling disturbance. This tree is far away from the formal trail, has a single stem without prominent features, and there are many large downed logs in the plot (**Appendix D**).

The tree plot with the largest trampled area in Tall Trees Grove (53% of 520 m^2) was around the tree with the largest DBH in the grove, one of the record holder trees that has been named and referenced on different websites (Fusion Giant or Melkor, **Figure 27**). The tree is easily visible from the trail, burls grow around half of its circumference, and it splits into two stems high up (**Appendix D;** plot diagrams with little trampling disturbance for Tall Trees Grove and Grove of Titans can be found in **Appendix E**).

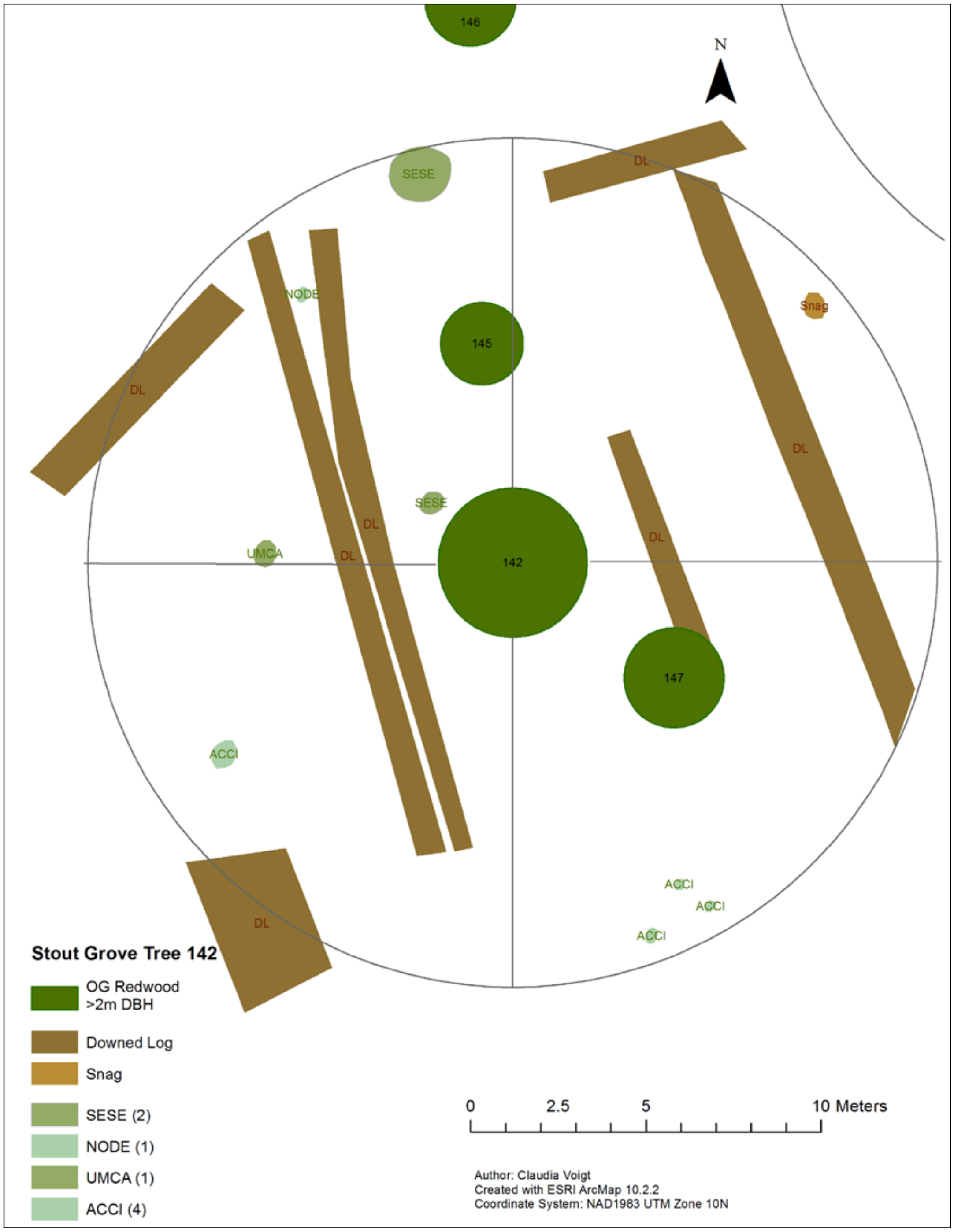

Figure 26. Plot diagram for tree 142, one of the three tree plots in **Stout Grove** with 0% trampling disturbance. The tree is far away from the formal trail, has a single stem without prominent features, is surrounded by two other old-growth redwoods and there are many big downed logs in the plot.

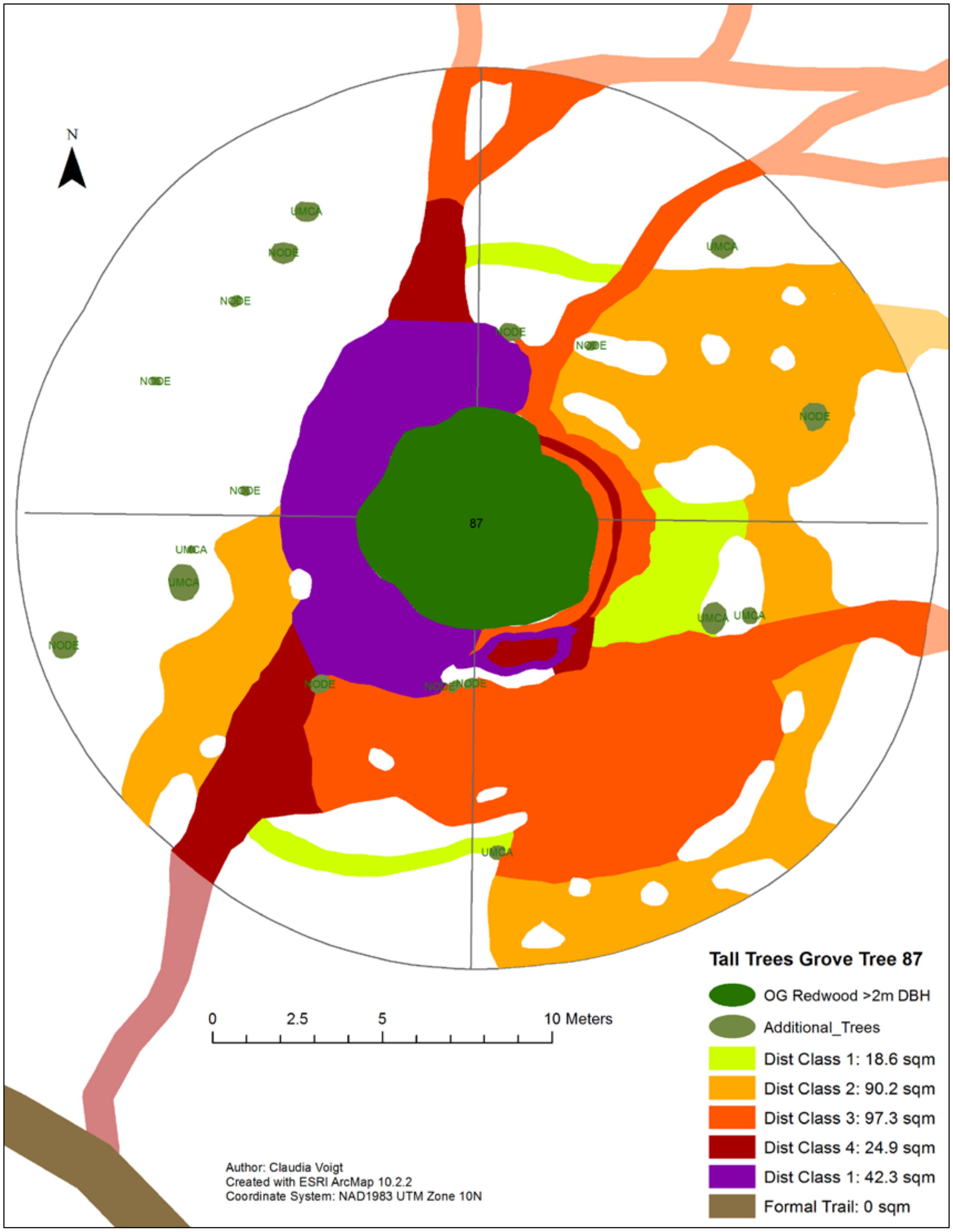

Figure 27. Plot diagram for tree 87, the plot with the biggest trampled area (53% of 520 m^2) in Tall Trees Grove. The plot is around the tree with the largest DBH in the grove, one of the record holder trees that has been named and referenced to on different websites (Fusion Giant, Melkor).

In Grove of Titans, the plot of Tree 1 has the largest trampled area (32% of 480 m^2) of the 20 sample trees (**Figure 28** and **Figure 29**). This three-stem tree stands across from tree 2, one of the most “famous” titans (“Screaming Titans”). Tree 2 has even more trampling directly at the tree base and the proximity partly causes the trampled area on the eastern side of Tree 1.

Figure 28. Trampling disturbance in tree plot 1 of Grove of Titans.

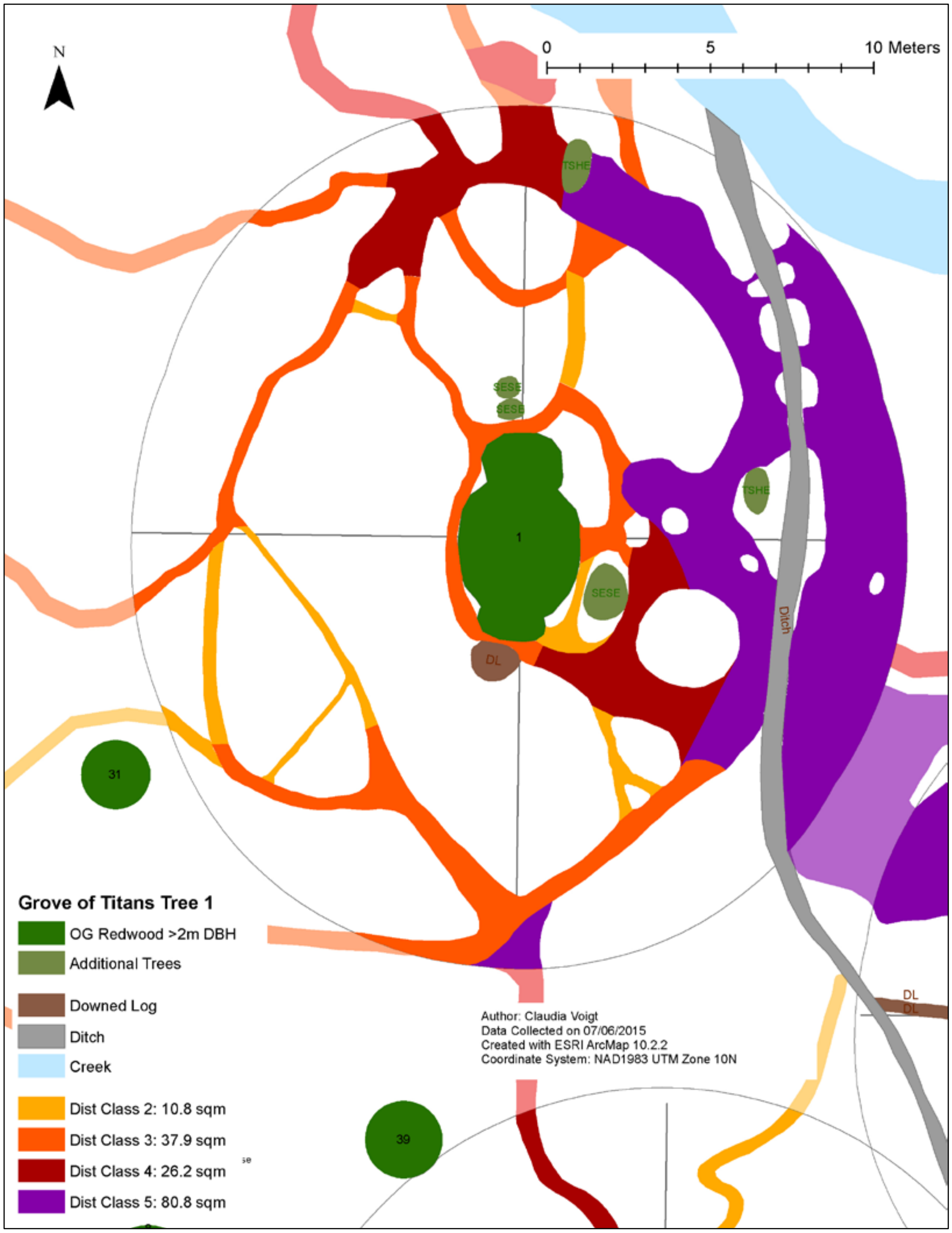

Figure 29. Plot diagram for tree 1, the plot with the largest trampled area (32% of 480 m^2) in the Grove of Titans. This 3-stem tree stands across from tree 2, one of the most “famous” titans (“Screaming Titans”). Tree 2 has even more trampling directly at the tree base and partly causes the trampled area on the eastern side of the plot for tree 1. The armored banks of a manmade ditch on plot 1’s eastern side have remained a sparsely vegetated area that is especially heavily trampled.

In Stout Grove, the number of quadrants, where both B-plots (close to the tree) and C-Plots (5-7 m away from the tree) were completely undisturbed was much higher than in the other two groves (**Table 5**). A quarter of all quadrants were undisturbed, and 14 of these 26 undisturbed quadrants were facing away from the trail. Because of the high number of undisturbed B-plots, mean and median trampled area was lower in Stout Grove B-plots than in Tall Trees and Grove of Titans (**Figure 30**). I had expected disturbance to be higher in B-plots than in C-plots, especially in plots facing the trail and in those adjacent to them. In Stout Grove this was not the case for plots facing the trail; in 13 of 34 plots percent disturbed area in the C-plots was much higher than in B-plots. I found these 13 plots around trees which were relatively close to the formal trail, which might explain why the C-plots were more trampled than the B-plots. In B-plots adjacent to those facing the trail, mean disturbance was significantly higher than in the C-Plots (Holm adjusted P=0.004, **Table 5**).

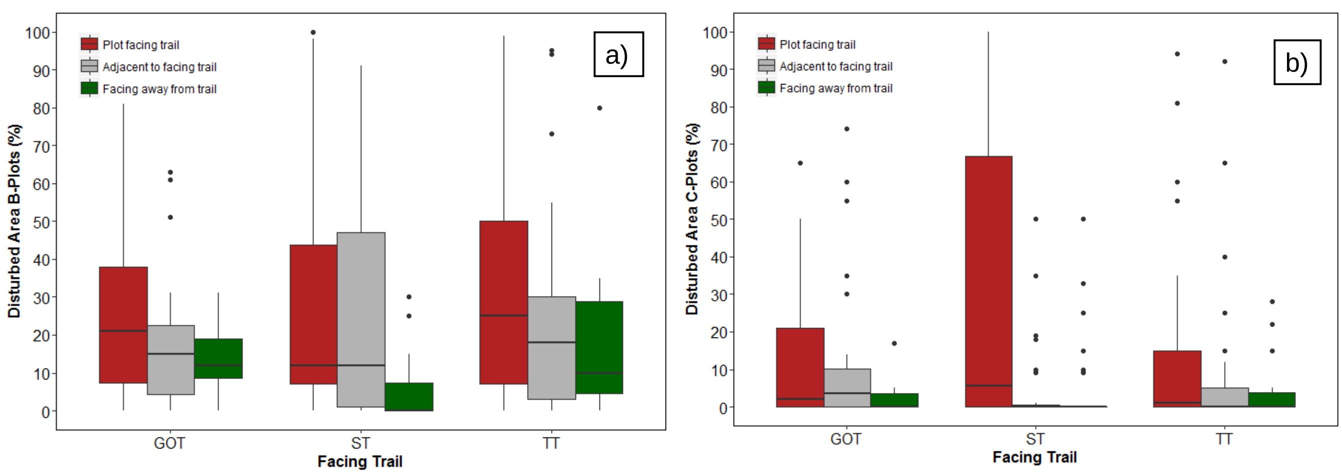

Figure 30. Difference in mean disturbed area between B-plots (30a, n=302) and C-plots (30b, n=290) for plots facing the formal trail or a class 4 social trail (1), plots adjacent to those (2) and plots facing away (3) in all three study sites (GOT= Grove of Titans, ST= Stout Grove, TT=Tall Trees Grove).

In Tall Trees Grove, mean disturbance was significantly lower in all C-plots than in B-plots, independent of whether the plots were facing the trail or not. In Grove of Titans I observed the same trend; the difference was significant for plots facing the trail and for adjacent plots (**Table 5**).

Table 5. Pairwise comparison of percent disturbed area between B-plots (n=283) and C-plots (n=279) split up for plots facing the formal trail or a class 4 social trail (1), plots adjacent to those (2), and plots facing away (3) in all three study sites (pairwise t-test with Holm adjustment of p-values).

Site	**Facing Trail**	***Total # of B-plots***	# of plots **%trampled area in B and C=0**	# of plots **Difference B-C > 0**	# of plots **Difference B-C < 0**	**Mean difference B-C [95% CI]**	***Adjusted P****
Stout Grove	1	*34*	4	17	13	-3 [-14 / 7]	0.506
	2	*29*	8	17	2	22 [9 / 33]	**0.004**
	3	*34*	14	13	7	-0.5 [-5 / 4]	0.599
Tall Trees Grove	1	*43*	7	29	7	22 [4 / 30]	**<0.001**
	2	*51*	11	34	4	13 [4 / 22]	**0.020**
	3	*14*	3	10	1	11 [3 /19]	**0.018**
Grove of Titans	1	*39*	4	26	9	14 [5 / 23]	**0.014**
	2	*24*	3	16	4	8 [1 / 14]	**0.036**
	3	*15*	1	12	1	5.3 [-2 / 13]	0.250

* Significant differences at > 95% level in bold.

Even though overall disturbance in Grove of Titans was less severe than in the other two groves, it was so wide-spread that fewer than ten percent of all B- and C-plots were completely undisturbed.

In Stout Grove, two variables - ‘facing trail’ (F=12.9, P < 0.001) and ‘distance from trail’ (t= -6.9, P < 0.001) - had significant effects on log transformed percent

disturbed area in the B-plots, and similar to results for the whole plots, DBH did not have a significant effect (*t*= 1.6, *P*=0.11). However, 'facing trail' did not improve the AICc score of a linear mixed effects model once 'distance from trail' had been accounted for (AICc of 'Facing Trail + Distance + 1 | TreeNr' = 426;
AICc of 'Distance + 1 | TreeNr' = 422, **Appendix F**).
The random effect added for multiple observations per tree had a meaningful effect in the model (Intra Class Correlation (ICC) = 0.39). Comparing individual levels of 'facing trail', there was a large difference in disturbance: In B-plots and C-plots facing trails disturbance was, on average, 25 percentage points higher than in plots facing away from trails (**Table 6**).

In Tall Trees Grove, there was no significant difference between plots facing the trail and facing away. In a linear mixed effects model, the only significant predictor for untransformed disturbance was DBH ($P < 0.001$) but it explained as little variance as in the linear model for the whole plots (marginal $r^2 = 0.23$). The random effect added for tree explained an additional 27% of the variance in the data (ICC= 0.27).

The plots in Grove of Titans showed the same trend as the ones in Stout Grove: there was significantly less trampling in plots facing away from the trails than in plots facing trails. But alarmingly, mean disturbance in the few B-plots facing away from the trail was much higher in Grove of Titans (14%) than in Stout Grove (5%).

Table 6 Multiple comparisons of mean percent disturbed area between plots facing a formal trail or a class 4 social trail (1), plots adjacent to those (2) and plots facing away (3) for B- and C-plots in all three study sites (Games-Howell Test).

	Facing Trail	**Stout Grove**		**Tall Trees Grove**		**Grove of Titans**	
		Adjusted p-values*	Mean % disturbance	Adjusted p-values*	Mean % disturbance	Adjusted p-values*	Mean % disturbance
B-plots	1-2	0.99	28-28	0.19	30-21	0.23	26-18
	1-3	**< 0.001**	28-5	0.20	30-18	**0.02**	26-14
	2-3	**0.002**	28-5	0.85	21-18	0.68	18-14
C-plots	1-2	**< 0.001**	31-5	0.38	12-7	0.98	14-13
	1-3	**< 0.001**	31-5	0.22	12-5	**0.005**	14-2
	2-3	1.0	5-5	0.90	7-5	0.07	13-2

* Significant differences at > 95% level in bold.

Resource conditions: Cover, vegetation and soil metrics

After giving a comprehensive picture of the differences in disturbance between sites and plots and examining which factors might explain these differences in trampling disturbance, in this section I evaluate the relationships amonng trampling disturbance and certain vegetation and soil metrics.

<u>Ground cover</u>

In all study sites, most social trails were almost completely devoid of vegetation; disturbed area overlapped with vegetation cover in only six of 302 B-plots and three of

298 C-plots. B- and C-Plots with less trampling disturbance had a higher overall vegetation cover (VC) (**Figure 31** and **32**).

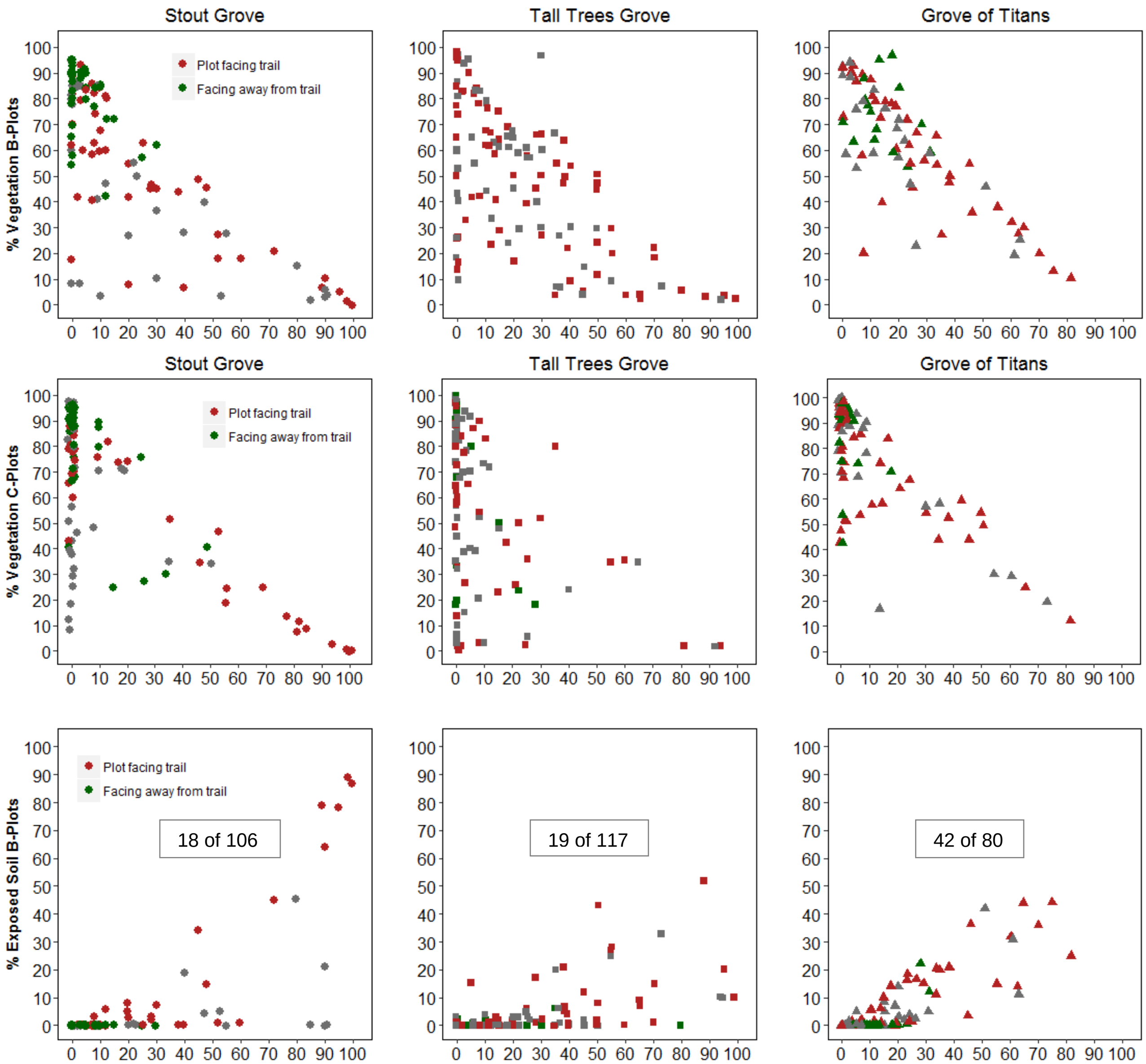

Figure 31. Comparison of percent vegetation cover, exposed soil and exposed roots relative to percent disturbed area within B-plots among study sites (n= 105 Stout Grove, 118 Tall Trees Grove, 79 Grove of Titans). For better visualization of overlapping data points, an offset was added to disturbance data. Boxes in exposed roots graphs give the number of plots in which exposed roots > 0%.

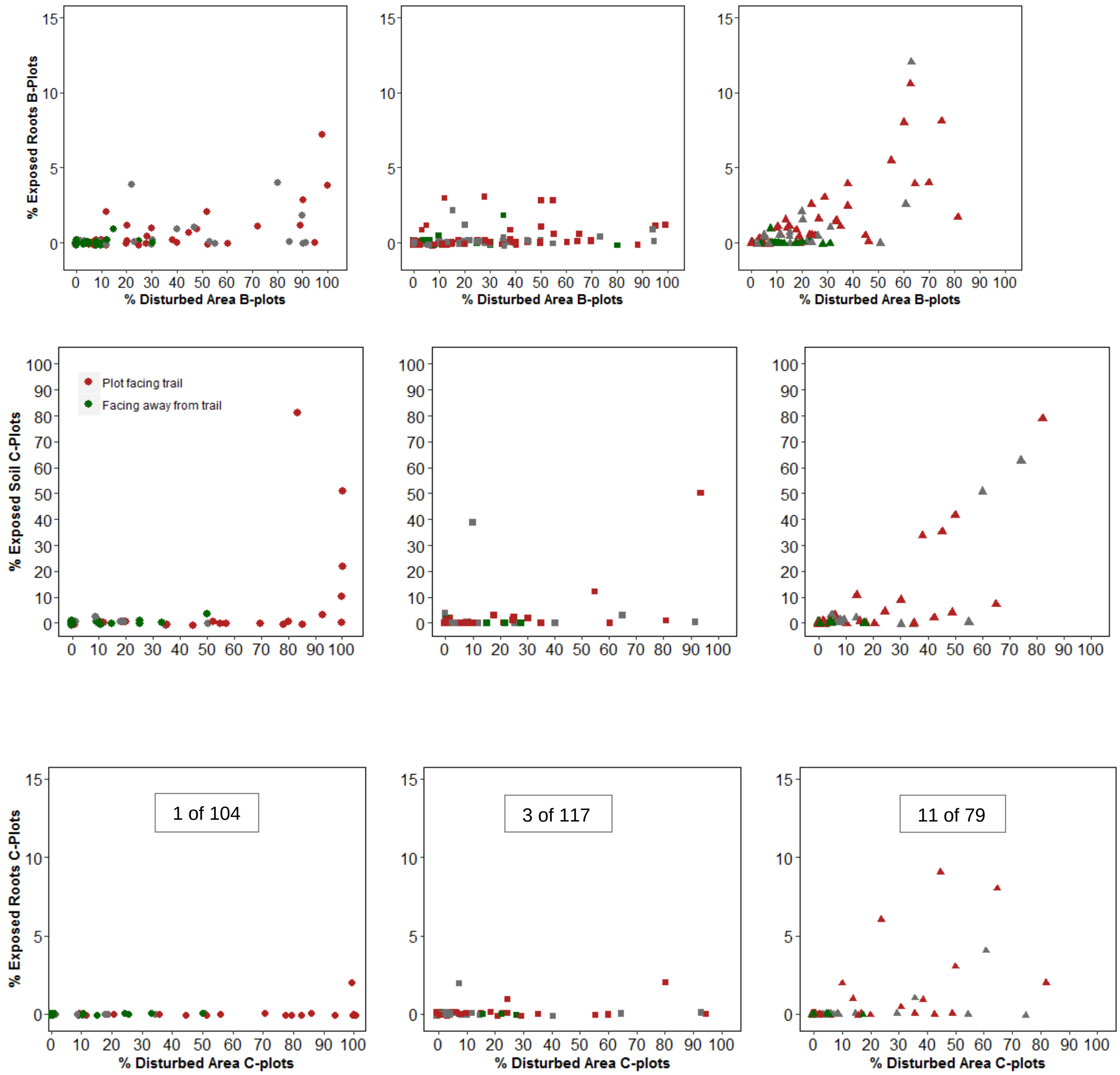

Figure 32 Comparison of percent vegetation cover, exposed soil and exposed roots relative to percent disturbed area within C-plots among study sites sites (n= 101 Stout Grove, 110 Tall Trees Grove, 79 Grove of Titans) . For better visualization of overlapping data points, an offset was added to disturbance data. Boxes in exposed roots graphs give the number of plots in which exposed roots > 0%.

In all groves, the mean VC was lower in B-plots than in C-plots (**Figure 33**). In Tall Trees Grove and Grove of Titans, the more than 10 percentage point decrease was highly significant (*t*= -4.59 and -4.1 respectively, Holm adjusted $P < 0.001$).

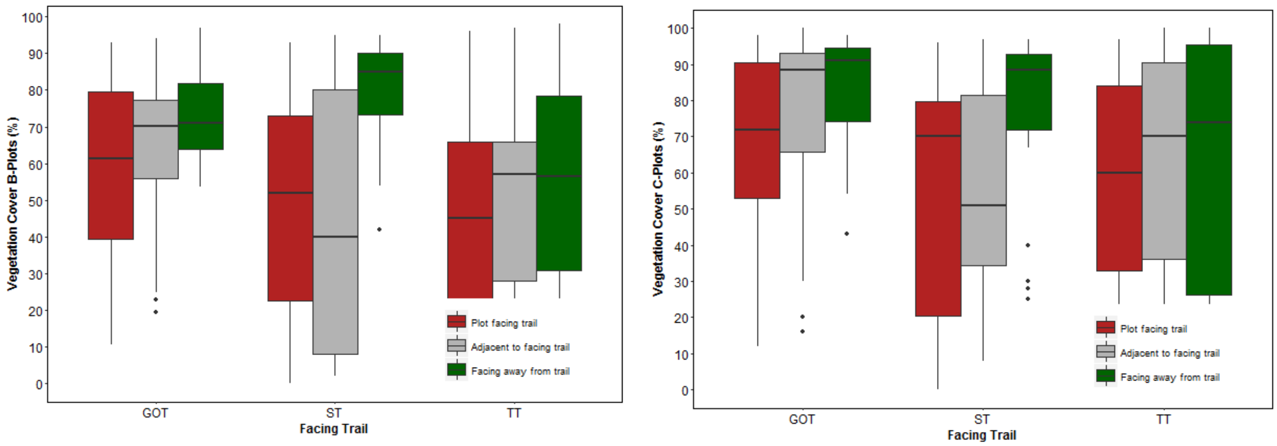

Figure 33. Difference in vegetation cover between plots facing the formal trail or a class 4 social trail, plots adjacent to those and plots facing away for B- and C-plots in all three study sites (n= 101 Stout Grove, 110 Tall Trees Grove, 79 Grove of Titans).

As mentioned before, there was less natural VC in Tall Trees Grove (mean VC in undisturbed B-plots= 58%, C-plots 70%) than in the other two moister sites (Stout Grove = 76%, Grove of Titans= 85% in B- and C-plots). This also explains why there is so much variation in Tall Trees Grove VC in plots facing away from the trail.

Among all three sites there was only one plot facing away from the trail with a VC less than 10 percent. In Grove of Titans, there were no B- or C-plots with <10% VC. Mean VC in B-plots facing away from the trail was lower in Grove of Titans than in Stout Grove, and mean exposed soil in B-plots was as high in Grove of Titans as in Stout Grove, and twice as high as in Tall Trees Grove (**Appendix G**). Even more alarming was the number of severely disturbed plots; in Grove of Titans there were 33 of 39 B-plots (and 10 of 38 C-plots) facing the trail where soil was exposed, compared to 20 out of 34

B-plots (and 5 out of 32 C-plots) in Stout Grove (**Figure 31** and **33**). There was no significant difference in mean exposed soil between B- and C- plots in any of the three sites.

Visible exposed roots were not as pronounced as exposed soil, but they occurred more frequently and severely in Grove of Titans than in the other two sites (**Figure 31** and **33**). Tree 16 had the two B-plots (11 and 12 %, **Figure 34**) and the C-plot (9 percent) with the overall highest percentage of root exposure. In all three sites, there were no exposed roots in C-plots facing away from the trail, and in only three C-plots adjacent to those facing the trail did root exposure occur. In B-plots, trampling disturbance of five trees extended far enough around the tree for exposed roots to occur in the plot facing away from the trail.

Figure 34. Exposed roots around Tree 16 in Grove of Titans.

Vegetation metrics

In Stout Grove and Tall Trees Grove, there was neither a significant correlation between the number of sprouts and seedlings under 1.86 m tall and percent plot disturbance, nor between number of saplings under 5 m and trampling disturbance (**Appendix H**). In Jedediah Smith SP, plots that contain vine maple (a prolific sprouter) had an especially high number of sprouts and saplings, even when other parts of the plot were trampled. This species was most prevalent in Grove of Titans where the overstory is patchy and open, so that the mean amount of regeneration per plot was higher there than in the other two sites ($\bar{x}_{(20)}$ regeneration <1.86 m = 30, $\bar{x}_{(20)}$ regeneration >1.86 m <5 m = 19). The amount of regeneration decreased with increasing disturbance (for regen <1.86 m P=0.05, ρ= -0.38, **Appendix H**). However, the only plot where I found no regeneration at all was also in Grove of Titans - Tree 25, with a relatively small area of disturbance, was on the bank of Mill Creek; part of the plot was cut off by the creek. In all sites, there were plots with clusters of redwood, tanoak or bay sprouts unrelated to their degree of trampling disturbance. In trampled plots the vigor of individual seedlings and sprouts in proximity to trampled areas had been reduced.

Invasive species around trails are a problem in other parts of the Redwood Parks, but were rarely found in any of my study sites. There was only one plot where I found an invasive species listed on the A-list for Humboldt and Del Norte counties—on the northern edge of Stout Grove a plot contained a small amount of English ivy (*Hedera helix*). In the riparian habitat in Tall Trees Grove I found individual specimens of four other invasive species (*Cirsium* sp., *Digitalis purpurea*, *Lapsana communis*, *Leucanthemum vulgare*), but only foxglove is considered a species of concern (on the B-list for Humboldt county). *Lapsana communis,* a species characteristic of disturbed places, was the only weed I found on the edge of a social trail, the other three species grew in untrampled areas.

Figure 35. Examples of plant species found in my plots; upper left: *Asyneuma prenanthoides* in Grove of Titans, upper right: *Cardamine californica* in Stout Grove; bottom: *Goodyera oblongifolia*, *Asarum caudatum* and *Oxalis oregana* in Stout Grove.

Species richness was highest in Tall Trees Grove, with 58 different plant species in the study site (**Table 7**). The two plots with the highest species richness were located at the edge of the redwood grove, at the interface with the riparian habitat along Redwood Creek—around Tree 19, I counted 24 plant species in the C-plots and 10 species in the B-plots; and around Tree 47 there were 20 species in the C-plots and 15 species in the B-plots (**Appendix I**). In comparison, in Grove of Titans the tree plots with the highest number of species contained 17 species in the C-Plots and 15 species in the B-plots. Species richness was not significantly correlated with trampling disturbance in B-plots or C-plots in either of the two sites. However, in Tall Trees Grove there was more variance in species richness in B- and C-plots with low trampling disturbance than in plots with high trampling disturbance.

Table 7. Comparison of plant species richness for different life forms in tree plots in all three study sites (Stout Grove *n* = 28, Grove of Titans *n* = 20, Tall Trees Grove *n* = 30).

Life Form	Stout Grove	Grove of Titans	Tall Trees Grove	Total
All	**43**	**36**	**58**	**77**
Trees	9	8	9	**12**
Shrubs	8	5	8	**15**
Forbs	17	14	28	**38**
Ferns & Allies	6	6	8	**8**

In Stout Grove the average distance between trees and the stream is much larger than in Tall Trees Grove and Grove of Titans; there is much less interface with riparian habitat. Here, I found 11 species in the B-Plots and C-plots of Tree 136 in the southeastern corner of the study site, far away from the formal trail. In B-plots, species richness significantly decreased with increasing trampling disturbance (P=0.03, ρ= -0.37), while in C-plots the correlation was not significant (P=0.28, ρ= -0.12).

Paired t-tests for differences in mean species richness between B-plots and C-plots revealed that the mean number of species in B-plots in Grove of Titans was significantly higher (adjusted *P*=0.029, *n*=20) but there was no significant difference in Stout Grove (adjusted *P*=0.68, *n*=28) and Tall Trees Grove (adjusted *P*=0.68, *n*=30), when species in all four plots around a tree where included.

Soil compaction and litter depth

Soil compaction base values and threshold values were compared for Stout Grove and Grove of Titans. I didn't run statistical tests for comparison between sites because of the differences in soil texture and soil moisture. In Stout Grove, a third of the 508 measurements I took in the B-plots were located on social trails; in the C-plots only 16% of the 492 measurements were on social trails. Fewer of the measurement points in the C-plots had uncompacted soil (≤ 5 kg/cm^2) at both 5 and 10 cm depth than did the B-plots (**Table 8**). In almost all points in untrampled areas in B- and C-plots the soil was uncompacted. In B-plots, in over half the measurements points on social trails there was no compaction at a depth of 5cm.

There were five trees around which penetration resistance at a depth of 5 cm went above the threshold at which the root growth of most plants is inhibited (15 kg/cm^2) in B- and C-plots. Around three of these trees penetration resistance was even above the threshold at which the roots of many plants quit growing (25 kg/cm^2). Over half of the measurements taken in the B-plots at the most disturbed tree (Tree 54) and five measurements around the Stout Tree had values ≥ 15 kg/cm^2. Penetration resistance reached values ≥ 25 kg/cm^2 only in the comparatively less disturbed north B-plot and the south C-plot around the Stout Tree. Percent trampling disturbance in the B-plots was significantly positively related with soil compaction measurements on social trails at a depth of 5 cm (n=161, ρ = 0.52, $P < 0.001$, **Appendix J**).

Table 8. Comparison of soil compaction values in undisturbed areas and on social and formal trails for B-plots and C-plots in Stout Grove.

		B-plots			**C-plots**		
		On armored formal trail	On Social Trail	Undisturbe d	On armored formal trail	On Social Trail	Undisturbed
soil compaction at 5 cm depth	# of measurements	16	161	331	28	78	386
	Mean (kg/cm^2)	55	8	3	40	8	3
	Min /Max (kg/cm^2)	55 / 55	2 / 27	2 / 10	5 / 55	2 / 25	2 / 15
	# of measurements ≤ 5 kg/cm^2	0	84	324	1	31	377
	# of measurements ≥15 kg/cm^2	16	24	0	25	11	1
	# of measurements ≥25 kg/cm^2	16	3	0	18	1	0
At 10 cm depth	Mean (kg/cm^2)	No measure-ment possible	9	3	40	11	3
	Min /Max (kg/cm^2)		2 / 30	2 / 13	5 / 55	2 / 40	2 / 20
	# of measurements ≤ 5 kg/cm^2		64	329	1	20	352
	# of measurements ≥15 kg/cm^2		31	0	26	21	2
	# of measurements ≥25 kg/cm^2		5	0	19	3	1

In Grove of Titans, soils on social trails were more severely compacted than in Stout Grove; 42 % of the 395 measurements I took in the B-plots were located on social trails; in the C-plots it was 20 % of the 377 measurements (**Table 9**). Here, mean compaction on social trails was limiting to root growth, and less than 10 percent of the measurement points on social trails were uncompacted. Around 17 of the 20 sample trees there were points in the B-plots where compaction exceeded 15 kg/cm^2, and around seven of these it exceeded 25 kg/cm^2. Over half of all measurement points around Tree 1 were severely compacted. Soil was especially compacted around a historic irrigation trench on the eastern side of the tree. Of all 226 untrampled measurement points in B-plots, only five showed any compaction, and all were taken around Tree 1. The plot was on the edge of the slope, where the soil starts to contain more clay and is more easily compacted.

Table 9. Comparison of soil compaction values in undisturbed areas and on social and formal trails for B-plots and C-plots in Grove of Titans. Mean values above the root growth limiting threshold of 15 kg/cm^2 are highlighted.

		B-plots			**C-plots**		
		On Formal trail	On Social Trail	Undisturbed	On formal trail	On Social Trail	Undisturbed
soil compaction at 5 cm depth	# of measurements	3	166	226	3	76	298
	Mean (kg/cm^2)	33	16	3	25	14	3
	Min /Max (kg/cm^2)	30 / 35	4 / 38	2 / (20)	21 / 28	2 / 29	2 / (33)
	# of measurements ≤ 5 kg/cm^2	0	14	221	0	10	286
	# of measurements ≥15 kg/cm^2	3	93	2	3	41	4
	# of measurements ≥25 kg/cm^2	3	21	0	2	4	1
at 10 cm depth	Mean (kg/cm^2)	40	18	3	28	17	3
	Min /Max (kg/cm^2)	38 / 42	4 / 38	2 / (22)	26 / 30	2 / 31	2 / (33)
	# of measurements ≤ 5 kg/cm^2	0	11	218	0	7	282
	# of measurements ≥15 kg/cm^2	3	113	3	3	45	7
	# of measurements ≥25 kg/cm^2	3	30	0	3	15	1

In general, soils in Grove of Titans contain more clay and silt than in the other two sites, which makes the soils more susceptible to trampling compaction. Additionally, there are more micro-terrain features in Grove of Titans, and also not as pronounced an alluvial flat as in the other two groves, which makes soils more erodible and more susceptible to trampling impacts. On the eastern side of Grove of Titans, the surface soil is more gravelly than on the other side of Mill Creek, which might facilitate erosion on social trails and partially explains higher penetration resistance values. On this eastern side, there are also three historic Native American elk traps around which soil might be more compacted. The high values I measured occurred only on social trails, especially on the most pronounced class 4 social trail in this part of the grove. Even though percent plot disturbance is low in adjacent plots, since this is the only trail leading through them, compaction was positively related to recent trampling.

Compaction on social trails was higher in the B-plots than the C-plots, where I measured growth limiting compaction around 12 trees. In both Stout Grove and Grove of Titans mean compaction and number of highly compacted points on social trails was higher at a depth of 10cm than at 5 cm (**Table 9**).

Litter depth in B-plots in Stout Grove was significantly greater in undisturbed areas ($\bar{x}_{(158)}$ = 11.3 cm, SE$\bar{x}$ = 0.8) than on social trails ($\bar{x}_{(61)}$ = 3.2 cm, SE$\bar{x}$ = 0.4, t=8.98, P < 0.001, **Figure 36**). In a linear regression, log transformed litter depth decreased by 20% for every 10 percentage point increase in disturbance (n=223, r^2=0.28, P < 0.001).

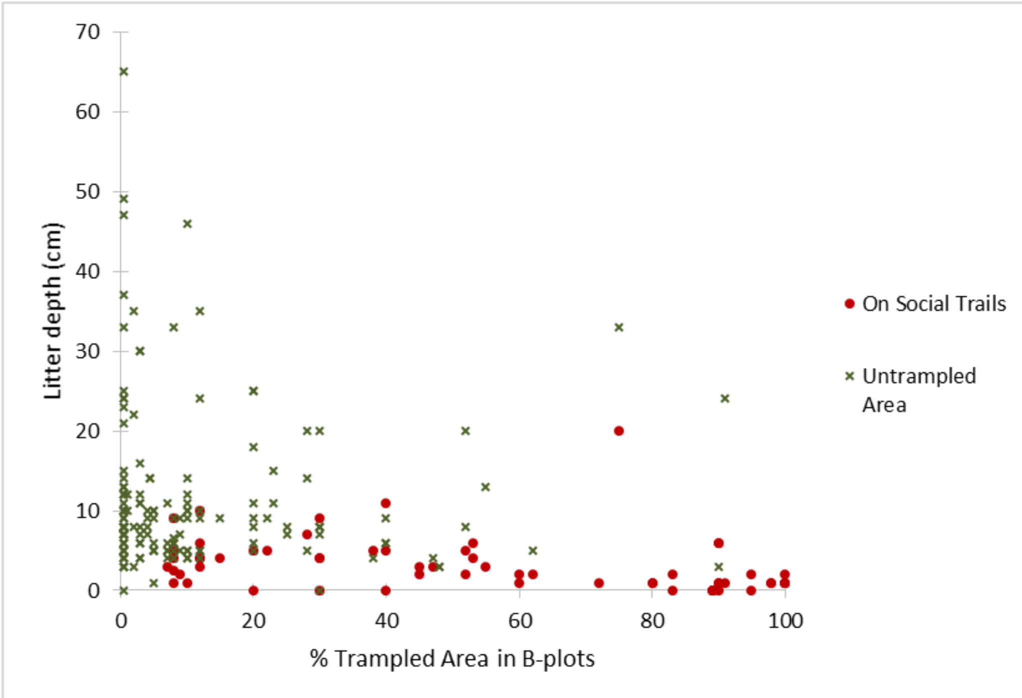

Figure 36. Decrease in litter depth along a gradient of trampling disturbance for B- plots in Stout Grove (n=223, r^2=0.28, P < 0.001). For comparison, measurement points in untrampled areas are plotted in green (n=162) and measurements on social trails in red (n=61).

DISCUSSION

My study showed that trampling disturbance has become a wide spread problem in the area around the trees known as the Grove of Titans. Concurrent with the findings of other trail impact studies (e.g., Cole 2004), the relatively small increase of dispersed use there over only a few years has caused substantial impacts. The specific type of visitor activities (exploring, finding different viewpoints of the trees) leads to multiple passes in the same area and increases the impacts that each visitor has on vegetation and soils. Metrics indicating severe trampling disturbance were equally high or higher in Grove of Titans than in the other two groves with higher use intensity. Compared to Stout Grove and Tall Trees Grove, social trail condition classes 4 and 5 made up a higher percentage of the trailed area in Grove of Titans (27 %) than the formal trail (21 %). In a few places, severely trampled areas have become hardened and will be harder to restore to their natural state (Johnson & Vande Kamp 1996). Trampling has spread so much that the percentage of undisturbed subplots was very low.

However, impacts in Grove of Titans have not yet reached the inflection point shown in **Figure 2**a, they are proliferating and spreading fast when new social trails appear much more rapidly than old trails can recover in the off-season or when replaced by a different route. If this trend is to be arrested, management actions urgently need to be implemented. Social trails are more concentrated in the area on the western side of Mill Creek, which is only half the size of what I defined as my study area (5.3 ha). In a next step, trail density and trail extent should be calculated for this part of the study area to get more fine-scaled trail distribution metrics.

While old-growth redwood trees are a protected resource in RNSP and specific measures should be taken to monitor certain aspects of this resource, monitoring should also assess if visitors impact certain habitat standards. The process of defining habitat standards has just started in RNSP. As part of this study, I collected data on an extensive number of vegetation and soil metrics that are connected to trampling disturbance, some of which was not included in this thesis but could help to define baseline values for future habitat standards. Management standards for old-growth redwood could, for example, include a threshold level of the percentage of disturbed understory habitat below which human trampling is acceptable. Elzinga et al. (1998) suggested this form of habitat monitoring in their guide to “Measuring and Monitoring Plant Populations”.

It is not feasible to compare results for individual vegetation and soil metrics of this study directly with specific results of other social trail impact studies, since those studies have been conducted in meadows and other open areas, or in subalpine and alpine forests where vegetation, soils and use intensity vary greatly from study sites in redwood groves. However, indicators adapted from other studies (Marion & Leung 2011, Leung et al. 2002) for definition of trail condition classes (**Table 1**) also proved useful in redwood groves. Similar to Leung et al.’s (2011a) study in Yosemite NP meadows, plots with fewer social trails had a higher total vegetation than plots with greater presence of trampling in my threes study sites. Cole et al. (1997) added threshold values for vegetation cover to their condition class descriptions. For assessment of social trail impacts in redwood groves, I would not recommend adding thresholds for certain metrics to those definitions since condition classes should be the same for different study areas; and I found for example natural vegetation cover to be site specific. In my study sites, I neither found a change in species composition nor invasive species in proximity to trails; two indicators that have been associated with trampling in other studies (Krenzelok 1974, Hall & Kuss 1989, Leung et al. 2011a). Especially in Tall Trees Grove and Grove of Titans, species composition changed and species richness increased with decreasing distance from riparian habitats. A possible relation between abundance of indicator species and trampling disturbance could be tested with repeated monitoring. Analogous to results of Cole’s (1995) study, in my study sites redwood sorrel appears to recover more quickly from trampling than western sword fern and regrows in areas with disturbed soils where I found no sword fern. My study only examined current disturbance, but large patches of redwood sorrel that are devoid of sword fern might be an indicator of past trampling disturbance that I found recovered in late spring before the main visitor season started.

My study also shares some trends with previous investigations into visitor impacts around coast redwoods, even though questions, methods and climate varied. Similar to Standish’s (1972) and Krenzelok’s (1974) study, there was an overall trend of increasing soil compaction in areas of higher trampling disturbance. However, penetration resistance measurements are difficult to replicate, which limits their use for monitoring trampling disturbance. This metric greatly varies with soil texture and moisture levels, wet soils will result in substantially lower values. A particularly wet spring had influenced the results of

Cole & Hall's (1992) long-term trampling study so no overall trend toward deterioration or improvement of closed sites could be observed. In my study I captured values at a relatively stable soil moisture per site and found little variability in compaction in undisturbed areas. I repeated all measurements for the Stout Tree two months later to assess if trampling disturbance and compaction were higher as the summer season progressed and as there was potentially less soil moisture. In the end of July maximum compaction values had increased for measurements on social trails as trampling had become more severe and penetration resistance reached values ≥ 25 kg/cm^2 in all four B-plots around the Stout Tree. However, values in undisturbed points remained the same.

When comparing litter and duff measurements along a trampling disturbance gradient, natural disturbances have to be taken into account. As mentioned, some sections of the alluvial flats are affected by big flood events, which might cause the base values for untrampled O-horizons to be lower, while in sections where big trees and other debris have fallen recently, litter and duff base values will be higher than in surrounding areas. To verify if differences between unflooded and flooded areas still persist, soil samples would have to be taken at each plot and results used to divide the study site into a flooded and unflooded part. Then litter and duff values could be analyzed for these parts separately. Standish (1972) related differences in accumulated litter in areas with similar trampling disturbance to differences in shrub cover, which I didn't analyze.

Future monitoring

Overall, spatial and resource condition indicators chosen for this study proved applicable to actual conditions found on sites. For future monitoring, I recommend the use of tablets for mapping social trail networks. Using ESRI ArcPad and other software, an interactive basemap can be loaded that includes study site boundaries, formal trails and informal trails with attribute tables, redwood trees, logs, and other easily identifiable reference features like trail signs and fences.

In my study, the number of prominent features of a tree was not used as a predictor of trampling disturbance since it was not independent of DBH in two sites and not a significant predictor in the third (where trees with little trampling around them also had prominent features). It may be noted though, that in Grove of Titans, trees with more prominent features were estimated to have on average a higher trampling disturbance for all four levels when DBH was not included in the model. I took notes about the specific prominent features of a tree (not just their count) and I recommend doing so in the future, since it also helps identify trees.

I would simplify the plot design and not include A-plots on the tree trunk. A plot setup that includes the A-Plot is harder to reproduce since the skirt boundary cannot be objectively measured. Damaged bark and damaged wood didn’t seem to be good indicators of trampling damage because they can be confounded with natural damage caused by burn scars (**Figure 37**), falling trees or flood events (**Figure 38**). On only very few tree trunks there were places where the bark was worn down all the way to the cambium. These instances should be noted as comments when rating impact severity and a picture should be taken.

Figure 37. A-plots with buttress of Tree 25 in Stout Grove, where wood is exposed in a goose pen and damage has been exacerbated by visitor use.

Figure 38. A-plots of Tree 42 in Stout Grove, where wood might have been exposed when big neighboring trees were falling or as a result of flood events.

I recommend changing the position of the B-plots to include the tree skirt. The first pin flag could be put as close as possible to tree trunk and the 2m plot width would be measured from there.

For this study, I did not record trail condition classes for soil compaction or litter depth measurement points on social trails, but rather tried to establish base values for the three sites. For future monitoring, I recommend measuring compaction and litter depth at one point per social trail condition class per subplot at one depth. In Grove of Titans compaction thresholds should be adjusted to reflect the different soil texture.

For my analysis, mean values and their comparison were not sufficient as indicators for metrics like vegetation cover. It proved more suitable to look at the number of plots or subplots that crossed a certain threshold. Thresholds have to be site specific; they can be defined using undisturbed values (e.g., vegetation cover in undisturbed B-plots was not below 50% in Stout Grove and not below 70% in Grove of Titans) or highly disturbed values (e.g., compaction thresholds). In later monitoring, mean values can be used to test for significant change over time.

In addition to the written definitions of trail condition classes, I have created a photo chart for each condition class (**Appendix J**). According to my measurements in RNSP, the trail width should be adjusted as follows:

class 2 - trails are less than 0.5m wide,
class 3 - trail treads are between 0.5 and 0.7m wide,
class 4 – trails are wider than 0.7m.

California State Parks, together with California Geological Survey, developed a road and trails inventory protocol which includes a point-based assessment of social trails, capturing intersections of formal trails with user-created trails. The database record will contain additional information on the point data, including how many trails emanate from the point, the length of the trail(s) out to 100 m, the width, and a slight/ moderate / severe rating. For severe conditions it will contain a prescription of a standard revegetation treatment for the trail. The North Coast Redwoods District of California SP started conducting the inventory in November 2014 at the southern end and it is expected to be completed by spring 2017. Data from my study can be integrated into the inventory once Jedediah Smith SP is included. The severity ratings translate well into the trail condition classes (**Table 10**). Results from State Parks' trail inventory can be used to identify areas in the parks where more detailed social trail monitoring is a high priority.

Table 10. Integration of trail condition classes with California State Parks severity rating.

Trail Condition Class	California State Parks severity rating (used in inventory of formal trail intersections with user-created trails)
1	Slight - a linear feature where living foliage may be absent but duff is intact and fully covers the mineral soil.
2	
3	Moderate - living foliage is absent and duff is worn and some bare patches of soil are visible.
4	Severe - living foliage and duff are absent and soil is visible along most of the trail tread.
5	

Redwood National Park last conducted a trail inventory in 2000 and social trails were not included. Formal trails are generally in better condition than in the Redwood State Parks since the National Park employs a permanent trail crew.

A systematic - and where possible site-specific- recording of visitor use has to be established. Redwood NP reported almost 700,000 annual visitors in 1988 and 1989 compared to just over 500,000 visitors in 2015. Jedediah Smith Redwoods SP reported 157,000 visitors in 1962 compared to 137,000 in 2014. To use these numbers in their planning managers have to know how the data was recorded: Did visitor numbers drastically fluctuate or did reporting change?

How often social trail monitoring should be repeated in the future depends partially on trends in visitor numbers. Visitor numbers to Jedediah Smith SP have presumably drastically increased from 2014 to 2015 (statistics have not been published yet); if numbers stay as high and management actions are taken, I recommend to do a first re-monitoring next year. Frequent monitoring is necessary if changing visitor numbers cause significantly different results. In general, monitoring should be done before and after restoration or mitigation measures have been applied. A 5-year interval could be sufficient for monitoring with quantitative procedures, but annual informal evaluations are needed to effectively guide the application of management actions.

Future research

For future social trail studies in RNSP, social science should be integrated with the recreation ecology aspects of the study. Visitor surveys and observations would provide knowledge about aspects of visitor behavior specific to RNSP and the values guiding these behaviors necessary to develop education and information programs (see Management Implications). The notion of what constitutes impairment of park ecosystems is normative. Perceptions of the acceptability of impact can be influenced by aesthetic concerns and inappropriate conclusions about the significance of observed effects (Monz et al. 2010).

Visitor observation data like the pictures I collected with trail cameras in Grove of Titans can be integrated into spatial analysis, e.g., with kernel density estimates to show where visitor use is most intense. Walden-Schreiner & Leung (2013) used this technique to cluster visitor use on social trails in Yosemite Valley meadows. Visitor use data can help direct the type and degree of management because ecological conditions alone may not fully explain visitor-related impacts. My findings suggest that in a high-use setting like Stout Grove, where visitors don't have to walk far from the parking lot or campground to access the site, trampling decreases with distance from formal trails. Most visitors seem less inclined to explore far away from the trail, their desire to walk up to or have their picture taken with an old-growth redwood tree is met close to the trail. Some visitors shortcut between the northern and southern side of the loop trail. In a low use setting like Tall Trees Grove, where visitors have to hike two km to access the site, trampling increases with the size of the trees. Visitors seem to be willing to walk farther and to be more likely to explore and search for the biggest trees. The privacy of the setting, where visitors might not encounter other people during most of their stay, might add to the sense of exploration. In Grove of Titans, I explained the impacts of off-trail hiking to visitors I encountered during my field work. Many of them felt that it was justified that they were in the grove, but at the same time wouldn't want other people to find and impact this special place. In Walden-Schreiner & Leung's (2013) study there was no significant relation between trail condition classes and visitor distribution, instead type of activity (stationary vs. actively moving) had a greater influence on visitor distribution. I will discuss management implications of these findings later.

The spatial data collected for this study could be used to calculate patch indices that inform about the fragmentation that social trails cause in a landscape. In Yosemite

Valley meadows and Mt Rainier NP, the two indices used were Weighted Mean Patch Index and Largest Five Patches Index (Moskal & Halabisky 2010, Leung et al. 2011b).

Management implications

Only one year after the United States passed its first wildland legislation, Frederick Law Olmsted (1865) foresaw the cumulative impacts of increasing visitor use and argued for rules and regulations to limit such visitor impacts to the Giant Sequoias in Mariposa Grove in Yosemite NP:

> "It is but sixteen years since the Yosemite was first seen by a white man, several visitors have since made a journey of several thousand miles at large cost to see it, and notwithstanding the difficulties which now interpose, hundreds resort to it annually. Before many years, if proper facilities are offered, these hundreds will become thousands and in a century the whole number of visitors will be counted by millions. An injury to the scenery so slight that it may be unheeded by any visitor now, will be one of deplorable magnitude when its effect upon each visitor's enjoyment is multiplied by these millions. …, if no care were taken to prevent it."

From RNSP staff and management I learned about different management practices that have been used in Stout Grove and in Tall Trees Grove in the past to reduce social trail impacts. I mentioned some of these practices in the site descriptions. Actions including construction and removal of split-rail fencing around trees with high perceived impacts, removal of signs with tree names and heights, trail signage with the message "Please stay on trail," obstructing social trail entrances with large woody debris and transplanting of sword ferns in social trail entrances were undertaken without systematic recording or monitoring of their effects. Their success or failure was determined only through anecdotes of park staff. To integrate my study results with a discussion of different management practices, I reviewed studies on their effectiveness and best practice reports from other parks. I have identified a combination of information/ education and site design/maintenance as the impact management strategies (Manning 2012) most relevant for social trails in RNSP. Adaptive management that combines the two strategies has been found most effective. I will evaluate different techniques used in these strategies separately and then discuss at case studies that combined the two.

Information and education programs

Only when visitors better understand which of their behaviors impairs protected area ecosystems in which way, and when they share a certain notion of impairment, of the acceptability of impact, and of their own responsibility, will they lastingly change their behavior. Information and education programs are designed to persuade visitors to adopt behaviors that reduce ecological and experiential impacts. Research suggests that this approach tends to be viewed very favorably by visitors (Manning 2012). Trampling is classified either as a careless action with a moderate potential to be positively addressed with education, or as unskilled and uninformed action with a high potential effectiveness of education practices. Visitors have been found to either be unaware of the impact they are causing, or to feel that their use of a social trail will have negligible impact (Park et al. 2008, Hockett et al. 2010). The presence of a social trail is seen as a 'releasor cue' encouraging its use and walking off-trail is justified easily. Empirical studies examining the effectiveness of information and education practices found that face-to-face contact with park personnel is often most effective in mitigating impacting behaviors. For example, in Mt. Rainier NP, day hikers in subalpine meadows were given a short, personal interpretive program on reasons for and importance of complying with guidelines for off-trail hiking (Kernan and Drogin 1995). Visitors were later observed while hiking: 42% of visitors who received the program went off-trail, while 64% of visitors who did not receive the program walked off trail. A personal message was also found most effective in Hockett et al.'s (2010) multiple techniques study (see below).

Where personal contact with visitors is not always possible, signs are commonly used to inform visitors. Some studies have examined the effectiveness of message text and sign location in reducing social trail use. On a small, low-use island with mixed broad-leaved forest at St. Lawrence Islands National Park, Canada, Bradford and McIntyre (2007) used camouflaged cameras to record visitor behavior. When no signs were present, 88 percent of visitors left the main trail. A sign with a short plea message ("Please stay on the wood-chipped trails") clearly differentiated maintained, designated trails from social trails, and although eliciting significant reductions in social trail use, was not as effective as this attribution message:

> "Your feet have trampled the vegetation on this island.
> Please stay on the wood-chipped trails."

When the attribution message was present, social trail use declined by 43 percent. Compared to the plea message, it additionally created awareness that off-trail trampling impacts are a problem, and that remaining on formal trails protects park resources, was personalized to internalize causality, and transferred the control and means of reducing impact to the individual. Bradford and McIntyre (2007) concluded that since the public's level of environmental concern remained positive over a long period, the use of messages that focus on personal responsibility and potentially encourage pro-environmental behavior is an effective and economically efficient management approach. When signs were posted at social trail entrances, use of the social trails was reduced significantly compared to messages located at entry points to the island (**Figure 39**). Earlier studies had also found locating signs along trails, where severe impact takes place, to be most effective in Mt. Rainier NP (Johnson &Swearingen 1992). Placing messages on bulletin boards at park entry points assumes visitors will spend time to read and absorb the information. However, a variety of factors may interfere with this, including information overload, and simply, wanting to get on the way. The average time taken in examining a single message is quite brief (3 to 10 seconds) (McCool & Cole 2002).

Figure 39. Educational sign with attribution message located at the entrance with a social trail in St. Lawrence Islands National Park, Canada (Bradford & McIntyre 2007).

Several studies have included a symbolic “no-step” icon on signs and prompters which communicates the message with just a glance and is understandable by children and non-English speaking visitors (Johnson &Swearingen 1992, Park et al. 2008, Hockett et al. 2010, **Figure 40** and **Figure 42**). Before the application of attribution theory had advanced message design into a new direction, Johnson & Swearingen (1992) tested a sanction message ("Off-trail hikers may be fined") and found it more effective than a plea sign ("Stay on paved trails and save the meadows"), reducing off-trail hiking in Mt. Rainier NP by 75 percent. They argued that in the special case, where trails are clearly marked and visitors know that off-trail hiking is prohibited or discouraged and choose to do it anyway to reach a desired location, an educational message would likely not be as effective as a sanction (Johnson & Swearingen 1992). However, Hockett et al. (2010) found that visitors are less supportive of increased ranger presence, and the fining of off-trail traffic. Park managers don't always deem such direct management techniques appropriate and favor information and persuasion, due in part to the unpopularity of the enforcement actions and to the cost of increased enforcement.

The study setting most comparable to RNSP was in the Giant Sequoia groves at Kings Canyon NP. There, Winter (2006) found that an injunctive-proscriptive sign ("Please don't go off the established paths and trails, in order to protect the Sequoias and natural vegetation in this park") was more effective than three other message types in reducing off-trail hiking. However, message length and design (e.g. font size) differed between the four treatments, potentially confounding those results.

The Leave No Trace (LNT) program forms the basis of much of the low impact education used by federal land managers. One of the seven LNT principles refers directly to off-trail travel (https://lnt.org/learn/principle-2) and the LNT Frontcountry program encourages visitors to "walk and ride on designated trails to protect trailside plants". Many visitors use the park's websites to inform themselves before actually travelling there. This would be the first place to deliver the message why people should stay on trail. A 2005 evaluation of the websites of 45 NPS units found that only two-thirds included mention of the LNT principles (Griffin 2005). Since NP websites are updated regularly, I assumed this study might be dated. On the RNP website (http://www.nps.gov/redw/learn/news/newspaper.htm), the 2014-2015 visitor guide still doesn't contain a general message about walking off-trail. It is only mentioned that visitors can protect themselves from ticks and poison oak and help protect parks from invasive species and diseases by staying on trail. On the 'Hiking' page LNT is not mentioned, but all seven principles are explained on the 'Backcountry' page. On the California Coastal Redwood State Parks websites, I found no mention of a staying-on-trail policy (for Jedediah Smith Redwoods SP: http://www.parks.ca.gov/?page_id=413).

<u>Site design and maintenance</u>

Formal trails can never provide complete access to all locations visitors wish to see, hence, some degree of informal trail development is inevitable and must be tolerated. Weighing recreation access and resource protection objectives, management has to determine which impacts are unacceptable and require management action. There are three general site design and maintenance strategies for managing social trail impacts: 1) Improve design and maintenance of existing formal trails; 2) Formalize and maintain social trails; 3) Close and restore unacceptable social trails.

1) Formal trail problems often contribute to the development of social trails, and addressing such problems is generally an effective and efficient management option (Marion 2008). Formal trails should be well-marked in a distinctive fashion so that

visitors can clearly distinguish between formal and social trails – a lack of this is often a reason visitors walk off-trail (Hockett et al. 2010). The treads of formal trails should be the most attractive location for walking, maintained to be free of muddiness or eroded ruts with exposed roots and rocks. When braided or multiple parallel treads occur managers should define a single intended tread throughout. Clearly defined trail borders (e.g. logs or spaced rocks) are necessary in some areas to provide needed visual cues to deter off-trail hiking. Especially for a high use site like Stout Grove it is very important to maintain formal trails well and keep trail boundaries clearly defined. Almost all class 5 trampling occurred directly adjacent to the formal trail. In these places the formal trail has widened significantly and trail boundaries have vanished.

In high use situations, hardening is a strategy to minimize impacts (e.g. gravelling, board-walks and other walk-ways). However, it can be expensive and may create additional environmental problems depending on vegetation type and the surface material used. Using gravel, native vegetation and soil are replaced with a hardened surface; in Hill and Pickering's (2006) study in alpine shrublands, decrease of vegetated area was 11- to 20-fold where a social trail was replaced with a gravel track. Additionally, gravel has high removal and rehabilitation costs, which is important in groves where trails have to be rerouted or adjusted when giant redwoods fall onto trailed area. In the same study, Hill and Pickering (2006) showed how the installation of raised steel mesh walkways effectively concentrated use on durable surfaces. Complete vegetation cover existed under the walkway, on the track verge and 3 m away despite high levels of visitor use. However, results for the effectiveness of raised walkways are not consistent: Sutter et al. (1993) found that a boardwalk did not eliminate trampling in low shrub vegetation in the Appalachians. The number of plots showing evidence of trampling, and the number of plots with severe trampling impacts, increased after the boardwalk was installed. The boardwalk attracted additional visitors to a rare plant community. In response to the study NPS posted signs and constructed railings along the entire length of the boardwalk. The authors recommended spur trails to the rock outcrops visitors are seeking.

2) Especially in Grove of Titans, informal trails access locations that more and more visitors want to see, and visitor access to these locations should be designated and managed as an extension of formal trails. These spur trails are considered to serve as "lightning rods" where visitor use and impacts are directed away from certain areas and to these developed facilities (Manning 2012). Concentrating visitor traffic on a defined tread protects adjacent vegetation from trampling damage. Using my visitor distribution data, a qualified trail design and maintenance professional should identify a route, with review by resource management staff. It will be necessary to replace several non-sustainable informal trails with a new well-designed formal trail. An objective evaluation of the cumulative impacts, including the total area of trampling disturbance, will generally support such a decision. Besides exploring, the main visitor activities in Grove of Titans are stationary. Visitors take pictures and many stay for extended amounts of time and are not just passing through. A raised walkway would promote controlled visitor access and a raised viewing platform would allow for stationary activities. Walden-

Schreiner & Leung (2013) suggested these management actions as a result of their social trail study for El Capitan Meadow in Yosemite NP.

In both Tall Trees Grove and Stout Grove, if stream access was formalized it might reduce the wide-spread trampling of visitors looking for the best possible access point to get views from and of the stream. In Tall Trees Grove, signs need to be put in place that help locate the access to Redwood Creek Trail. A maintained (social) trail could also reduce the severity of trampling impacts leading to the banks of Mill Creek on the west side of Grove of Titans. An existing trail or previously disturbed route is always preferable, though visitors rarely choose the most durable or sustainable routes.

3) There are a variety of site management actions for closing social trails that have been found to be successful in combination with temporary educational signs necessary to obtain a level of compliance that allows vegetative recovery. In prioritizing areas for management, first impacts that can be easily avoided should be mitigated – such as when duplicative informal trails in close proximity to each other lead to a location that could be accessed by a single trail. Lightly used trails can be closed by naturalizing and hiding their tread disturbance along initial visible sections where visitors make the decision to venture down them. In the past, one of the more commonly used practices involved obstructing trail entrances with nearby logs and branches, but if this technique is applied alone without signage, it often resulted in the removal of logs and branches or additional trampling by visitors creating new bypass informal trails (Johnson et al. 1987). Such actions may happen because hikers do not understand the reasons for trail brushing or restoration work. A more effective practice is to spread organic litter and light non-

obstructing brush to camouflage an informal trail, along with randomly placed woody debris, thus removing the 'releaser cue' of an obvious path. If visitors still discern and use the informal trail they will at least not add trampling with new bypass trails.

Organic litter can also speed natural recovery. An important implication of slow recovery times is that rest-rotation schemes that seek to allow unassisted recovery on temporarily closed sites or trails will be less successful (Monz & Cole 2010). Active restoration with transplanted vegetation and seeding at the beginning of wet seasons have been found to be more effective (e.g. Cole & Spildie 2000 on closed campsites in the Eagle Cap Wilderness, Ebersole et al. 2004 on closed social trails with alpine vegetation in Colorado). However, intensive restoration work should only be applied when effective measures are in place to prevent further trampling. Success of restoration efforts to recover vegetation on social trails varied by studied ecoregion with more direct intervention required in more severe ecological environments; in all cases success was dependent on the complete closure of the impacted areas (Widman 2010). A study on closed sites in riparian ecosystems in the eastern US found no observable evidence of disturbance in the amount of vegetation cover or soil compaction after six years (Marion & Cole 2006). Vegetation composition and structure though remained to be different from undisturbed control sites.

In RNSP, transplanting sword fern has proven to be an effective measure of standard revegetation, since it is much less inviting to visitors to walk through a thick sword fern forest than on a carpet of redwood sorrel. On lightly used trails, lower visitation rates in the rainy winter season have been seen as sufficient for recovery, but since it takes much longer for sword ferns and shrubs to recolonize an area without assistance than for redwood sorrel and other forbs, an area with forb cover will likely be the first to be trampled once the summer season starts. In Grove of Titans, some trails are in areas with micro-terrain and their closure would require the addition of soil to fill ruts and reestablish the original surface contour. Temporary signs to communicate the location of the preferred alternate route might be necessary where the only visible access trail is closed.

For such well-used trails, it is hard to fully disguise the disturbed substrates and vegetation, so greater efficacy was found in additionally constructing a visually obvious border along the main trail, such as a log, row of rocks or various methods of fencing to obstruct access at the entrance to closed trails and communicate the management intent of the blockage. Two studies at Mt. Rainier (Swearingen & Johnson 1988, Rochefort & Gibbons 1992) revealed a yellow rope barrier to be the most effective site management technique for reducing off-trail walking. Rochefort & Gibbons (1992) noted that effectiveness was further improved through the presence of a uniformed employee.

In their multiple techniques study, Park et al. (2008) also used low symbolic rope fences to effectively deter off-trail traffic. At the heavily used summit of Cadillac Mountain in Acadia NP, symbolic fencing along certain trail margins was combined with signs located near informal trails. Without any of the four management practices in place, 74 percent of observed visitors walked off the paved trail and all of the management practices reduced social trail use. One educational sign was placed at the trail entrance, two shorter reminder signs along the trail (**Figure 40**) and the addition of 24 wooden block prompters with a “no walking” icon on the most prominent social trail intersections further improved effectiveness.

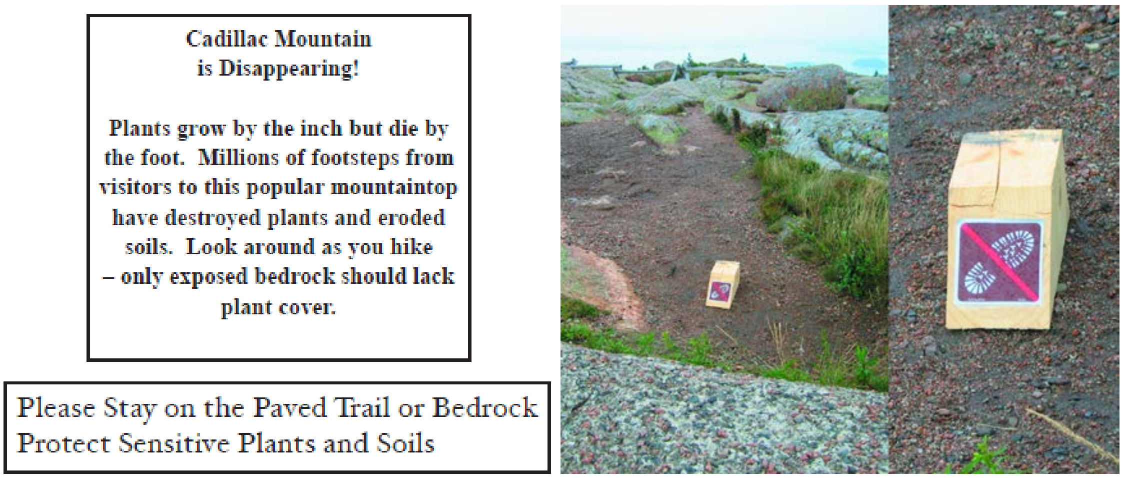

Figure 40. Top left: educational sign placed at the trail entrance; bottom left: reminder signs placed twice along the trail; right: wooden block prompters with “no walking” icon installed at most prominent informal trail entrances on Cadillac Mt. in Acadia NP (Park et al. 2008).

However, in this high use setting no combination of information practices reduced walking off-trail to a degree that is likely to allow recovery of damaged soil and vegetation. The symbolic rope fence was only in place for the first 45m of the trail, and 99% of visitors stayed on the paved trail within the fenced portion, but beyond the fence as many people walked off-trail as did when only signs and prompters were in place (24%). Although visitors remembered seeing trailhead signs most of them did not recall the content of these signs and noticed few or none of the environmental impacts that have occurred on Cadillac Mountain. The authors recommended installation of unobtrusive fencing along the entire trail margin and redesigning the paved trail to include short spur trails to key photo points. **Figure 41** shows a well-designed sign that has been used in past and current management on Cadillac Mt. and allows stepping off-trail on bedrock.

Figure 41. Educational sign to keep visitors on durable surfaces, allows stepping off-trail on bedrock on Cadillac Mt. in Acadia NP.

Visitor support for direct management like fencing and boardwalks is lowest in wilderness settings, and highest in settings with a tradition of direct management (Cahill et al.2008). Land managers are reluctant to employ such restrictive or obstrusive techniques, due in part to the unpopularity of the actions but also due to the cost of installation and maintenance of permanent structures and the potential burden associated with environmental reviews and changes to management plans.

Another multiple techniques study that has been quoted as best practice in different management guidelines (e.g. Marion 2008) was conducted on Bear Island in the Potomac River Gorge (Hockett et al. 2010). Four different treatments, designed to be additive, were compared against the off-trail hiking rates in control areas. The greatest decrease in off-trail travel occurred with this combination of interventions: symbolic “no-hiking” prompter signs attached to logs blocking the intersection with every informal trail (**Figure 42**, right) that clearly communicated management intent; light brushing with non-obstructive woody debris and organic litter which naturalized the initial visible portions (3-5 m) of informal trails; and an education message relayed to each hiker by a uniformed volunteer (more effective than the educational sign in **Figure 42**).

Figure 42. Left: educational sign using an attribution message placed at 3 trail heads; middle: restoration area signs placed at 14 restoration sites (of 155 total informal trails); right: prompter sign with "no walking" icon installed on a log blocking all 155 informal trail entrances on Bear Island (Hockett et al. 2010).

Self-reported off-trail hiking declined from 70 % to 43 % for this combination treatment, while observation along two trail segments revealed a decline from 30 % to 0 %. Adding symbolic restoration areas with a low rope fence, 5 m of Jute matting, and a restoration sign (**Figure 42**, middle) to the brushing/prompter sign treatment, had only little effect in further reducing off-trail hiking during the whole visit, but no one hiked on the fenced trails. The most common motivations were to get to a photo point, avoid or pass other visitors, or avoid poor condition of formal trails. The survey findings suggest that although the treatments significantly reduced off-trail travel, many visitors continued to go off-trail at least once during their hike for a variety of reasons, even when asked not to by a trail steward and informed of the ecological consequences of off-trail travel.

Visitors who talked to the trail steward were more supportive of all suggested management actions. For further reducing off-trail travel researchers recommended (among other things) to further improve formal trail maintenance and trail markings. While many new paint blazes were added to the trail prior to the study, about 30 percent of hikers in the control and treatments stated they hiked off-trail accidentally because the trail was poorly marked.

In conclusion, a combination of multiple practices more effectively alters behaviors than any single method. This is likely due to the fact that different methods affect different motivations of off-trail hiking. Yet no combination of practices eliminated informal trail use completely. Recreation ecology studies assessing resource conditions revealed that even limited continued use of trails or recreation sites can prevent unassisted vegetation and soil recovery (Cole 1987, Leung & Marion 2000, Willard 2007), but only a few studies have investigated effects of combined social trail management practices on recovering resource conditions. After the education and site design practices implemented with Hockett et al.'s (2010) study had been in place for one year, Widman (2010) assessed spatial and resource condition indicators to evaluate how these practices promoted resource recovery. She found 3.4 fewer km of social trails, a decrease of 21%, and reduced average trail widths, resulting in 29% (2600 m^2) less total trampled area. On the trail treads, mean exposed soil decreased by half, and mean vegetation cover increased from 6% to 21%, so that mean condition class ratings were much lower. Some trail segments became completely disconnected from the social trail network and were not recognizable as social trails anymore, while in other areas the prompter signs were damaged or removed regularly and a lot of maintenance by volunteers was required. She compared the area where treatments were in place with an adjacent area on the island without management practices and found that in the control area impacts continued to increase and condition classes were on average rated higher after one year. This study shows, that even after a short time overall resource conditions improved significantly when appropriate management was in place. Growing conditions in my three study sites are exceptionally good, and I expect recovery rates in northern California coastal forests to be much faster than in other ecoregions, which improves the effectiveness of management actions. Nonetheless, I expect unassisted recovery rates in Grove of Titans to be slower than in the other two groves. Due to the higher clay and silt content of soils there, it will take longer for compacted soils to recover to a level that won’t restrict root growth and this will prolong revegetation times. Thus, management in Grove of Titans is more urgent, but might also have to be sustained over a longer time than in other groves. The dynamics of an old-growth redwood forest, where downed trees and other large woody debris regularly cover substantial parts of a grove’s surfaces, both aid in the process of recovery by disguising social trails and covering damaged areas, and create the “need” for more off-trail hiking when the formal trail is obstructed or becomes less distinguishable from the surrounding areas.

Adaptive management practices to reduce off-trail hiking are implemented as experiments guided by empirical recreation ecology studies, and monitoring results should be used as feedback to refine site management and education practices. Regular monitoring of spatial attributes of and resource conditions connected to social trail impacts are critical to management success.

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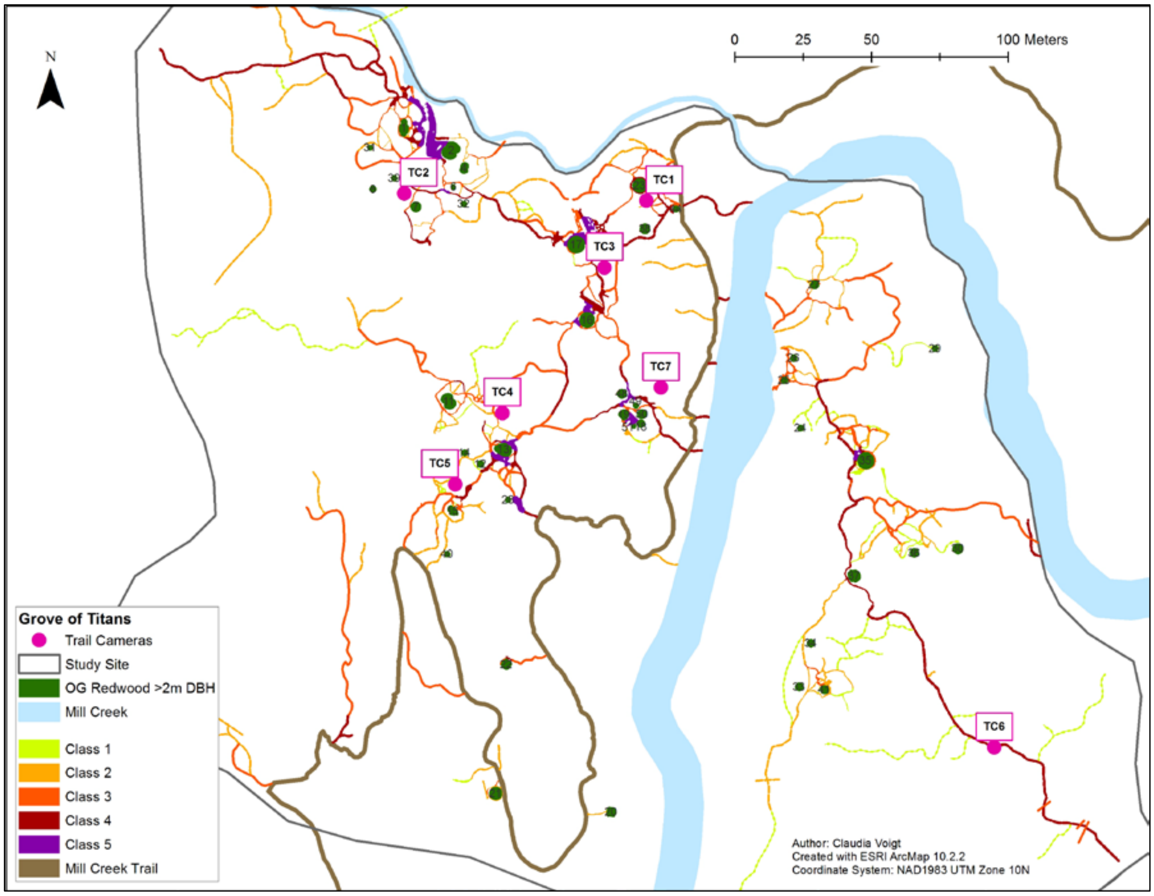
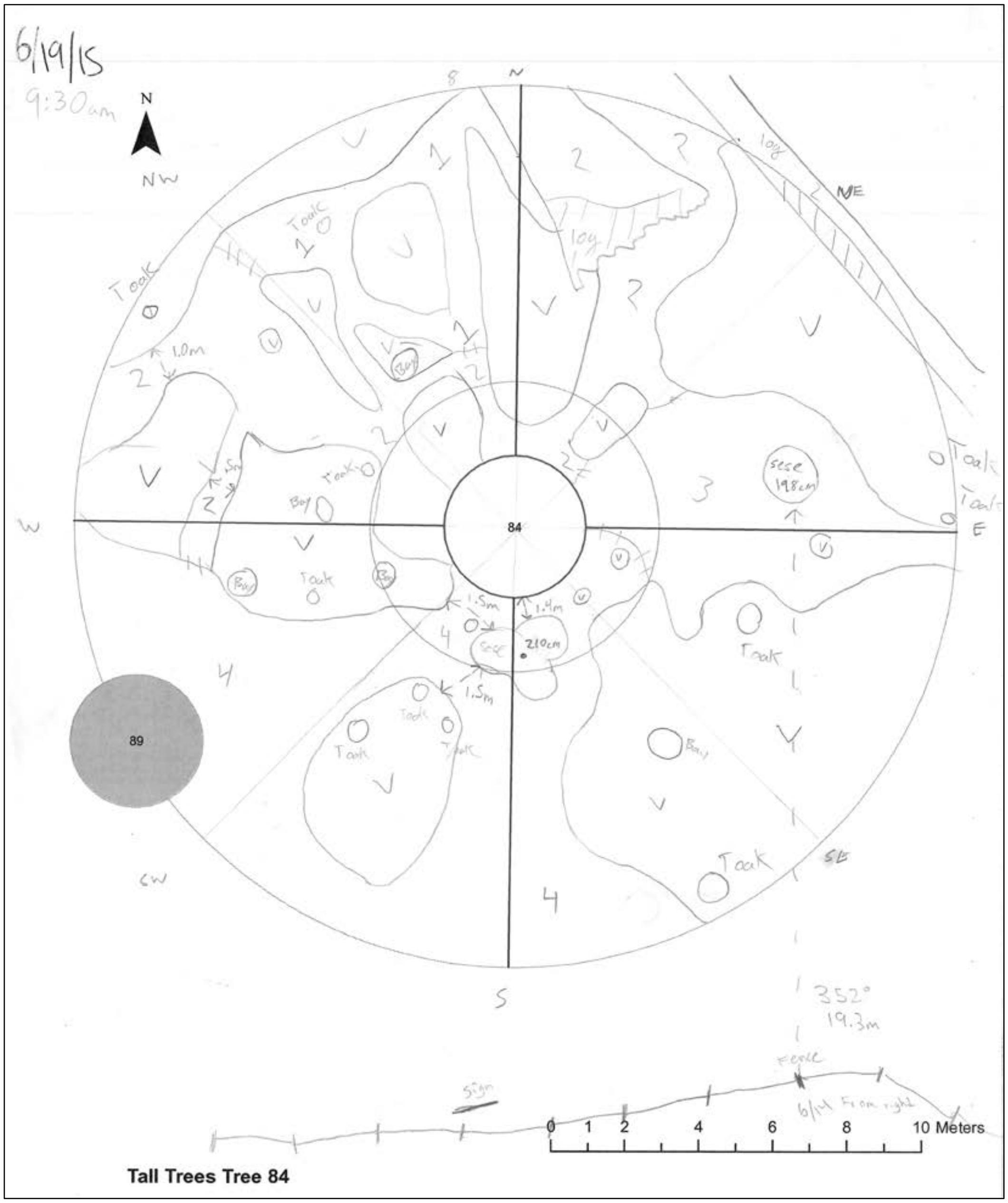
APPENDIX A: TRAIL CAMERA LOCATIONS



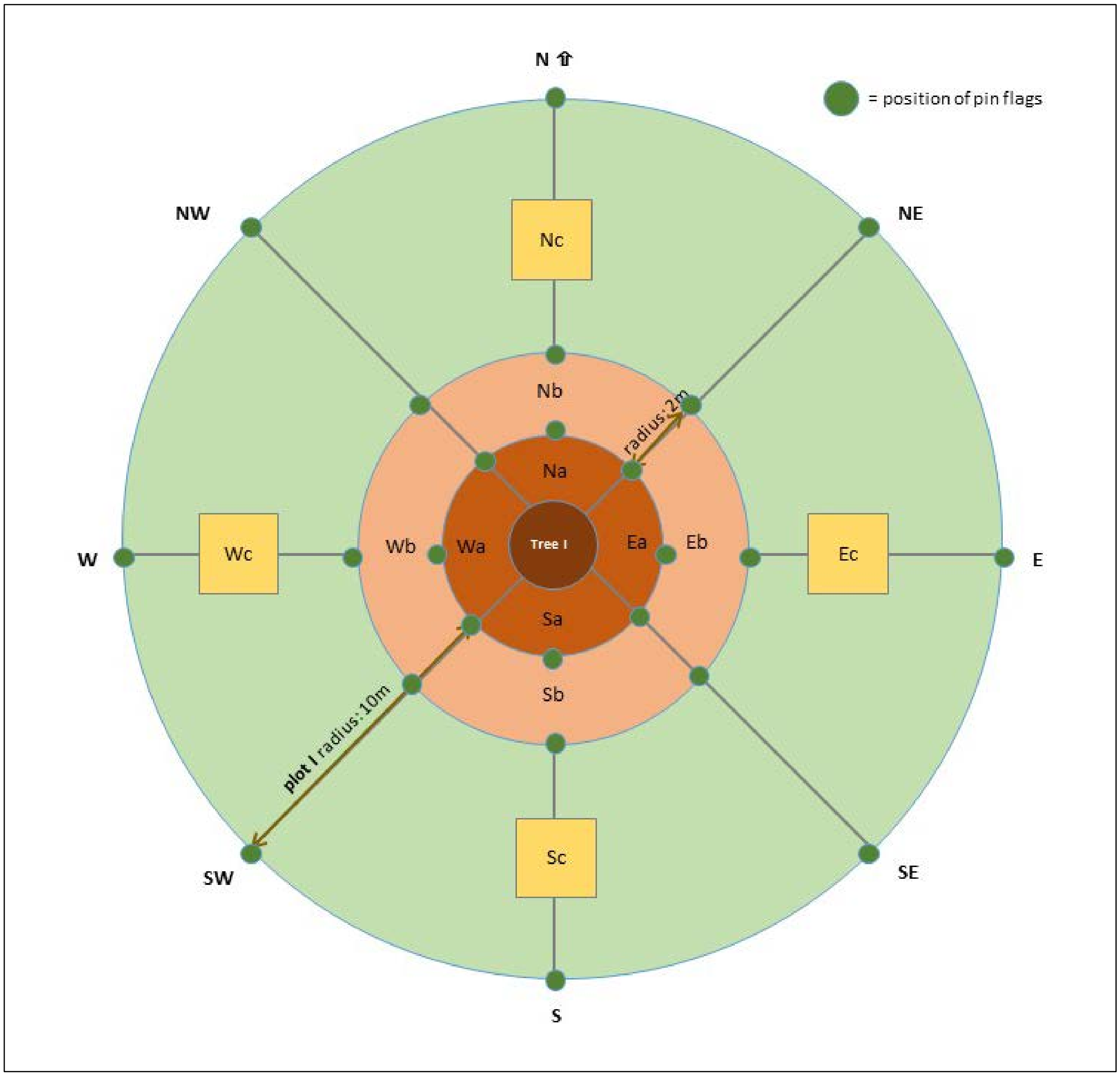
Appendix A. Social trail map of Grove of Titans showing the location of the seven trail cameras.

APPENDIX B: PLOT DRAWING



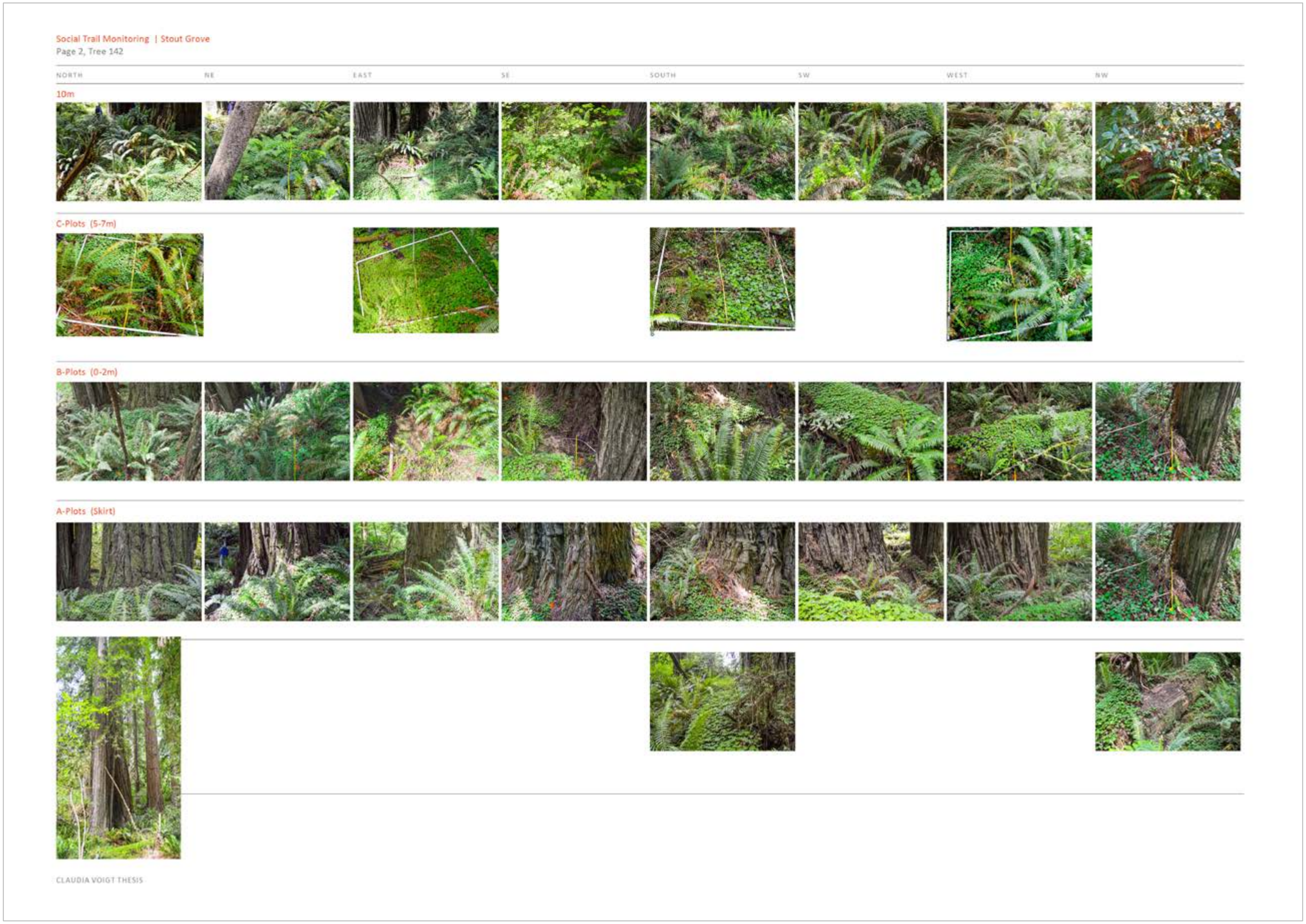
Appendix B. Plot diagram with hand-drawn trampled areas for Tall Trees tree 84.

APPENDIX C: PIN FLAGS

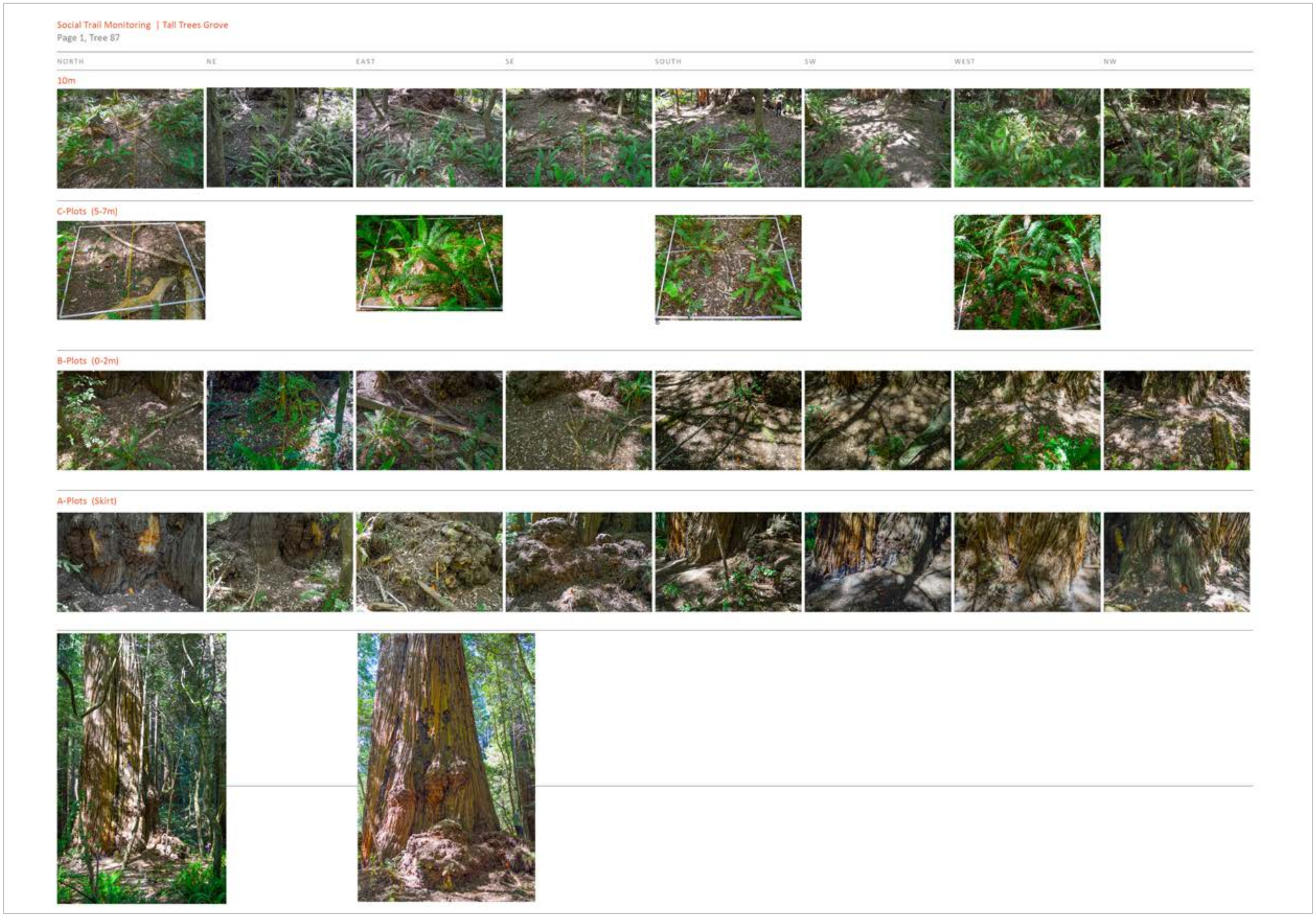


Appendix C. Plot diagram with 24 pin flags.

APPENDIX D: PHOTO CHARTS

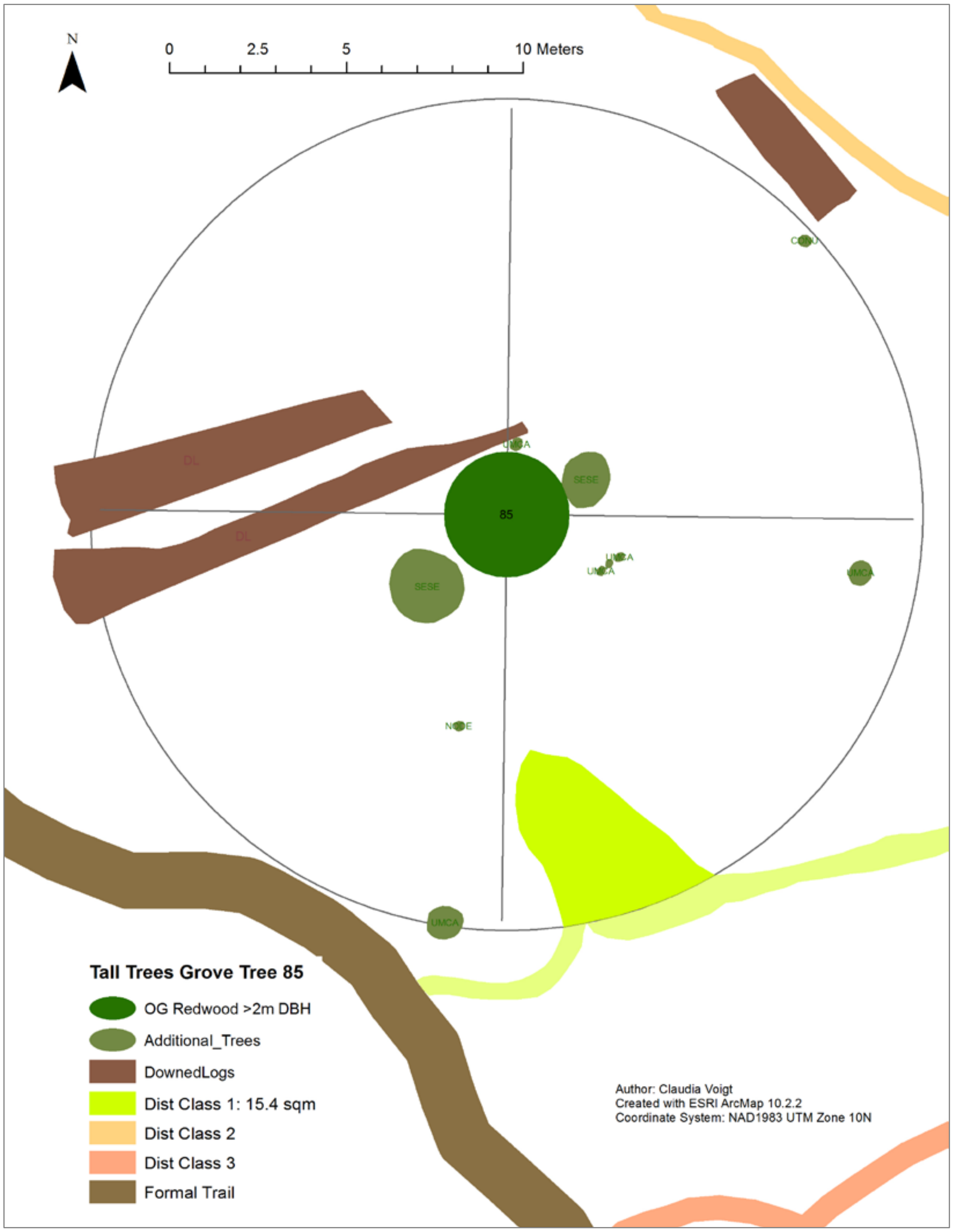


Appendix D. Photo chart examples for trees 54 and 142 in Stout Grove.

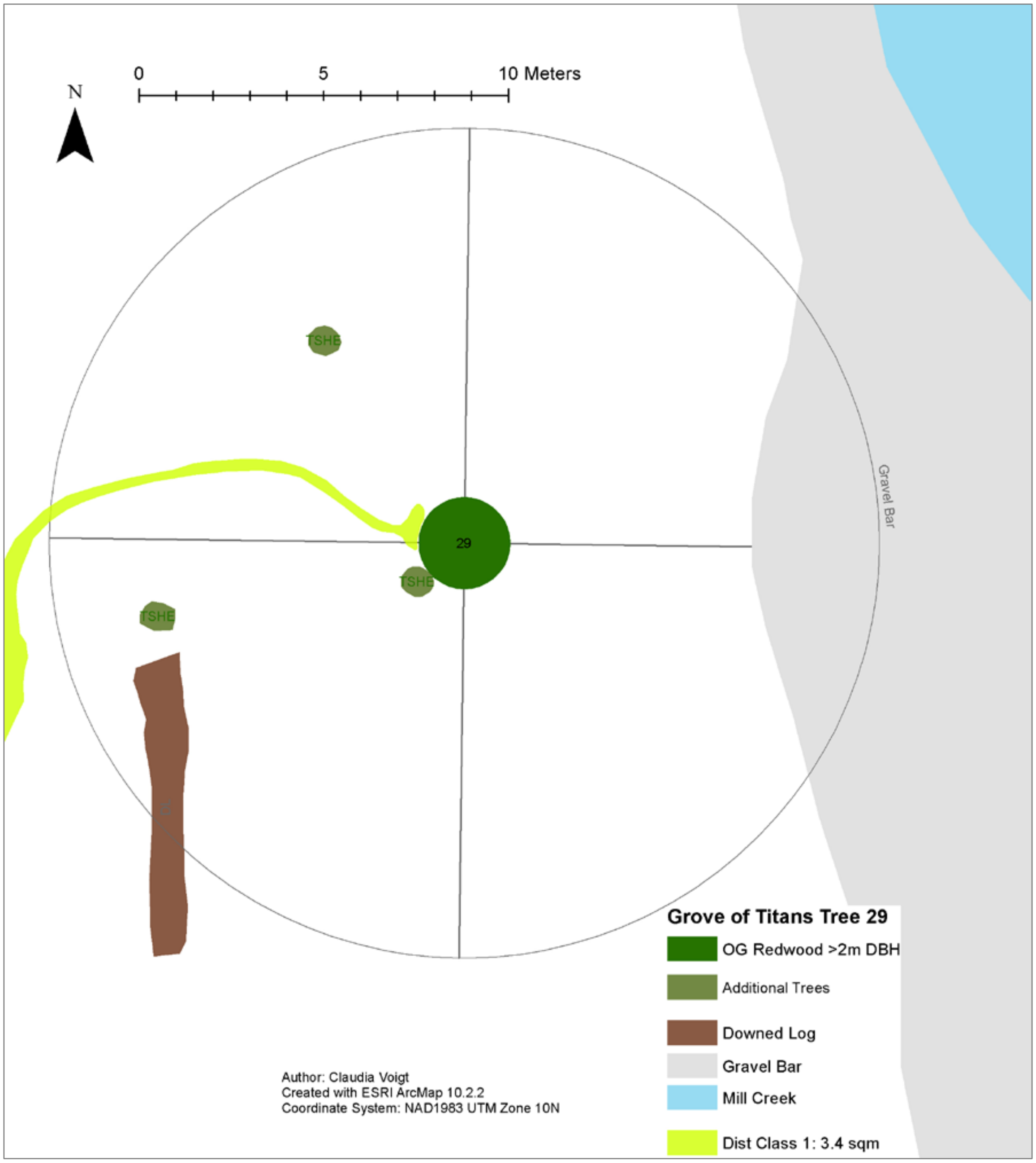


Appendix D. Photo chart examples for tree 87 in Tall Trees Grove.

APPENDIX E: PLOT DIAGRAMS UNDISTURBED TREES



Appendix E. Plot diagram for tree 85, one of the least disturbed plots (4%) in Tall Trees Grove. There is only 1 patch of class 1 disturbance. The interesting bark of the tree is visible from trail.



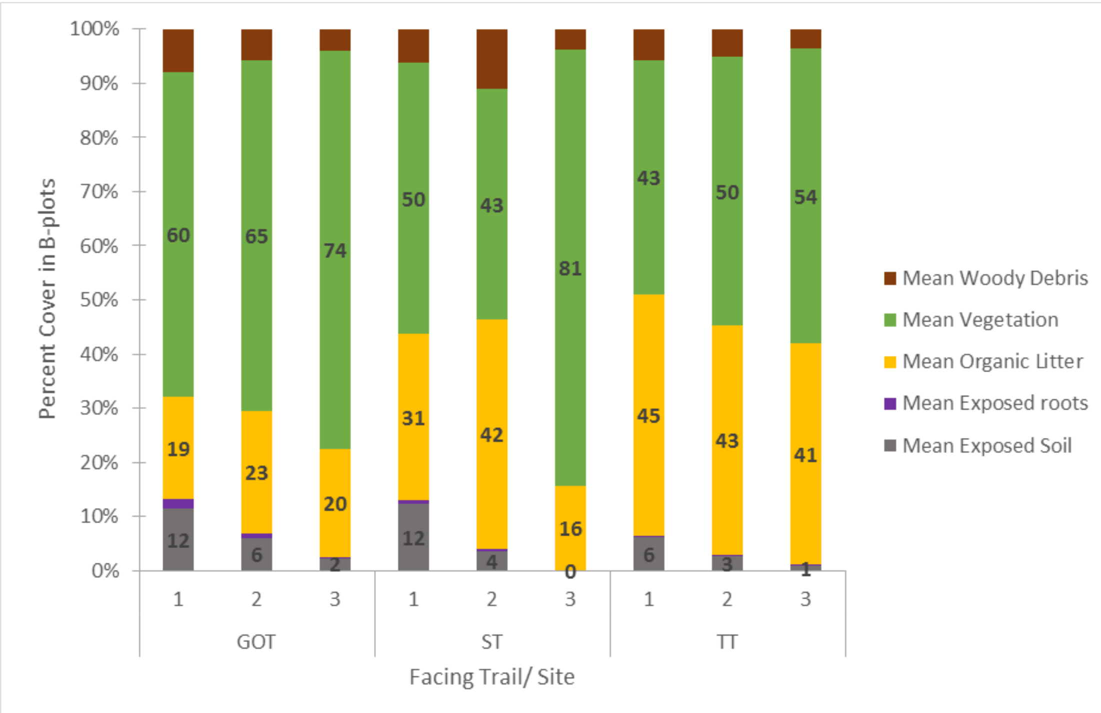
Appendix E. Plot diagram for tree 29, the tree plot with least disturbance (99% undisturbed) in Grove of Titans. A single stem tree on the eastern side of Mill Creek.

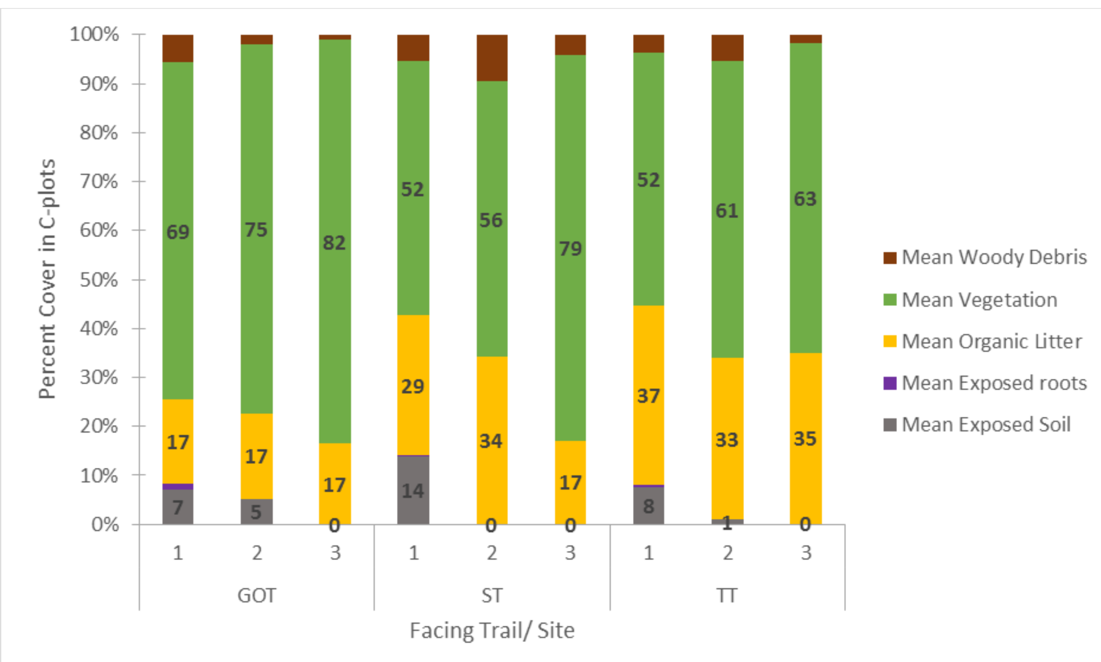
APPENDIX F: AKAIKE'S INFORMATION CRITERION (AICC) TABLE

Appendix F. Akaike's Information Criterion (AICc) table ranking four candidate models for predicting log transformed trampling disturbance in B-plots in Stout Grove. The first two models contain distance from trail and facing trail uni-variately, the third model contains both predictors, and the fourth model contains distance from trail and DBH. Akaike's Information Criterion score (AICc) is based on 2 x log likelihood and the number of parameters (K) in the model. Models are ranked by AICc score, difference in AIC values between models (ΔAICc), and Akaike weights (wi).

Fixed Effects	Random Effect	K	AICc	ΔAICc	w_i
Distance from trail	1 | Tree	4	422.23	0	0.54
Facing trail	1 | Tree	5	434.83	12.61	0.00
Facing trail + Distance from trail	1 | Tree	6	426.46	4.23	0.07
Distance from trail + DBH	1 | Tree	5	423.11	0.88	0.35

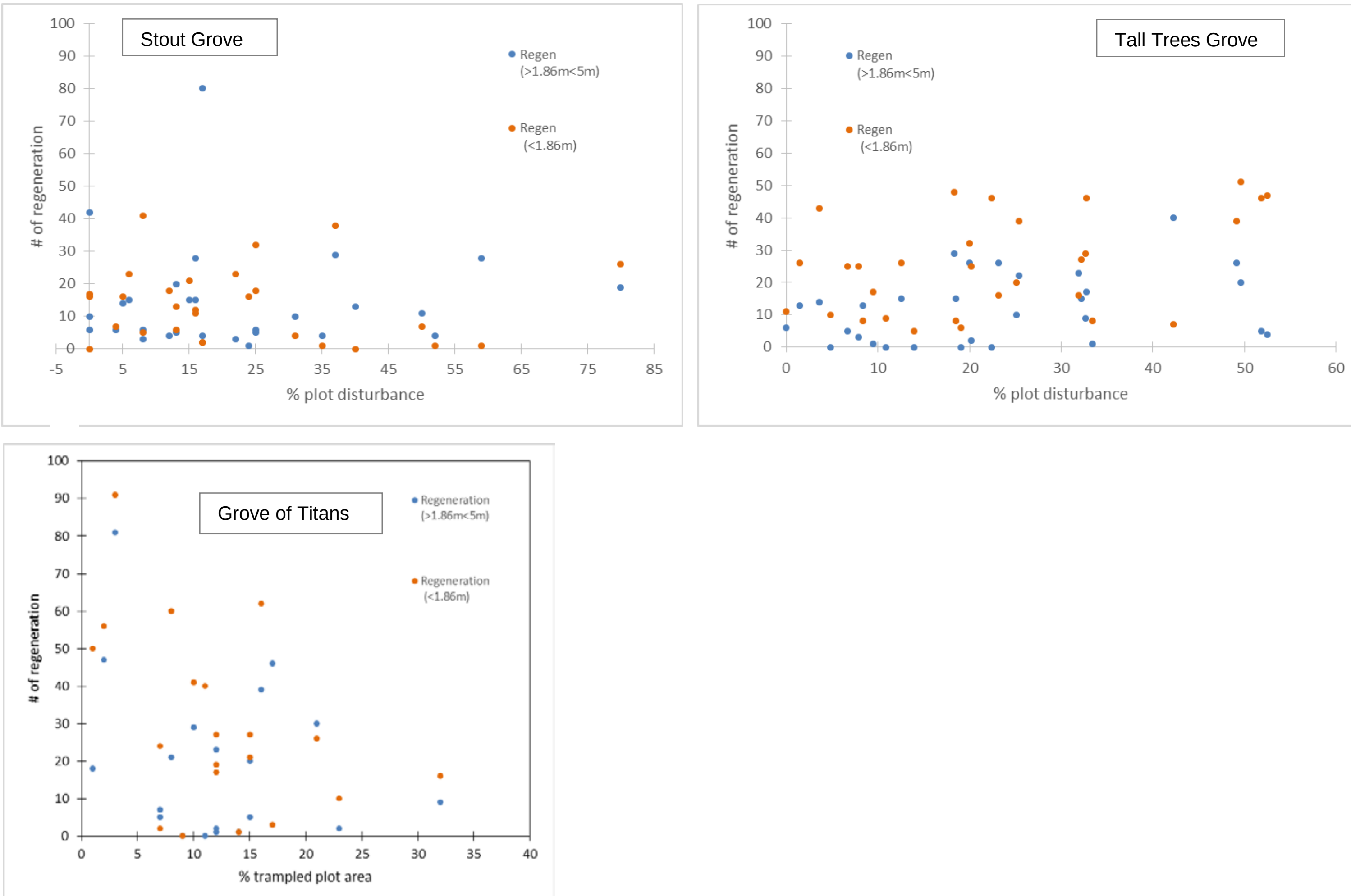
APPENDIX G: COVER ELEMENTS





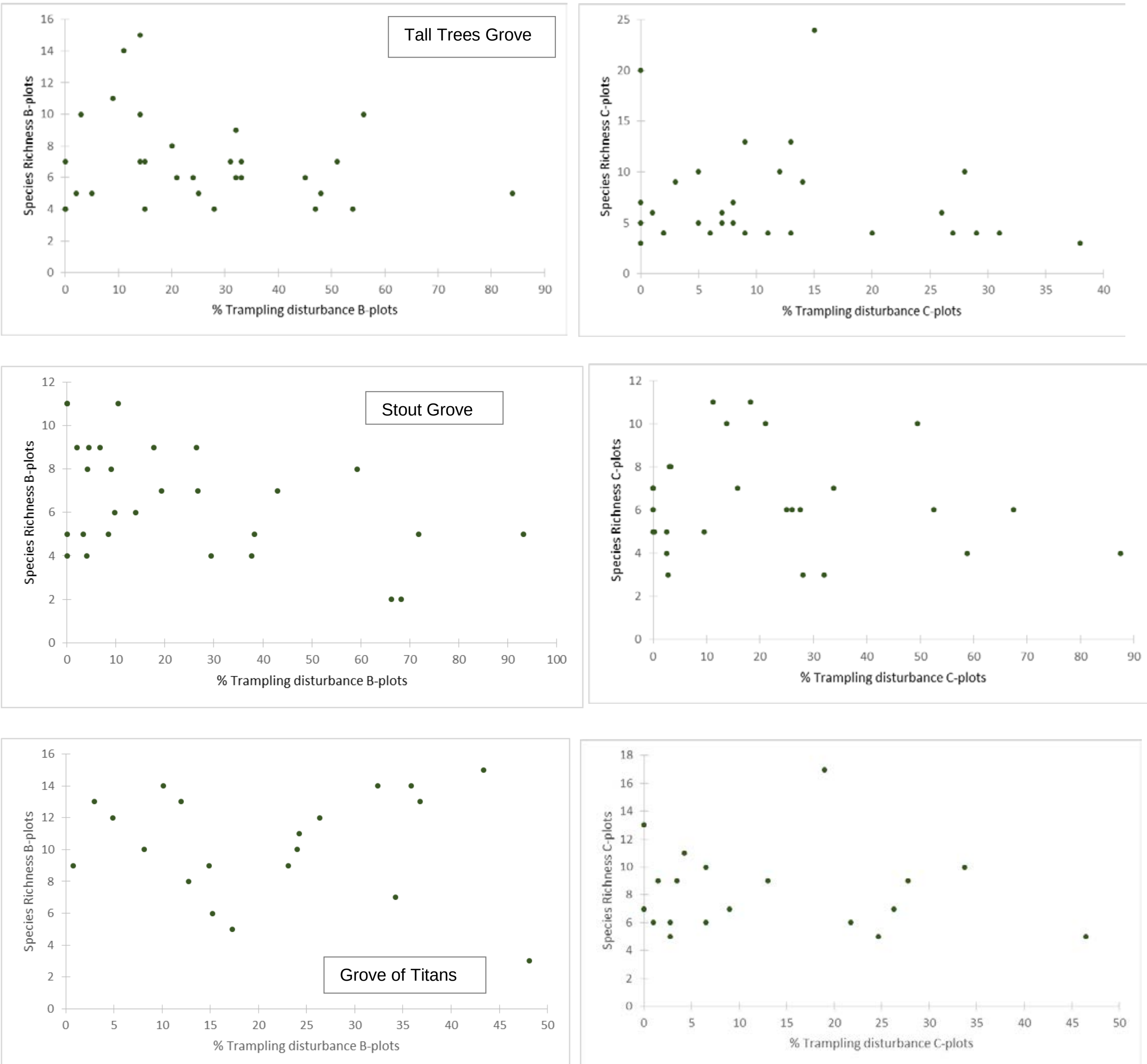
Appendix G. Difference in mean cover between plots facing the formal trail or a class 4 social trail, plots adjacent to those and plots facing away for B- and C-plots in Grove of Titans (n= 79), Stout Grove (n= 105), Tall Trees Grove (n= 117).

APPENDIX H: REGENERATION



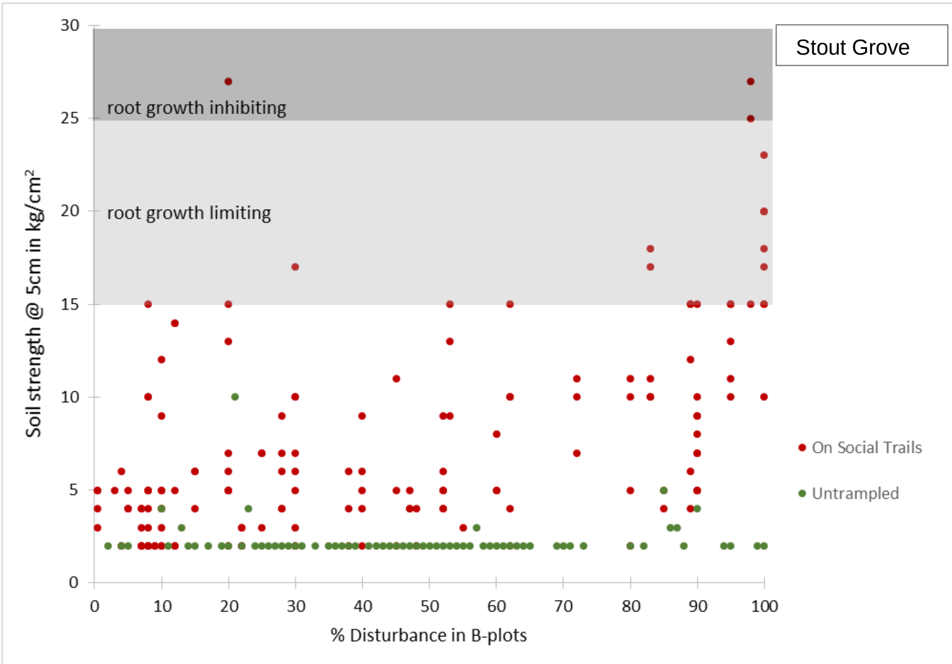
Appendix H. Number of seedlings/ sprouts and saplings per sample plot along a gradient of trampling disturbance for three study sites. In Stout Grove (n= 28) and Tall Trees Grove (n= 30) there was no significant correlation between the number of seedlings/ sprouts or saplings and percent plot disturbance. In Grove Of Titans (n= 20), the number of seedlings/ sprouts decreased with increasing disturbance (for regen <1.86m *p*=0.05, *ρ*= -0.38).

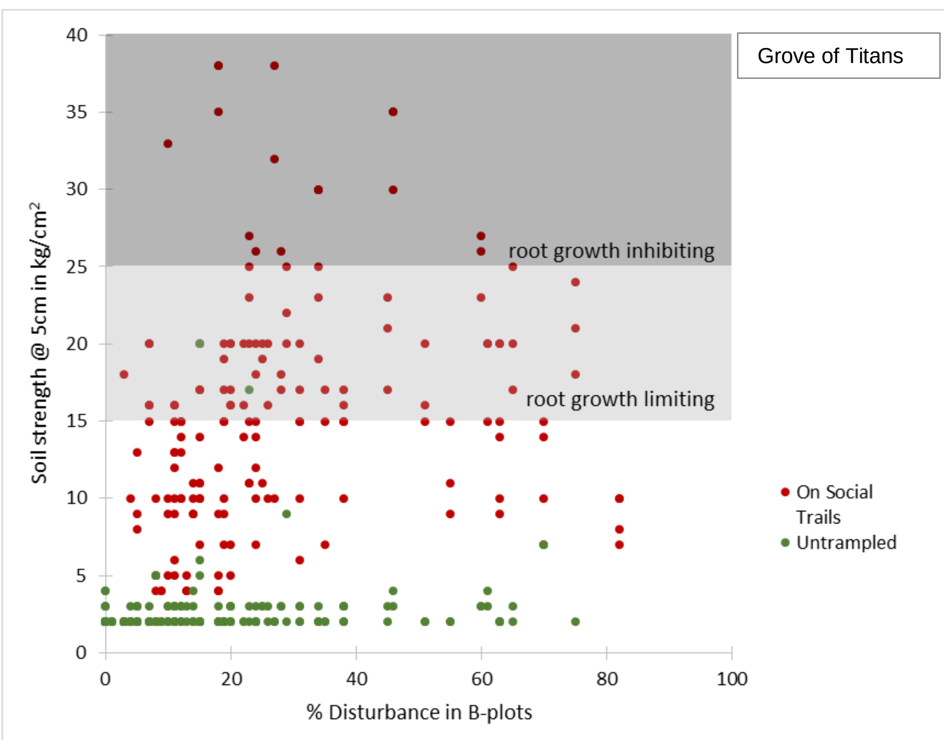
APPENDIX I: SPECIES RICHNESS



Appendix I. Comparison of species richness in B- and C- plots along a gradient of trampling disturbance for a) Tall Trees Grove (n= 30, no significant correlation between species richness and trampling disturbance (B-plots p=0.50, ρ= -0.13 and C-plots p=0.56, ρ= -0.11)), b) Stout Grove (n= 28, in B-plots, species richness significantly decreased with increasing trampling disturbance (p=0.03, ρ= -0.37), no significant correlation in C-plots), c) Grove of Titans (n= 20, no significant correlation (B-plots p=0.61, ρ= 0.07 and C-plots p=0.37, ρ= -0.08), Spearman rank correlation test).

APPENDIX J: SOIL COMPACTION





Appendix J. Increase in soil compaction along a gradient of trampling disturbance for B- plots in Stout Grove (n=161, ρ = 0.52, P < 0.001, Spearman's rank correlation of compaction measurements on social trails at a depth of 5 cm and % trampling) and Grove of Titans (n= 169, ρ = 0.50, P < 0.001, incl <u>all</u> compaction measurements at a depth of 5 cm) For comparison, measurement points in untrampled areas are plotted in green Stout n=331).

APPENDIX K: CONDITION CLASSES


Titans Class4
Titans Class4
Tall Trees Class4
Titans Class4 (Downed Log)+ Class5
Stout Class4
Stout Class4

Appendix K. Photo charts with examples of trail condition classes 1 to 5 for mapping social trails.