THE IMPACT OF ELEVATION AND PROXIMITY TO TRAILS ON PLANT BIODIVERSITY IN MOUNTAIN ECOSYSTEMS SURROUNDINGFLAGSTAFF, AZ, USA

by

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DEDICATION

I dedicate this paper to all my past, present, and future students to serve as a role model for life long learning. I hope that I can inspire you to pursue the education you dream of. For my nieces Hayley and Jadyn and my nephew Silas, I hope this inspires you.

ACKNOWLEDGEMENTS

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ABSTRACT

The objectives of this project were to compare biodiversity along an elevation gradient in the mountains surrounding Flagstaff, Arizona. In addition, identify the presence or absence of four specific non-native species being monitored using the Mountain Invasion Research Network (MIREN) protocol: common yarrow (*Achillea millefolium*), red clover (*Trifolium pratense*), white clover (*Trifolium repens*), narrowleaf plantain (*Plantago lanceolata*). The study used T-shaped transects at randomly selected sampling locations to collect data on richness and abundance of plant species up to 22 m from four hiking trails. Measured sample location was the middle point of the trailside or "near" sample unit. The "near" sample unit (2 m deep * 10 m parallel) was parallel with the trail. The other two sample units "middle" and "far" were perpendicular to the trail, starting 2 m from the measured sample location. Simpsons (1-D) and Shannon's Index were used to determine alpha biodiversity (diversity within a community (Magurran & McGill, 2011) along the elevation gradient. Jaccard Index and Morista-Horn Index used to compare dissimilarity of beta diversity (diversity between communities (Magurran & McGill, 2011)) between elevation zones and proximity to the trail. Dissimilarity is the amount of difference between communities. The study demonstrated species richness decreased as sample location elevation increased. Species richness also decreased as the distance from the trail increased. Simpson's and Shannon's biodiversity indices both showed a statistically significant difference in biodiversity values decreasing with an increase in elevation. Dissimilarity index values for both beta diversity indices indicated a statistically significant difference in dissimilarity based on proximity to the trail. The presence of common yarrow was only found at two sampling locations preventing further analysis. All trails had similar relative abundances but the dominant species along each trail was different. Elevation plays a determining role in the richness and diversity of species in mountain ecosystems surrounding Flagstaff, Arizona.

CHAPTER ONE

INTRODUCTION

Biodiversity

Biodiversity or biological diversity is a measure of biological variety at scales ranging from genetic to ecosystem diversity (Wilson, 1999). A variety of factors are known to influence biodiversity. Abiotic factors such as climate and biotic factors such as competition influence alpha and beta diversity in a region. Alpha diversity refers to the diversity within a community and beta diversity refers to the diversity between communities (Magurran & McGill, 2011). Biodiversity is impacted on multiple scales ranging from the local scale influenced by human interactions to global scales that are influenced by available energy in the system (Seipel et al., 2011).

Biodiversity can be measured and compared using a variety of techniques and many consider species evenness as well as the richness (Magurran & McGill, 2011). Some common techniques use species richness (a measure of the number of species present in a sample), alpha diversity, and beta diversity to compare diversity along elevation gradients. Common calculations of alpha diversity are Simpson's Biodiversity Index and Shannon's Diversity Index; both produce a biodiversity value that can be compared between samples. Beta diversity can be calculated as a measure of dissimilarity

using Jaccard or Morista-Horn Indices. Dissimilarity is the amount of difference in species composition between communities.

Mountain Ecosystems

Mountain ecosystems provide a novel location for biodiversity study due to the elevation gradient from base to peak and the changes in climatic conditions that come with that gradient. Along the elevation gradients, range limits for species and beta diversity may change with the shifting climate, available water and nutrients, as well as amount of open canopy. Patterns in biodiversity have been observed along elevational gradients. Over shorter distances, along an elevation gradient, the pattern may be linear. Over longer distances, from base to peak, a "hump shape" or bell curve shaped pattern of species richness is observed with the highest species richness found in the mid-elevations (Haider et al., 2018; Lee et al., 2013; Seipel et al., 2011). Haider et al. (2018) explains the "hump" as the location where there is the greatest overlap in the range of species from lower and upper elevations. Studies of plant alpha and beta diversity on the Iberian Peninsula demonstrated that alpha functional diversity decreased with increasing elevation adding to the support for this concept (Molina-Venegas et al., 2016). Mountain ecosystems are also known to have a high proportion of endemic species due to the unique conditions that are created by elevation (Lee et al., 2013). Additionally, biodiversity is used as a metric for ecosystem health, with ecosystems containing high biodiversity generally considered healthier and more stable.

Ecosystem Services

Mountain ecosystems provide not only unique habitats along their elevational gradient but offer ecosystem services to the populations that live near the mountains. Mountains provide economic benefits such as timber, freshwater collection and filtration via surface and groundwater, and ecotourism (Mina et al., 2016; Halofsky et al., 2017). Understanding the biodiversity present in mountain ecosystems is vital to understanding the future ability of these ecosystems to continue providing these ecosystem services (Joseph et al., 2012). The varied habitats of mountain ecosystems make them prime locations for invading species which could disrupt these ecosystem services with increasing disturbance (Pauchard et al., 2009). Research suggests that non-native species are less abundant at higher elevations (Pauchard et al., 2009; Seipel et al., 2011). At high elevations, there tends to be less human influence on the land and less human visitation which may explain the low abundance of non-native species at higher elevations (Seipel et al., 2011). Many mountain areas in the United States are also preserved in parks, national forests, etc. further limiting human interference. Researchers hypothesize that most invasions to mountain ecosystems will come from the valleys below and so natural selection may select traits suited to the lower elevations prior to species expanding to increased elevations (Alexander et al., 2011; Pauchard et al., 2009; Seipel et al, 2011, 2016). In mountains studied around the world, species from lower elevations were filtered by changing environmental factors unique to the specific mountain being studied across increasing elevation (Haider et al., 2018; Seipel et al., 2011, 2016).

Elevation

An elevational gradient has one of the most influential effects on local biodiversity (Eisenlohr et al., 2013). Elevation gradient correlates strongly with the climate gradient (temperature and precipitation) which influences patterns of biodiversity (Lee et al., 2013; Eisenlohr et al., 2013; Joseph et al., 2012). The cooler temperatures that occur as the elevation increases is likely one of the driving reasons for the decrease in species richness along an increasing elevation gradient (Sergio & Pedrini, 2007). The increase in elevation also supports more rainfall and snow cover, in most regions, which will affect the survivorship of the species and limit species richness (Sergio & Pedrini, 2007). Studies conducted in West Java demonstrated that species richness was correlated with elevational gradient (Kudo et al., 2014). While the pattern between species richness and elevation is well documented, Haider et al. (2018) indicated more research is needed to investigate other biodiversity metrics including beta diversity dissimilarity along elevation gradients. Lee et al. (2013) also suggest that "Rapoport's Elevational Rule" effects diversity along elevational gradients with species found in the upper most elevations having the most flexibility to withstand the changing environmental conditions allowing these species to have a wider elevational range than less flexible species from lower elevations.

Human Disturbance

Ecotourism around the world has led to many benefits for the environment. Diversion of money from ecosystem harm (extractive industries) to ecosystem preservation has had success in numerous locations stabilizing the loss of biodiversity. Ecosystems with stabilized biodiversity show improvement in the health and productivity of the land (Culotta, 1996). Biodiversity is considered a major factor in the resistance and reliance of an ecosystem to disturbance (Lee et al., 2013). For example, altering plant diversity can affect food webs with a consequence of reduced biodiversity becoming evident in the top predators of an ecosystem (Culotta, 1996). Increased tourism has increased the opportunity to introduce non-native species (Wimpey & Marion, 2011; Pauchard et al., 2009). Investigations into non-native species along road sides on elevation gradients in eight to ten mountain regions around the world have indicated an increase in non-native species presence over time at higher elevations (Pauchard et al, 2009; Seipel et al, 2011, 2016).

Roads and Trails

Researchers worldwide have been concerned about the influence of roads and trails, for tourism, on the introduction of non-native species and the alteration of biodiversity. Constructing trails and roads to increase access to natural areas offers a pathway for non-native species into once pristine ecosystems (Kc & Gautam, 2016). The construction of trails or roads through an ecosystem will create disturbance opening new

and novel environments for species to establish (Kc & Gautam, 2016; Laurance et al., 2009; Le et al., 2018). Road sides provide an altered microenvironment for non-native species to establish with a more open canopy and altered soil nutrients for any non-native seed bank that has been built by visitors to the roads or trails (Kudo et al., 2014; Lembrechts et al., 2016). Road side disturbance offers an avenue for faster spread to higher elevations for both native and non-native species (Lembrechts et al., 2016). The range of non-native plant species roadside has been documented as broader than in lands near roads (Lembrechts et al., 2016). Current research suggests that non-native species have not invaded far into habitat adjacent to roads. Trails are like roads in that they open the canopy and alter the trail side microenvironment. The possibility exists that the same patterns of native and non-native species diversity observed along roads may exist along hiking trails.

As tourists infiltrate further into mountain regions along roads and trails they bring seeds from where they have previously recreated. There are many examples from various parts of the world where these investigations of introduction via trail have occurred. A study along trails in Malaysia found *Clidemia hirta* established along trails but had not spread beyond five meters from the trail while other locations with this species suggest *C. hirta* may invade further (Le et al., 2018). Studies of trails in the Rocky Mountains of Colorado, USA found that non-native species had higher percentage of cover near sampled trails compared to four-meter distances from the trails (Well et al., 2012). In Mediterranean forests, Marcantonio et al. (2013) determined that the disturbance of a road only altered the soil conditions within a relatively narrow band

alongside the roads and this influenced the ability of a species to invade further into adjacent vegetation.

Objectives

The objective of this study is to determine how plant diversity changes with elevation along hiking trails in the mountains surrounding of Flagstaff, Arizona and investigate if non-native species are present that may affect plant diversity. The objectives of this project are to compare plant: 1) species richness, 2) biodiversity indices, 3) species evenness, 4) rank abundance along trails following an elevational gradient in mountain ecosystems, 5) presence of four target non-native species. The general hypothesis for this study is that species richness, diversity, and evenness will decrease with increase in elevation.

CHAPTER TWO

METHODS

Site Description

Many mountains of Arizona rise sharply out of flat valleys. These mountains are called “sky islands” (Ober et al., 2011). Hiking trails follow the steep elevation gradients of the mountains. The San Francisco Peaks are unique because they are an extinct stratovolcano that rises out of the already higher elevation of Northern Arizona. The San Francisco Peaks are visited by individuals from around the world because of proximity to Grand Canyon National Park. Visitors can bring, on their clothing, shoes, equipment, or vehicles, seeds or plant materials from other places they have traveled (Pickering et al., 2003). This makes hiking trails a critical point of introduction for non-native species.

Sampling for this study occurred in the late summer of 2018 which was preceded by a drier winter receiving 50-70% less snow than the previous two snow seasons ("Arizona Snowbowl Snow History", 2019). Arizona Snowbowl is on Coconino National Forest and is on a peak adjacent to all the trails in the study, so it serves as a reliable indicator of snow depth. The state received historic rains between the two sampling dates causing the second sampling to occur after the rains ended. It is possible that the additional rain and seed bank were still in early life stages and may not have emerged from the soil to be identified (Flagstaff Weather Forecast Office, 2014). The region, on average, receives 6.48 cm of rain and received 10.7 cm of rain which split the sampling

from late September 2018 to the first weekend after the rain which was early November 2018 (Flagstaff Weather Forecast Office, 2014).

Field Methods

Species richness was sampled along four trails: Bear Jaw Trail, Abineau Trail, Aspen Trail and A Mountain Trail in the Coconino National Forest surrounding the City of Flagstaff, Arizona (Figure 1). Two trails originate at the same location but transverse different parts of the mountain. Bear Jaw Trail gains 365 m of elevation along the 3.6 km trail ("Bear Jaw Trail #26, Arizona", 2008 N35° 23.173’ W111° 40.595’). Abineau Trail (#127) gains 545 m elevation along 3.8 km ("Abineau Trail #127, Arizona", 2000 N 35° 22.988’ W111° 40.400’). Aspen Trail gains 91 m of elevation along 3.0 km trail ("Aspen Nature Loop, Arizona" (35.3217° N, 111.7235° W). A-1 Mountain Trail (A Mountain) gains 176 m elevation along 2.8 km trail ("A-1 Mountain - CNF, Arizona" N35° 14.393’ W111° 44.500’).

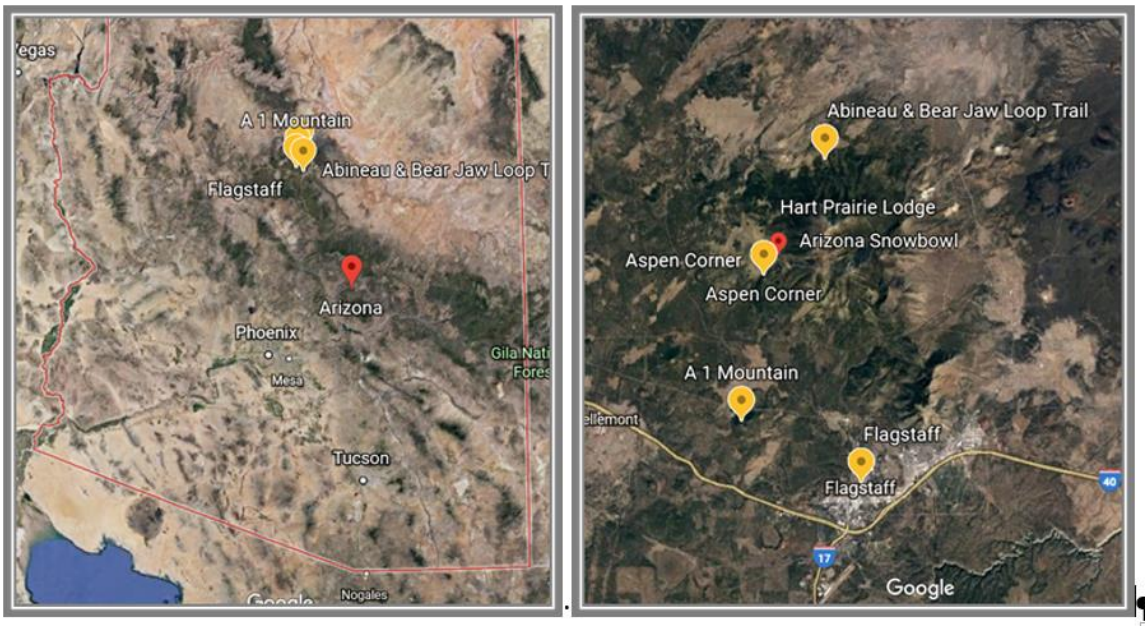

Figure 1: The left map is of the State of Arizona with the trails marked in the upper middle portion of the image and the researcher's home in Phoenix. The right map shows the location of each of the four sampled trails relative to each other and Flagstaff, AZ.

Five sample locations were located along each trail, one each at the start and end and three randomly in between. A random number generator was used to determine the locations and which direction from the trail (right or left) for each sample site. Elevation points were numbered 1-5 with one representing the lowest elevation and five the highest elevation along an inclined trail. The methodology used is modelled after the "T" shaped (Figure 2 and 3) road and trail sampling by the Mountain Invasion Research Network (MIREN), first detailed for roads by Seipel et al. (2011) and modified for trails (Barrows et al., 2018), however they utilize equidistant points not random distance samples. At each of the five sampling locations along each trail, a T-shaped transect was used (Barrows et al., 2018; Seipel et al., 2011). The first "near" transect (10 m * 2m) was

parallel with the trail, the other two sample transects were perpendicular to the trail: 2 m* 12 m from the trail for the “middle” transect and 12 m * 22 m for the “far” transect. A total of 60 sample plots were surveyed.

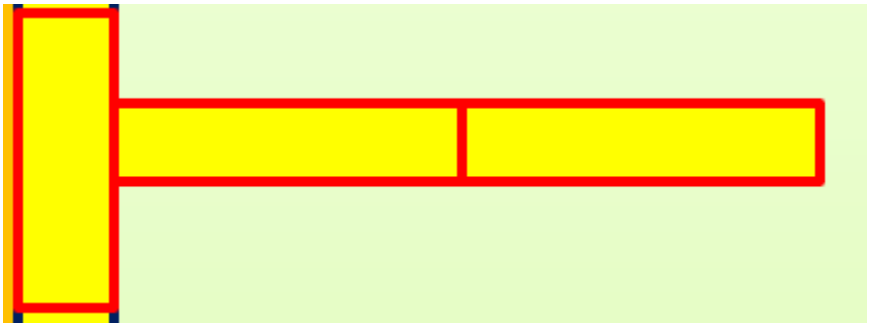

Figure 2: This is an image provided by Barros et al. (2018) for how to construct a T-shaped transect. Each rectangle is 2 m x 10 m

Figure 3: This image shows the “near” position plot adjacent to the Bear Jaw Trail. I am currently taking ocular abundance measurements for the species in this plot.

For each transect sampling unit, species richness and abundance were collected using ocular percent cover estimates. In addition to observing species

richness and abundance, four non-native species were noted when present within the samples: common yarrow (*Achillea millefolium*), red clover (*Trifolium pratense*), white clover (*Trifolium repens*), and narrowleaf plantain (*Plantago lanceolata*). These four non-native species are of interest to Barros et al. (2018) as part of the MIREN Trail Survey study.

Data Analysis

Species richness and abundance data were used to calculate biodiversity index values for Simpson's (1-D) and Shannon alpha biodiversity indices, and Jaccard's and Morista-Horn beta evenness indices using the vegan package in R (2018) (see Appendix A-C). Total abundance was computed for each trail. Species richness is the number of species in each sample of the T transect. Simpson's (1-D) and Shannon's Biodiversity Index provide values based on the abundance and evenness of species in the samples to represent biodiversity (Magurran & McGill, 2011). Jaccard index and Morista-Horn allow the examination of dissimilarity between community composition along the elevation gradient and relative to the trail(see Appendix A).

Initial assessment of the data was completed visually by graphing species richness, Simpson's and Shannon's indices by elevation zone and distance (position) to the trail to identify any possible patterns. The effect of elevation and position adjacent to the trail, and trail on species richness, was analyzed with a generalized linear model with Poisson distribution. I assessed for interactions between elevation and position, choosing the most parsimonious model. The same variables were evaluated for alpha and beta

diversity, again choosing the most parsimonious model. For Simpson and Shannon alpha diversity indices, analysis of variance (ANOVA) used, and beta diversity was evaluated using Jaccard and Morista-Horn index with analysis of variance using distance matrices (ADONIS). Principal Coordinate Analysis was performed comparing both the trails and the elevation points. All analysis was completed using R statistical software version 3.3.1.

CHAPTER THREE

RESULTS

Species Richness

Mean species richness decreases with the increase in elevation and with distance from the trail and there was no effect of trail (Figure 4). More specifically, species richness decreases from the trailhead to elevation 2 (p=0.007) and elevation 5 (p=8 E-05) and the near plots were significantly different from the far plots (p=0.01) (Table 1). There was no difference in species richness by trail.

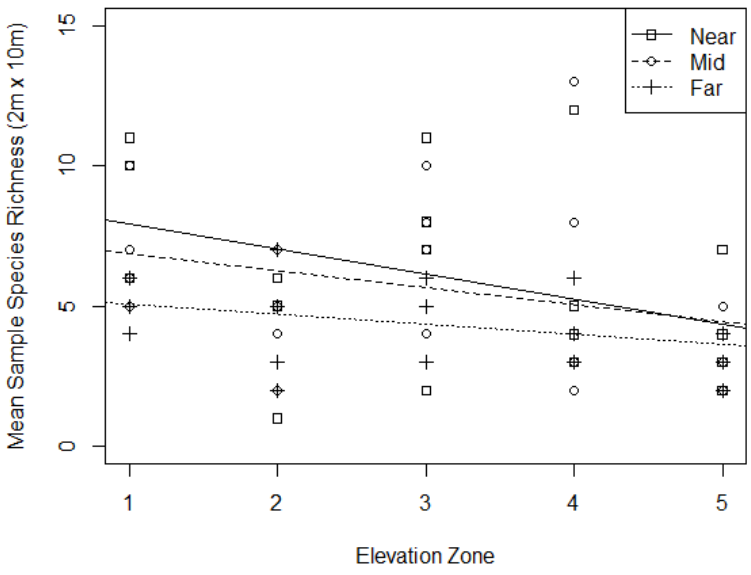

Figure 4: Species richness declines with elevation (low to high (1-5)) and proximity to the trail (square=near, circle=middle, += far) along four trails in the mountains surrounding Flagstaff, AZ.

Table 1: Species richness decreases with an increase in elevation and distance from the trail with no effect of trail location. Values in bold indicate statistically significant differences ($p < 0.05$). The trailhead (elevation 1) and the transect sample adjacent to the trail one, Abineau, are used as the comparison.

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
(Intercept)	2.0690	0.1624	12.743	**< 2e-16**
Elevation2	**-0.4724**	**0.1750**	**-2.699**	**0.00696**
Elevation3	-0.1119	0.1579	-0.709	0.47837
Elevation4	-0.2085	0.1620	-1.287	0.19810
Elevation5	**-0.7538**	**0.1917**	**-3.931**	**8.45e-05**
Middle	0.0848	0.1303	-0.651	0.51520
Far	**-0.3463**	**0.1401**	**-2.472**	**0.01344**
A Mountain	-0.1951	0.1675	-1.165	0.24409
Aspen	0.1079	0.1550	0.696	0.48636
Bear Jaw	0.1414	0.1538	0.920	0.35778

Alpha Diversity

Alpha diversity calculated using Simpson's diversity (1-D) index decreases with elevation ($p=0.007$) (Figure 5). More specifically, biodiversity differs from the trailhead to elevation 2 ($p=0.010$) and elevation 5 ($p=0.002$) (Table 2). Diversity declined more rapidly on Bear Jaw than Abineau ($p=0.036$). Shannon's diversity index elevation 2 ($p=0.008$) and elevation 5 ($p=1.00$ E -3) (Table 3) shows a similar decreasing pattern with elevation from the trailhead (Figure 6).

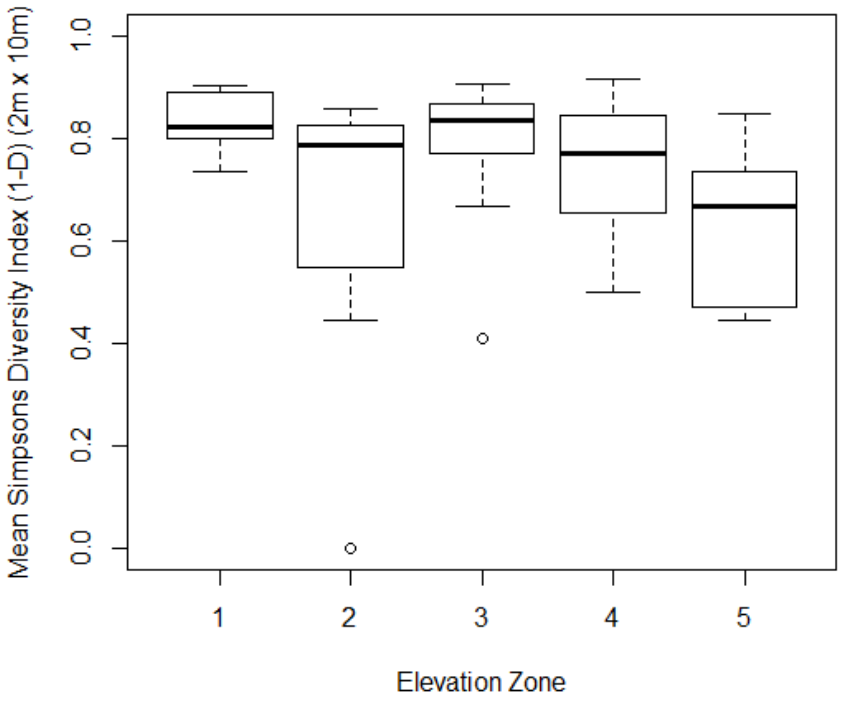

Figure 5: Simpson's Diversity Index declines with elevation zone (low to high (1-5)) along four trails in the mountains surrounding Flagstaff, AZ.

Table 2: General linear model results for Simpson's Diversity Index (1-D) along Elevation zones (1-5) and distance from the trail (near, middle, far) for four trails in the mountains surrounding Flagstaff, AZ. Values in bold indicate statistically significant differences ($P < 0.05$). The trailhead (elevation 1) and the transect sample adjacent to the trail one, Abineau, are used as the comparison.

Coefficients	Est.	SE	t value	P(>|t|)
(Intercept)	0.88797	0.06284	14.130	2E-16
Elevation2	**-0.16789**	**0.06284**	**-2.672**	**0.01016**
Elevation3	-0.04690	0.06284	-0.746	0.45900
Elevation4	-0.08007	0.06284	-1.274	0.20852
Elevation5	**-0.20144**	**0.06284**	**-3.205**	**0.00235**
Middle	0.00740	0.04868	0.152	0.87978
Far	-0.01305	0.04868	-0.268	0.78971
A mountain	-0.07705	0.05621	-1.371	0.17657
Aspen	-0.00970	0.05621	-0.173	0.86369
Bear Jaw	**-0.12102**	**0.05621**	**-2.153**	**0.03615**

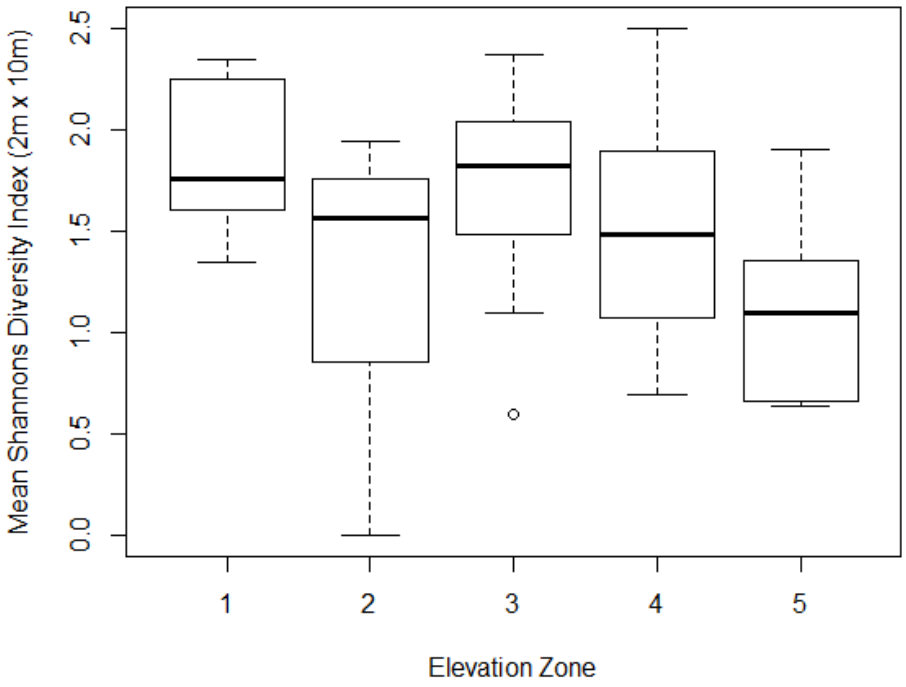

Figure 6: Shannon's Diversity Index by elevation position low to high demonstrates statistically significant (p=0.001) decrease in biodiversity with an increase in elevation.

Table 3: General linear model results for Shannon's Diversity Index along elevation zones (1-5) and distance from the trail (near, middle, far) for four trails in the mountains surrounding Flagstaff, AZ. Values in bold indicate statistically significant differences ($P < 0.05$). The trailhead (elevation 1) and the transect sample adjacent to the trail one, Abineau, are used as the comparison.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	2.05294	0.20046	10.241	**7.16e-14**
Elevation2	-0.55293	0.20046	-2.758	**0.008093**
Elevation3	-0.16171	0.20046	-0.807	0.423662
Elevation4	-0.31318	0.20046	-1.562	0.124522
Elevation5	-0.77216	0.20046	-3.852	**0.000334**
Middle	-0.05542	0.15527	-0.357	0.722655
Far	-0.22294	0.15527	-1.436	0.157294
A Mountain	-0.25338	0.17930	-1.413	0.163786
Aspen	0.03491	0.17930	0.195	0.846403
Bear Jaw	-0.13772	0.17930	-0.768	0.446014

Beta Diversity

The results of the Jaccard index identified dissimilarity along the elevation zones (p=0.001) (Table 4) with index values for elevation zones ranging from 80%-85% (see Appendix B). Trails were also dissimilar (p=0.001) (Table 4) with index values ranging from 53%-84% with Abineau and A Mountain trails having the highest similarity sharing 98% of species and A Mountain and Aspen trails being the most dissimilar with 83% (see Appendix C).

Table 4: Adonis distance matrices analysis of Jaccard index identifies dissimilarity differed by elevation zone (p=0.001) and trail (p=0.001). Values in bold indicate statistically significant differences ($p < 0.05$).

	Df	Sums Of Sqs	Mean Sqs	F. Model	R2	Pr (>F)
Elevation zone	**4**	**1.9822**	**0.49555**	**2.1552**	**0.08902**	**0.001**
Proximity to trail	2	0.6032	0.30158	1.3116	0.02709	0.149
Trail	**3**	**8.1854**	**2.72848**	**11.8665**	**0.36760**	**0.001**

Morista-Horn index indicates a pattern of dissimilarity in beta diversity based on elevation (p=0.001) (Table 5) with dissimilarity values between 69-79% (see Appendix D); there were also differences between the four trails (p=0.001) (Table 5). Principal coordinate analysis (Figure 7) displays the Morista-Horn beta analysis indicating that the trails are dissimilar with elevation graphically displaying that each trail's points are of inconsistent distances from their center.

Table 5: Adonis distance matrices analysis of Morista-Horn index by elevation plus position and trail. Results show that elevation (p=0.001) is an important factor in beta diversity of the trails. The trail (p=0.001) is also important in determining dissimilarity of beta diversity. Values in bold indicate statistically significant differences ($p < 0.05$).

	Df	Sums of Sqs	Mean Sqs	F. model	R2	Pr (>F)
Elevation zone	**4**	**1.6587**	**0.41468**	**2.7563**	**0.08888**	**0.001**
Proximity	2	0.4970	0.24848	1.6516	0.02663	0.096
Trail	**3**	**8.9849**	**2.99495**	**19.9066**	**0.48142**	**0.001**

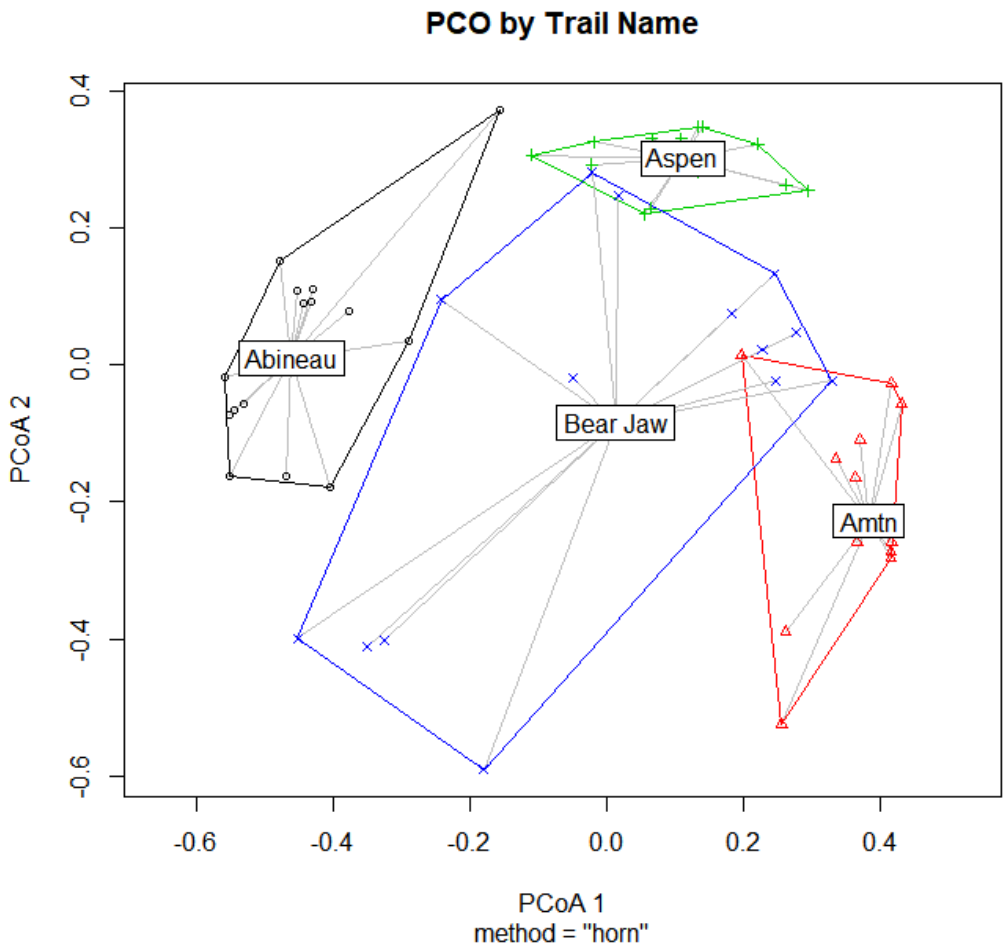

Figure 7: Principal coordinate analysis by trail demonstrates the differences in beta diversity among the trails. Bear Jaw has some similarity in species present based on the overlapping polygon with A Mountain (Amtn) and Aspen. All trails differ in their similarity based on the varied distances of points from the center for each trail.

Finally, the relative species rank abundance curves show similar patterns for each trail (Figure 8), though the dominant species differ (Table 6). A Mountain and Aspen Trails have a much higher abundance for the first two ranked species compared to the other two trails followed by a sharp decline in abundance for the next most abundant species. *Populus tremuloides* is the most abundant along Abineau Trail; *Pinus ponderosa* is most abundant along A Mountain Trail; *Bromus ciliates* is most abundant along Aspen Trail; *Mahonia repens* is most abundant along Bear Jaw Trail (Table 6). When looking at the top ten most abundant species along individual trails, forbs are the most abundant overall classification of plant type present ranging from 30-60%. Trees make up 10-40% of the most abundant species along individual trails. Grasses made up 0-30% of the most abundant species present and were absent along Abineau Trail. Bear Jaw Trail has the highest species richness with 30 species identified. The other trails ranged from A Mountain with 12 species to Aspen Trail with 19 species.

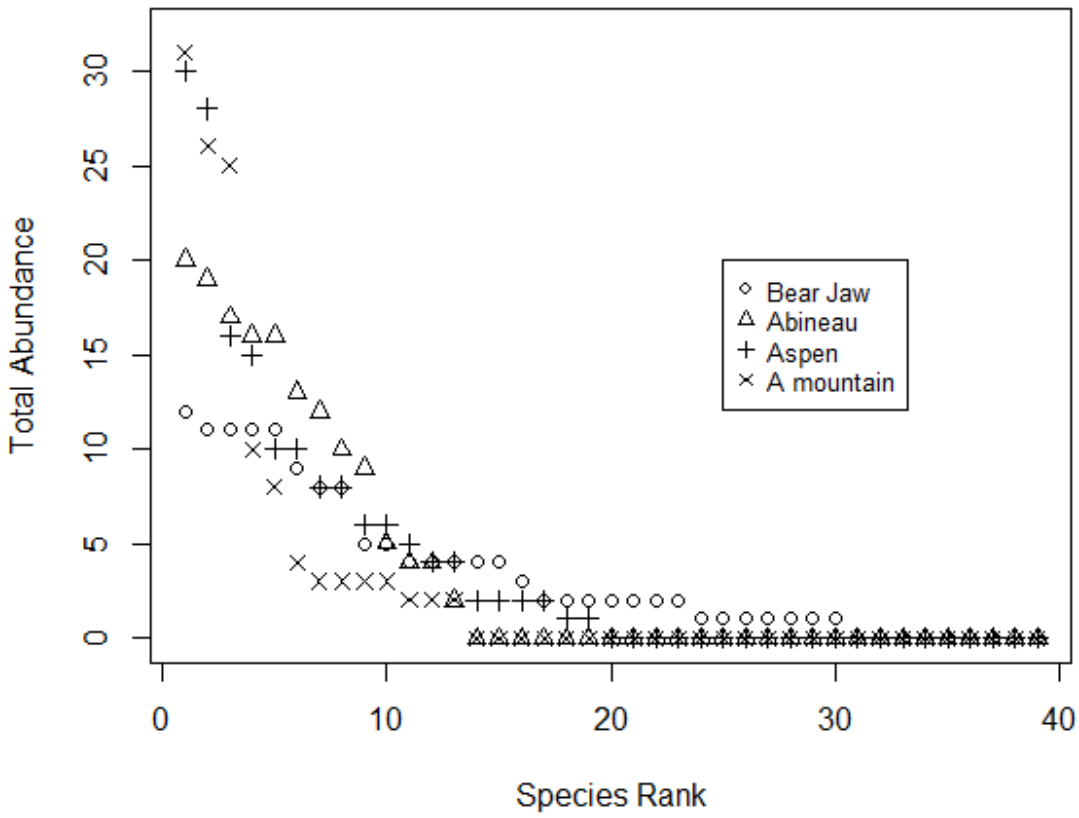

Figure 8: Total abundance of species by trail calculated for Bear Jaw (circle), Abineau (triangles), Aspen (+), and A Mountain (x). Illustrates that A Mountain and Aspen Trails has a much higher abundance for the first two ranked species compared to the other two trails followed by a sharp decline in abundance for the next most abundant species. Results show that A Mountain consistently has a higher relative abundance of *Pinus ponderosa* compared to the other trails but that when comparing each trail to the others the most relatively abundant species varied (Table 6).

Table 6: The ten most abundant species by trail (1 is most abundant).

Rank Abundance	**Abineau**	**A Mountain**	**Aspen**	**Bear Jaw**
1	*Populus tremuloides*	*Pinus ponderosa*	*Bromus ciliates*	*Mahonia repens*
2	*Pseudotsuga menziesii*	*Festuca arizonica*	*Festuca arizonica*	*Bromus ciliates*
3	*Thalictrum fendleri*	*Aristida purpurea*	*Pinus flexilis*	*Lupinus* spp.
4	*Pinus flexilis*	*Lupinus* spp.	*Lupinus* spp	*Muhlenbergia montana*
5	*Unknown plant #1*	*Vicia pulchella*	*Erigeron eximiu*	*Festuca arizonica*
6	*Erigeron eximiu*	*Bromus ciliates*	*Besseya plantaginea*	*Pinus ponderosa*
7	*Mahonia repens*	*Antennaria purvifolia*	*Antennaria parvifolia*	*Pseudocymopterus montanus*
8	*Lupinus* spp.	*Taraxacum officinale*	*Populus tremuloides*	*Aristida purpurea*
9	*Geranium richarsonii*	*Erigeron annuus*	*Helianthella quinquenervis*	*Erigeron eximiu*
10	*Abies concolor*	*Rosa woodsii*	*Unknown plant #2*	*Pinus flexilis*

Non-native Species

The four-non-native species of interest in Barros et al. (2018) are uncommon on the sampled trails in this study. *Achillea millefolium* is observed in two of sixty plots or 3.3% of the sampled plots. The two trails that contain *A. millefolium* are Bear Jaw elevation zone four and middle position from the trail and Aspen Trail elevation zone one and near position to the trail. The elevation range where this non-native species is observed is between 2623-2720 meters. None of the three other non-native species were observed. There is not enough data on the non-native species to complete an analysis.

CHAPTER FOUR

DISCUSSION

Discussion of Results

Species richness decreases with elevation in the mountain regions surrounding Flagstaff, AZ. This study supports that alpha diversity is altered by elevation gradients. Several studies demonstrate a strong correlation between elevation and woody plant species in mountain ecosystems in various ecosystems around the globe (Seipel et al., 2011; Ivanova & Soukhovolsky, 2016; Mallen-Cooper & Pickering, 2008). Beta diversity, when compared between elevation zone, also demonstrates significant declines in this study, further supporting established research that elevational gradient impacts species composition (Haider et al., 2018). The change in elevation creates unique ecosystems sometimes at short distances depending on the slope angle. As changes in elevation are closely correlated with climate factors such as temperature and precipitation, it is likely these are the key factors driving my biodiversity results as has been observed in other studies (Eisenlohr et al., 2013; Pauchard et al., 2009; Seipel et al., 2011, 2016; Mallen-Cooper & Pickering, 2008). Variation in species richness and abundance could be due to the local small-scale topography differences (Joseph et al., 2012). The beta diversity, while similar for all four trails, did indicate that there are statistical differences in the species composition. This difference is also related to elevation change.

In this study, the proximity to the trail also demonstrates a significant impact on species richness and biodiversity. Other research concludes species richness is higher adjacent to the trails and roads compared to sampled plots farther away (McDougall et al., 2018; Marcantonio et al., 2013; Seipel et al., 2011). The construction of trails may alter the abiotic characteristics of the environment adjacent to the trails generally providing bare ground initially and perhaps changing soil moisture, soil compaction, and increased erosion of which may have altered the soil chemistry (Lembrechts et al., 2017; Marcantonio et al., 2013; Wimpey & Marion, 2011). Like roads, trails open the vegetation canopy in a forest changing the amount of solar energy able to reach the ground which can provide the necessary light for non-native species or even local species that require more sunlight to germinate. Le et al., (2018) positively correlated the openness of the canopy along trails with the presence of the *Clidemia hirta* along trails in Malaysia. The openings and disturbed habitat along a trail may allow species both native and non-native to expand their realized niche in the positions parallel to the trail (McDougall et al., 2018, Lembrechts et al., 2017).

Further Investigations

"Sky islands" in the southwestern US offer further exploration of the interaction between biodiversity and non-native species presence along elevation gradients. Generally, there is evidence that species invade upwards from lower elevations or valleys

into higher elevations making the “sky islands” an ideal site to study a previously uncolonized location (Lembrechts et al., 2017). The sky islands are isolated like actual ocean islands and the desert floor acts as a barrier to both the genetic mixing and spread of new species (Ober et al, 2011). Isolation is known to create endemic species and could also make those endemic species more susceptible to impact by an invading species. Previous research demonstrates that well established non-native species populations are found to be spreading to higher elevations adjacent to the population, so removing that foundational population would provide valuable information about invasion potential (Seipel et al, 2016).

Another concern is that non-native species often have adaptive ability and can, once introduced, show plasticity in their genes and adapt towards cooler climates at higher elevations (Moran et al., 2017). Moran et al. (2017) determined that some non-native species can rapidly select new traits, due to their short life cycles, which allows expansion. The cool climate and reduced species richness that comes with increased elevations could open niches for these non-native species to expand (Pouteau et al., 2018). The use of elevational gradients to determine the impact of changing temperatures could yield a more reliable measure of whether non-natives will out compete local species in new temperature regimes.

Additional studies should be conducted at lower elevations investigating trails through desert mountains globally where the vegetation is primarily desert-scrub. The topography and microclimate of desert mountains absent of large trees may allow a haven

for drought tolerant non-native species. Does species richness also decrease along an elevational gradient in these unique desert montane ecosystems? Mina et al. (2016) suggests that climate change will affect each mountain ecosystem differently due to the specific microenvironments each has suggesting that this is an area of need in research.

Climate Change

While the results suggest that species richness and biodiversity decrease as elevation increases, the changing climate may alter this pattern or at least shift altitudinal position upward (Lenoir et al., 2008). Shifting altitudinal position may cause more overlap in species ranges and assuming no niches are in competition, the species richness may increase with native species as well as non-native species along the elevational gradient. Species that do not have the genetic plasticity to move up in altitude (or down) will face a potential local extinction (Lenoir et al., 2008). Forest species at the outer edge of their habitable range have been shifting upwards during the 20th century (Lenoir et al., 2008). European tree species are shifting their optimum elevation upwards with more shifting upwards in the last half of the 1900s than the first half of the 1900s (Lenoir et al., 2008). This shift upward, to match the increasing temperatures, may open new niches where native species have left for non-native species to occupy (Ruiz-Labourdette et al., 2011). Mediterranean mountains are also home to unique species that have been able to shelter in the cooler higher elevation locations as the regions historically have shifted to

different, more arid and warm climates (Ruiz-Labourdette et al., 2011). These species can become increasingly isolated as the climate shifts and temperatures increase even more. Species already at the upper elevations may not have any additional geographic locations to take refuge and may die off allowing non-native species to replace them or native lower elevation species to replace them (Ruiz-Labourdette et al., 2011).

Non-native Species

Only one of the four targeted non-native species was located in my study plots. While *Achillea millefolium* is present, the species is not abundant or taking advantage of the trailside disturbances. *Achillea millefolium* is listed as both a native and naturalized species in the State of Arizona (Arizona Cooperative Extension Yavapai County, 2017). A concern is that global climate change may alter this abundance. Currently, non-native species have demonstrated a decrease in richness with an increase in elevation (Haider et al., 2018) and a decrease in richness away from roads due to filtering effects favoring perennials (McDougall et al., 2018). As the planet warms, the mountain ecosystems will become warmer potentially allowing relatively less abundant non-native species to take advantage of the new more compatible climatic conditions, thus causing an invasion (Ivanova & Soukhovolsky, 2016; Pauchard et al., 2009; Seipel et al., 2016). Mina et al. (2016) report that there is already evidence that mountain forests have altered their growth and mortality patterns and climate shifts have been documented (Haider et al.,

2018). Some non-native species have biological characteristics that allow them to reproduce quicker than native species and the non-native plants may have a larger range of tolerance for environmental conditions offering a reproductive advantage. Genetic plasticity of non-natives may allow them to adapt quicker or warming may accelerate the phenology of the plant (Scheepens & Stöcklin, 2013). Regional climate change may also impact the biodiversity across elevational gradients. Additionally, the presence or persistence of non-native species in the seed bank may present opportunities for future expansion as climatic conditions shift or local weather produces more favorable conditions for the seeds to emerge (Wells et al., 2012).

For now, the absence of the four targeted non-native species, may indicate that species are not invading high desert ponderosa pine mountain systems. There are many factors that impact the establishment and spread of a non-native species. Species must be introduced in sufficient amounts or enough times that they are able to establish a reproductive colony. Local climate is also a barrier to establishment. The possibility exists that Arizona's arid landscape makes it more difficult for these four non-native species to establish at lower elevations which would also impact their dispersal to higher elevations. The dry climate while cooler due to elevation may be a barrier especially when the snows that would normally sustain soil moisture and groundwater are inconsistent.

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APPENDICES

APPENDIX A

DATA ANALYSIS EQUATIONS

Indices	**Equations**	**Variables**
Simpson's Diversity Index	$1 - \Sigma_i p_i^2$	p=relative abundance
Shannon's Diversity Index	$-\Sigma_i p_i \log p_i$	p=relative abundance
Jaccard Index	$\frac{(\frac{\bar{S}}{S} - \frac{1}{N})}{(1 - 1/N)}$	$\bar{S}$=average number of species N=sets of species abundance
Morista-Horn Index	$C_{2N} = 1 - \frac{2\sum_{i=1}^{S}\sum_{j<k} p_{ij}p_{ik}}{(N-1)\sum_{i=1}^{S}\sum_{j=1}^{N} p_{ij}^2}$	N=number of assemblages S=total species $p_{ir=}$relative abundance for each species in each assemblage

APPENDIX B

JACCARD INDEX)

APPENDIX B: Jaccard index examining similarity between elevation zone Adonis analysis (Table 3) indicated elevation had a statistically significant difference in beta diversity (p=0.001).

	1	2	3	4	5
1	**0.8250621**	0.8730539	0.8598004	0.8277817	0.8708041
2	0.8730539	**0.8591758**	0.8582610	0.8634047	0.8675022
3	0.8598004	0.8582610	**0.8410755**	0.8220161	0.8718048
4	0.8277817	0.8634047	0.8220161	**0.8008865**	0.8509420
5	0.8708041	0.8675022	0.8718048	0.8509420	**0.8546531**

APPENDIX C

JACCARD INDEX BY TRAIL

APPENDIX C: Jaccard index examining similarity between trails. Adonis analysis (Table 3) found similarity was found to be significantly different (p=0.001).

	Abineau	A Mountain	Aspen	Bear Jaw
Abineau	**0.7109799**	0.9834448	0.9065461	0.9439490
A Mountain	0.9834448	**0.5314086**	0.8375941	0.8849716
Aspen	0.9065461	0.8375941	**0.6191827**	0.8889156
Bear Jaw	0.9439490	0.8849716	0.8889156	**0.8444283**

APPENDIX D

MORISTA-HORN INDEX

APPENDIX D: Morista-Horn index examining dissimilarity by elevation zone. Beta diversity is between 69-79% dissimilar between sampled elevations. Morista-Horn index values support a change in biodiversity across elevation.

Elevation	**1**	**2**	**3**	**4**	**5**
1	**0.7066499**	0.7855921	0.7584324	0.7107677	0.7779909
2	0.7855921	**0.7843355**	0.7649209	0.7763851	0.7838737
3	0.7584324	0.7649209	**0.7477907**	0.7235096	0.7914569
4	0.7107677	0.7763851	0.7235096	**0.6906323**	0.7705349
5	0.7779909	0.7838737	0.7914569	0.7705349	**0.7843665**