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Matching the Spatial Distribution of Upland and Lowland Pollen Grains with the Temperature and Humidity in the Columbia Basin

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Airborne pollen is a highly influential factor in biosphere and also in anthroposphere; pollen is a source of food for numerous species of animals and is responsible for the transfer of genetic material in the biosphere. Fossil pollen grains are indicators of past climatic changes and play an important role in forensic analysis. Pollen is also an allergen causing rhinitis. In order to properly identify pollen and plant relationships, detailed studies of pollen distribution and accumulation in the environment are needed. In this paper, special attention was paid to the geographic distribution of pollen with respect to biologic and geomorphic conditions. Geomorphology (size and shapes) of land features is closely connected to changes in temperature, moisture, air pressure, wind speed, wind direction and precipitation, which in turn affect the distribution and dynamic of biomass change. The spatial patterns of two bioclimatic variables: temperature and evapotranspiration were studied with respect to the distribution of arid and forest pollen. Results indicate a significant relationship between elevation, pollen depositions patterns, and changes in bioclimatic parameters. This relationship exhibits a concentric pattern which reflects a basin geomorphology. The importance of understanding the correlation between pollen dispersion patterns and actual vegetation communities is one of the essential means used to understand paleo-vegetative records, and it can become an important guide in geolocation questions related to using pollen as a forensic tool.

Keywords: *Ecosystem, Geomorphology, Geostatistics, Pollen Grains, Spatial Analysis.*

Introduction

The purpose of this research is to determine the differences between spatial distribution patterns for two pollen groups and the way they represent basin geomorphology. In addition, the study looks at the pollen transport on the slopes

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of the surrounding mountains. Pollen grains are transported in the atmosphere away from their source by laminar or turbulent flows of air. This transport is heavily influenced by the local geomorphology and consequently depends on bioclimatic conditions. A basin is a unique geomorphic feature that consists of two distinct parts: (a) - the outer and elevated natural wall that rises up to the drainage divide enclosing an inner space and (b) - the basin floor. This geomorphic structure has developed its own climatic and biologic identity resembling a closed natural system consisting of a unique microclimate. The basic hypothesis is that pollen grains produced at the bottom of the basin stay there and move only within the basin perimeter, but pollen grains from the elevated slopes also accumulate in larger amounts on the basin floor. This study focuses on the ecosystems in the Columbia Basin, which resembles a natural, elongated bowl that extends in a roughly east-west direction in the northwestern part of the United States. The lower part of the basin is covered by thick basalt deposits that provide valuable minerals to a variety of plants in this ecosystem. The geomorphology of the studied area dictates the tight relationship between the basin microclimate and the biosphere. Due to the high wall of Cascade Mountains in the west, the incoming moisture from Pacific Ocean is blocked and the central part of the basin remains dry; the precipitation gradually increases with elevation, especially in the eastern part of the basin. The variability of the soils' physical and chemical characteristics depends on the lithology. Basalt underlies the entire bottom of the Columbia Basin, and its breakdown and disintegration causes the release of minerals into the pedosphere. The weathering of this material mixed with sand, silt and loess deposited during and immediately after the Wisconsin Glacial Period of the Late Quaternary results in a soil parent material that is rich in minerals and continues to influence ecosystems today.

The first pollen study happened more than a century ago when Lennart von Post recovered pollen from buried deposits and compared them with samples of modern pollen grains found in different types of plant communities (Fries 1967). What he discovered would lay the groundwork for the field of pollen analysis and for the application of using pollen spectra from modern pollen environments (called pollen prints) as analogs for interpreting past vegetation cycles (Manten 1967). During the decade since it was first developed, palynologists depended on modern pollen data to form qualitative and intuitive interpretations of fossil pollen analyses of buried sediments. One thing became clear from the beginning of the study by von Post (1916), there is not a 1:1 relationship between what one finds in the pollen record of a plant community and the actual ratios of the major plants growing in that same community. Experiments and research through decades of study revealed that some plant genera and species such as the grasses, conifers, oaks, elm, ash, ragweed, and many others produce and disperse millions of pollen grains into the atmosphere because they use a type of pollination, wind-pollination, which is haphazard and few pollen grains actually reach their intended destination and complete fertilization. This means that millions and even billions of spent pollen grains fall to the surface in a coating called "the pollen rain." Studies also noted that other types of plants, such as roses, sunflowers, carnations, tulips, and others rely on insects such as bees, wasps, and butterflies, or other means (i.e., bats, humming birds, sugar glider, beetles, etc.) to carry pollen from one plant to another of the same species. This second method is highly efficient and the plants need to produce smaller amounts of pollen that normally do not become airborne until the flowers die. These factors are what makes it impossible to construct a true 1:1 relationship of the pollen rain to the actual plants that produced the pollen; nevertheless, with modern statistical methods, palynologists believe they can resolve this problem.

Palynologists soon discovered there were other factors that influenced the distribution of pollen in the landscape. Wind currents, humidity, temperature, ground surface obstacles including rocks, mountains, forests, and manmade building structures could divert and/or trap certain types and amounts of dispersed pollen and thus remove it from the normal pollen rain (Tauber 1967). Most important was the adiabatic lapse rate during and immediately after the dispersion of pollen from anthers. The lapse rate varies strongly with temperature, and moisture, which creates the temperature profile of the atmosphere (Steiner et al. 2015). Thus, high convection currents can be created by surface radiation and a high adiabatic lapse during dry conditions, while inversions can trap cold air below streams of hot air suppressing pollen dispersion, especially in valleys and basins. Forest fires, timber cutting, earthquakes, tsunamis, and floods also effect the distribution of pollen that has been dispersed. Hurricanes, tornadoes, and strong winds can recycle pollen previously deposited on the surface and carry it to new locations, making interpretations about the original plant communities difficult and sometimes confusing (Liu and Fearn 2000).

In the Columbia Basin, over 100 samples are recorded in the North American Pollen Database (Whitmore et al. 2005) as well as more than 60 bioclimatic variables covering 130 major pollen taxa in North America. The Columbia Basin and adjacent slopes contain records for 44 of the 130 plant pollen types scattered throughout the bottom and adjacent slopes around the basin. In this project, the pollen count data were grouped into two categories: basin floor (lowland pollen) and upland pollen. The lowland group is represented by *Artemisia*, *Aster*X, Chenoams (Amaranthaceae) and Poaceae. These are the main pollen producers. They are located mostly at the bottom of the Columbia Basin where drier conditions support the growth of these species. In contrast, the upland group consists of *Abies*, *Alnus*X, *Betula*, *Larix*, *Picea*, *Pinus* and *Tsuga* – tree taxa. The upland environment is dominated by lower temperatures, higher evapotranspiration regimes and higher precipitation levels. In addition, geomorphology is mostly composed of slope gradients and a variety of slope aspects that change continuously around the basin, leading to the reception of different types of solar radiation. Therefore, this research underlines the connectivity between geomorphic and bioclimatic characteristics; even subtle changes in terrain morphology can change the heat and moisture distribution as well as have an impact on the local and macro-scale.

Literature Review

Much attention has been paid in literature to the pollen records of the basin floor in the Columbia Basin (Mack and Bryant 1974, Barnosky 1984, Mack et al. 1996). These studies indicate that the mostly treeless floor has been dominated by *Artemisia* pollen for the last 100 thousand years. In addition, the phytolith and pollen record in this area near the center of the basin confirm the existence of an alternating xeric *Festuca-Poa* and mesic *Festuca-Koeleria* grassland vegetation (Blinnikov et al. 2002). Pollen deposition in arid areas has been studied in other regions of the world. For example, five major pollen types (Cheno-Ams (Amaranthaceae), Poaceae, *Juniperus, Pinus, and Quercus*) in the Big Bend desert ecosystem were analyzed spatially in relationship with the source vegetation from the desert floor and the nearby Chisos Mountains (Siska et al. 2001). Similarly, in the Quidam Basin of the Tibetan Plateau, *Artemisia* pollen and Cheno-Ams were studied using the relative representation index and principal component analysis (Zhao and Herzschuh 2009). The correlation between pollen dispersion and two climatic variables (temperature and moisture) is one of the most common themes in pollen literature. Minckley and Whitlock (2000) studied the distribution of pollen grains along the gradients of temperature and effective moisture in the western USA. They determined that east of the Cascade Mountain Range in the basin floor, shrub steppe and woodlands dominate and the effective moisture is low. In that rain shadow area, *Artemisia*, Cupressaceae and *Pinus* pollen are dominant. In contrast, in the higher areas of higher effective moisture, *Pinus*, *Abies* and *Picea* pollen are common. The humidity and temperature have a strong influence on microsporangium dehiscence and pollen dispersal; for example, this is documented in studies of *Cedrus deodora* in the Himalayas (Khanduri and Sharma 2002). Temperature and humidity also have an impact on the daily pollen concentrations of olive tree (*Olea europaea*) pollen in the Mediterranean region (Recio et al. 1997).

Perhaps, Siska and Polacik (2014) have conducted the most comprehensive work that relates to many pollen types in diverse bioclimatic conditions in the Columbia Basin. Using a factorial analysis of 44 pollen types and 69 bioclimatic variables, they delineated homogeneous environmental regions in the basin. In a basin environment which is usually surrounded by a backdrop of mountains, a turbulent flow of air causes pollen deposition to move uphill or downhill. According to Frei (1997), local pollen grains can be easily transported over 2,000 m high mountain slopes in the complex topography of the Swiss Alps. For example, the *Castanea* pollen that was dispersed by plants at low elevations on the southern slopes of the Alps was trapped at the location of Guetsch, Switzerland (2,300 m). Therefore, people suffering from allergic rhinitis may also be exposed to large quantities of pollen even at high elevations in the Alps. When pollen grains are ruptured due to a high humidity environment, numerous microscopic sub-pollen particles (SPPs) are created. These microscopic SPPs can form a cloud and remain at high altitudes in the atmosphere while travelling long distances (Steiner et al. 2015). Moreover, pollen dispersal in a basin environment has its own characteristics. Prentice (1985) modified Sutton's equation and predicted that the basin's pollen source area is a function of basin size and deposition velocity of pollen types. Both Sutton's and Prentice's models assume continuity in pollen dispersal. Jackson and Lyford (1999) based their dispersion model on Gaussian puffs, due to the nature of how pollen leaves anthers in a series of "puffs" rather than as one continuous type of emission. Pollen is also one of the most favorite subjects to visualize as indicated in the work of Siska et al. (2012) and Desjardins et al. (2017).

Methodology

One of the most important analytical tools for characterizing the spatial distribution of pollen is geostatistics. Since pollen grains are microscopic particles invisible to the human eye, interpolation methods are needed to reveal the patterns of spatial distribution of different types of pollen grains in order to know what and where these quantities are accumulating on the ground. Geostatistics provides a set of statistical tools that take into account the spatial relationship between pollen counts and predicts the values at unsampled locations under the constraints of unbiasedness and minimum error variance (Goovaerts, 1998). A spatial structure is expected according to the first law of geography stating that pollen counts that are close to each other in space are more alike than those further apart. The presence of such a spatial structure is a prerequisite to the application of geostatistics, and its description is a preliminary step towards spatial prediction. In geostatistical literature, spatial patterns are usually described in terms of dissimilarity among the observations as a function of the separation distance, using a curve called the semivariogram. In this project, we describe the spatial structure by fitting cubic variogram models to both upland and basin floor pollen grain counts. The cubic variograms are in the form:

$$\gamma(\mathrm{h}) = \begin{cases} c_0\left[7\left(\frac{h}{a_0}\right)^2 - \frac{35}{4}\left(\frac{h}{a_0}\right)^3 + \frac{7}{2}\left(\frac{h}{a_0}\right)^5 - \frac{3}{4}\left(\frac{h}{a_0}\right)^7\right] & \text{for } h \leq a_0 \\ c_0 & \text{for } h > a_0 \end{cases}$$

The existence of this spatial correlation allows for the interpolation of pollen data at locations where no samples were collected. Kriging is a generic name adopted by geostatisticians for a family of generalized least-squares regression algorithms. Like straightforward interpolation methods, such as inverse distance methods, kriging estimates the unknown value as a weighted average of data collected at neighboring locations. It is apparent that there is a significant variation in the local means of pollen counts across the study area, but ordinary kriging (OK) allows one to account for local variation in the mean by limiting the domain of stationarity to the local neighborhood centered on the location being estimated (Goovaerts, 1998). The ordinary kriging equation is then:

$$Z_{OK}(u) = \sum_{\alpha=1}^{n} \lambda_\alpha \; Z(u_\alpha) + \left(1 - \sum_{\alpha=1}^{n} \lambda_\alpha\right) m(u)$$

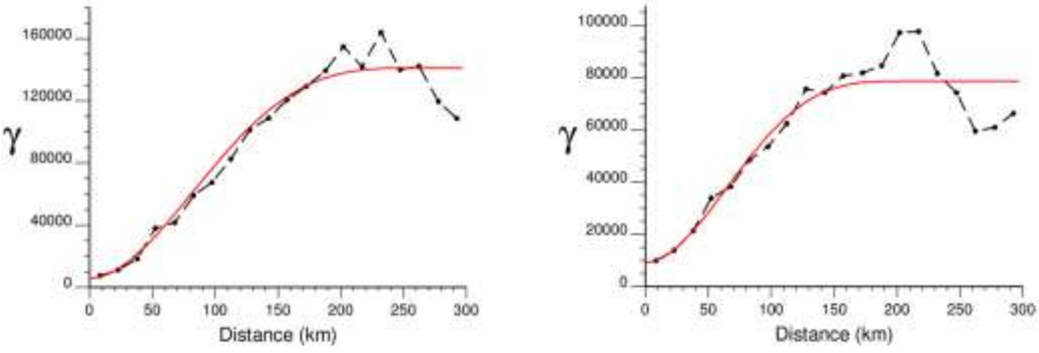
where lambda represents kriging weights, Z_{OK} are the kriging estimates and $Z(u_\alpha)$ are the sample values at locations u_α. By forcing the kriging weights to sum to one, the system is then radically simplified and the knowledge of the mean value $m(u)$ is no longer necessary.

Besides using geostatistical methods, the zonal statistic function was used to calculate the amount of pollen grains in each land use zone. In addition to computing the sum of pollen grains in each land use category, the mean, variance, minimum, maximum amounts of pollen, then range and density per square kilometer of pollen grains were also calculated. The main contribution of this analysis is to understand pollen and its source relationships. This analysis also answers the question about what quantities of pollen accumulate in the areas that are dominantly inhabited by the source vegetation. It is assumed that the largest amount of pollen will be dispersed close to the plant of dispersal. While this intuitive knowledge regarding the largest amount of pollen deposition near its own source region is often confirmed, the proportion of the pollen that accumulates elsewhere is often unknown. Therefore parallel mapping of pollen and vegetation was conducted and the amount of pollen grains was calculated in every source plant pixel. In an effort to establish more specific pollen-source relationships, two representatives from both groups were selected for zonal analysis: Cheno-Ams for the lowland (basin floor) pollen and PineX from upland group; these were chosen for their prolific pollen production.

Results

The variograms show a strong spatial structure that reflects the natural processes operating in the Columbia Basin region as well as a parabolic behavior at the origin, indicating continuous changes in space. Both variograms reach a sill at a similar range a_0, i.e., the distance beyond which pollen counts become spatially uncorrelated (Figure 1).

Figure 1. *Cubic Variograms of the Basin Floor* (left) *Upland Pollen Groups* (right)



Maps of kriging estimates (Figure 2) highlight a significant difference in spatial patterns between basin floor pollen assemblages and upland pollen deposition. For the lowland group, dominating concentric patterns of pollen accumulation reveal the influence of the basin geomorphology. This is the result of the prevailing vegetation cover, basin morphology and wind influence. The lower portion of the prevailing wind system is from the southwest area, which is forced to turn along the slopes of the adjacent Cascade Mountains in a rotating fashion inside the basin interior. As the speed decreases at the end of the rotation, the pollen rain drops in the central and north-central part of the basin. Pollen accumulation is at its highest near the confluence of two major rivers (the Snake and Columbia Rivers at Kennewick). On the other hand, the spatial distribution of upland pollen indicates a very different pattern. In most areas of the Columbia Basin, the spatial distributions of upland and lowland pollen are exactly opposite. The central and north central parts of the basin contain the smallest counts of upland pollen with some overlap in the southeastern part. This area with low amounts of upland pollen coincides with the area where the amount of lowland pollen is the highest. On the other hand, the eastern and southeastern part of the Columbia Basin is heavily overloaded with upland pollen grains, while the lowland pollen counts in those areas are very low. Finally, the upland and lowland pollen amounts vary similarly in the third sub region with both groups exhibiting low pollen deposition and accumulation. This southwestern area begins roughly north of Highway 84 and continues in a southern direction, and indicating a significant decrease of both upland and basin types of pollen; therefore, there is a stronger positive geographic relationship between upland and lowland pollen counts. The explanation for the existence of these three sub-regions can be partially found in the matching pollen distribution patterns with their parent plant sources. Figure 3, shows the distribution of vegetation cover in the Columbia Basin.

Figure 2. *Spatial Distribution of Basin Floor* (left) *Upland Pollen Groups (right)*

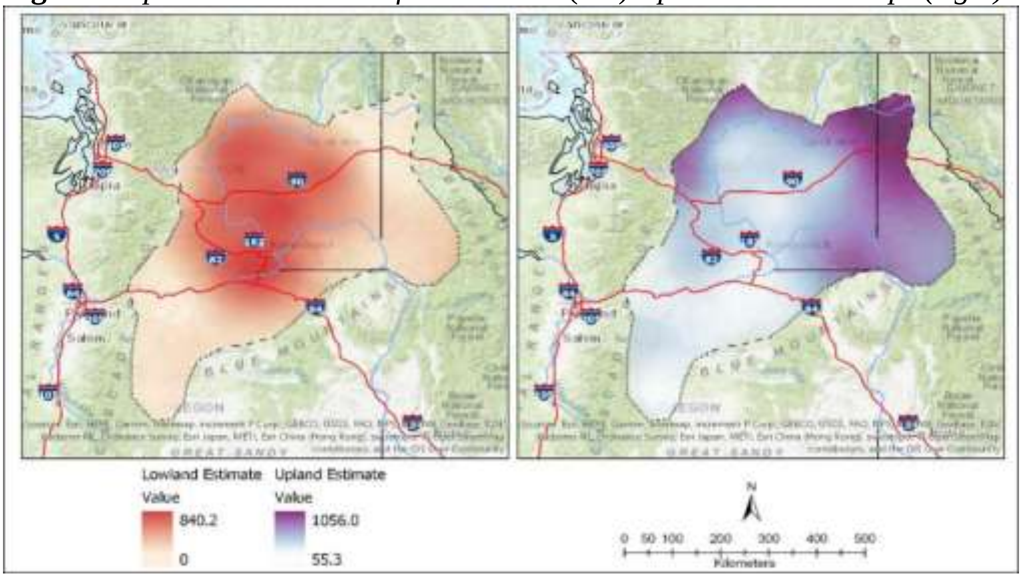
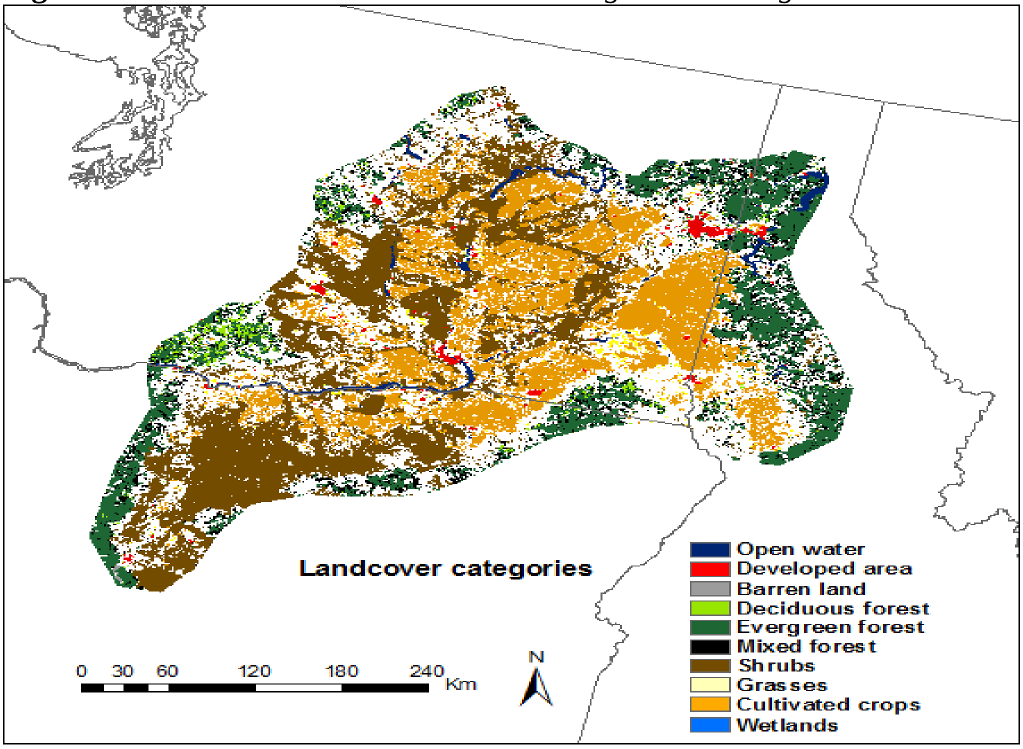


Figure 3. *National Landuse and Landcover Vegetation Categories*

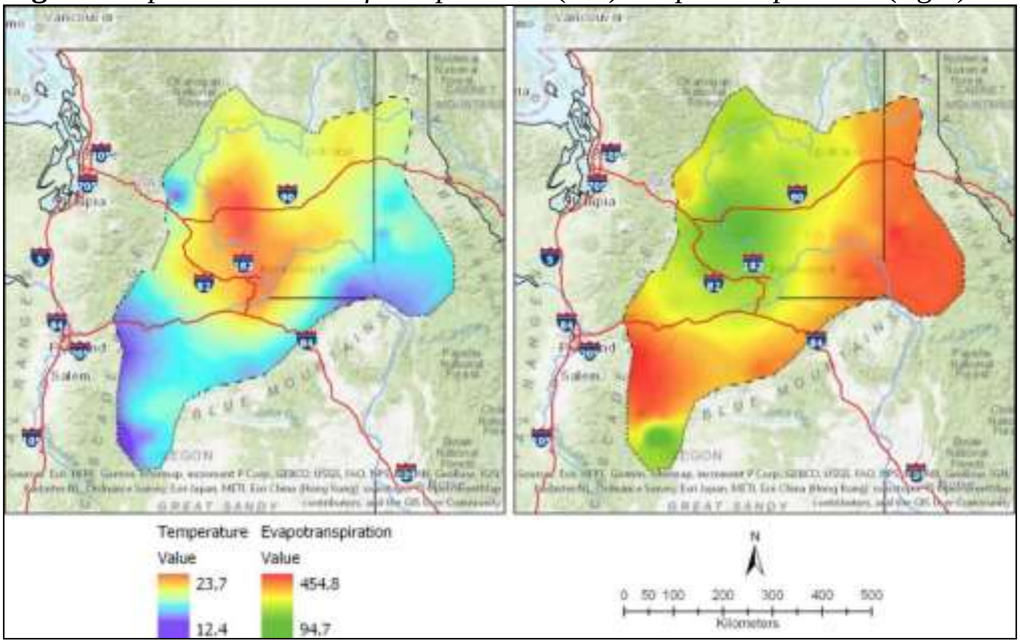


The land use zones (vegetation types) are represented by fifteen categories and zonal statistic function computes the quantities of selected pollen types in each land use category. These categories are: the open water category (code 11) that includes all areas of open water with less than 25 percent vegetation or the soil cover, the open space developed areas (code 21) that include a mixture of construction work and lawn grasses and less than 20% of impervious surfaces caused partly by single family housing, golf courses, parks and recreation places. The category with low intensity developed areas (code 22) consists from impervious surfaces (20-49%) and single-family housing units. The medium intensity developed areas (code 23) have typically between 50-79% impervious surfaces and consists of mostly single family housing units. The last high intensity developed category (code 24) includes urban development with a high density of population, apartment complexes, condensed single housing units, commercial, and industrial areas which contribute to impervious surfaces that occupy between 80 to 100% of the total area. The category of barren land areas (code 31) includes bedrock, desert pavement, a variety of other rock material, strip mines, and sand dunes where the vegetation represents less than 15 percent of the total area. The next category is the deciduous forest (code 41) which occupied a less significant amount of space than the evergreen forest (code 42). It includes trees taller than five meters. The total extent of forests is more than 20 percent of the vegetation cover, and more than 75% of the tree species in this category maintain their leaves year around. Category 43 is dominated by mixed forest where trees are smaller than five meters and occupy more than 20% of the total vegetation cover.

The areas that are overgrown by shrubs (marked code 52) play one of the most significant roles in the Columbia Basin. Shrubs are less than five meter tall and occupy more than 20% of the total vegetation cover. The naturally grown grasses (code 71), on the other hand, occupy a smaller portion of the basin floor. They are dominated by grammanoid or herbaceous vegetation with more than 80% of the total population. Agriculture plays an important role in the vegetation system of the basin floor because it is based on irrigation. For mapping purposes the agricultural land use is divided into category 81 that includes pasture and hay areas with a grass-legume mixture planted for livestock, and category 82, that includes cultivated crops used for the production of corn, soybeans, vegetables, tobacco, cotton, orchards and vineyards. The crop vegetation accounts for more than 20% of total vegetation. Woody wetlands and palustrine shrub wetland (codes 90 and 91) occupy only small areas in the Columbia Basin.

The highest amount of upland pollen matches with the coniferous forest that extends along the western slope of the Bitterroot Mountains and the northern slopes of the Blue Mountains. This extension also proceeds to the southern slopes of the Thompson-Okanagan Rocky Mountains system. However, more than half of the Columbia Basin rim does not exhibit elevated amounts of upland pollen despite the fact that the land cover map indicates the existence of a coniferous forest in the northwestern part of the area. A corner of the Columbia Basin north of Highway 84 indicates low amounts of upland or lowland pollen in spite of the fact that there is a significant patch of deciduous forest. In fact, the complete southwestern region is characterized by a low amount of accumulated pollen (Figure 2). The main cause for this pattern is the southwestern winds that carry pollen grains towards the central part of the basin. In addition, the eastern slopes of the Cascades are overgrown with low pollen producers, as opposed to most conifers, such as hemlock and juniper. Therefore, the hypothesis that the rim of the basin will contain elevated amounts of coniferous pollen in all areas was not confirmed. As indicated in the literature review, two climatic parameters, temperature and humidity both have a significant impact on pollen dispersion. Therefore, two other environmental parameters were included into this analysis: temperature and evapotranspiration (Figure 4). On the other hand, the eastern part with its lower temperatures and high amount of upland pollen grains exhibits the highest loss of water through evapotranspiration. Perhaps the most complex area is the southwestern region that indicates low upland and lowland pollen accumulation and dispersal; this area also exhibits low temperatures. The loss of water through evapotranspiration by plants is one of the highest here (Figure 4). This area is covered by shrub vegetation and also has a streak of coniferous forest. The high level of evapotranspiration is attributed to the shrubs and shrub-steppe ecosystem. In this area, the shrub-steppe exhibits the most continuous spatial extent.

Figure 4. *Spatial Patterns of Temperature* (left) *Evapotranspiration* (right)

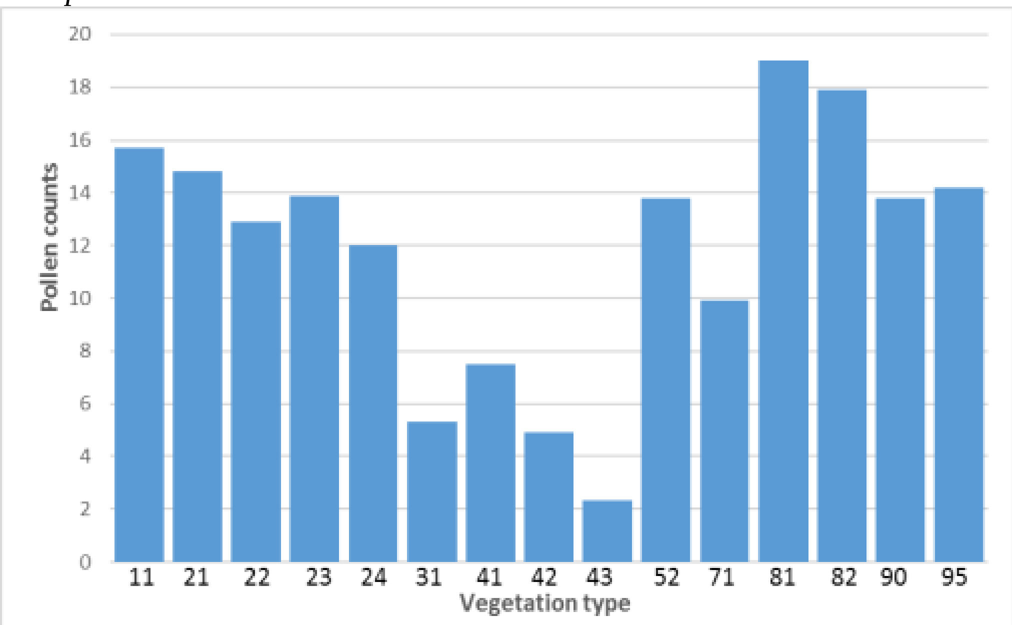


Discussion

One of the main goals of pollen spatial analysis is to identify the relationships between pollen sources and pollen grain dispersal as well as accumulation. In order to answer the question "where do pollen grains accumulate in relationship to their sources," parallel mapping was used and zonal statistics were calculated. In order to fulfill this task, land cover data – vegetation types (Homer et al. 2004) were used and pollen grains were counted within the boundaries of specific vegetation classes (Figure 3). The research indicates that in the interior of the Columbia Basin, most of the pollen grains coming from the lowland group, accumulate in the "shrub-scrub" vegetation category (corresponding to number 52 class on the land cover map); almost 25,000 pollen grains were measured in the samples with an average of 453 pollen grains per sample. There is also a significant deposition of grass and sedge pollen grains in the cultivated crops area (class 82). The total number of pollen grains was lower than the basin floor pollen, yet over 600 pollen grains on average were found in each sample. The deposition of the basin floor pollen in the evergreen forest was significantly lower than 3000 pollen grains in samples with an average of 113 pollen grains per sample; however, it also includes the contribution of semiarid pollen in the uplands. Significantly larger amounts of semiarid (basin floor) pollen accumulated in the developed open space land cover (class category 21) that could cause allergy problems to those sensitive to airborne pollen grains. The accumulation per sample (over 800 pollen grains per sample) indicated that it is the highest amount of pollen in the vegetation category groups. Other categories such as woody wetlands, grassland herbaceous, and barren land were represented by only very limited amounts of pollen. It was also surprising to find an insignificant accumulation of basin floor pollen in the deciduous forests. The spatial analysis of upland pollen deposition revealed that sixty percent of upland pollen is almost equally deposited in three main vegetation zones. Twenty percent of the upland pollen grains were deposited in the evergreen forest areas (class 42) but 23.5% was deposited in the shrub and scrub category area (class 52) while 17.1% was deposited in the area of cultivated crops. As we noted, a large amount of upland pollen was actually deposited in the basin floor areas of the Columbia Basin. Over 10% of all pollen from the open spaces was also deposited with medium intensity in developed urban areas.

In order to establish pollen and source vegetation relationships in more detail, two representatives from both groups were selected and zonal statistics were used to quantify the accumulation of these two pollen types in all of the fifteen vegetation categories that play a significant role in the Columbia Basin. The first type is pollen from the family Amaranthaceae, which includes the former family Chenopodiaceae (previously called Cheno-Ams). These herbs and shrubs are one of the most common plant species found in the arid and semiarid areas. They also occupy the central part of the Columbia Basin floor. Figure 5 shows pollen grain densities in each of the land use-vegetation categories. As noted, the highest densities of the Cheno-Am type pollen accumulated in pastures and cultivated crops areas. Hence, agriculture was developed in places where the original plant species in the Amaranthaceae dominated. Agriculture can only exist in this area through irrigation. The developed regions also indicated high pollen densities of Cheno-Ams, another proof that urbanization encroaches into lowland pollen producers and the potential problem for rhinitis increases. The lowest amount of Amaranthaceae pollen is as expected in areas occupied by tree vegetation.

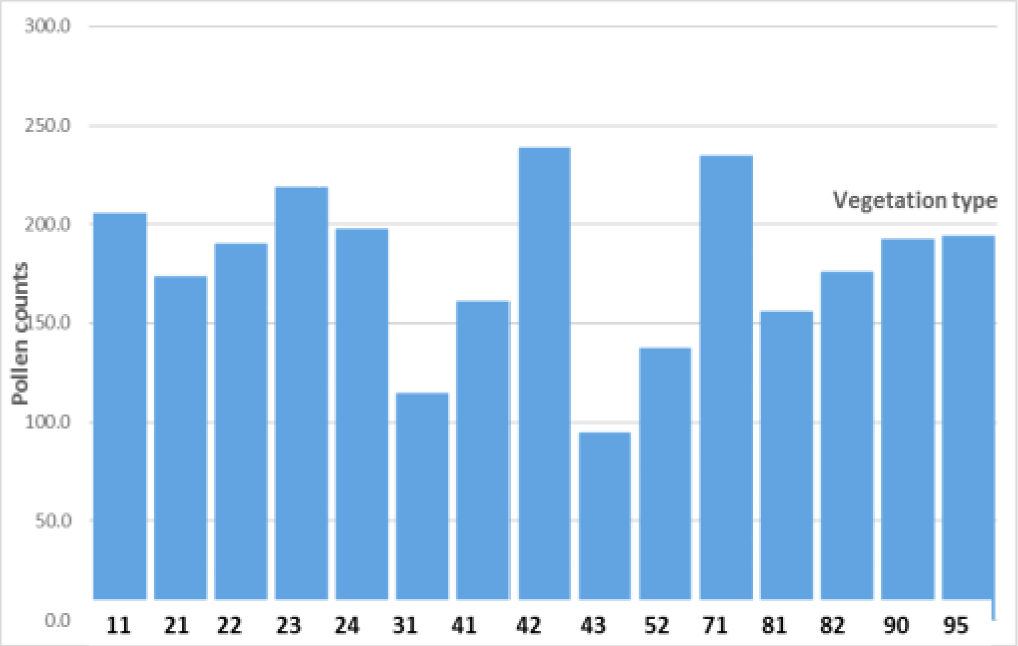
Figure 5. *The Density of Amaranthaceae Pollen (Cheno-Ams) in Vegetation Groups*



In terms of total pollen accumulation as indicated in Figure 7, there are only four main areas where Amaranthaceae pollen is deposited: (1) source plants (shrub/scrub category), (2) agricultural areas (category 82), (3) evergreen forests (category marked by letter 42), and (4) grassland-herbaceous areas (category 71). While Cheno-Ams pollen accumulation in the shrub/scrub, agricultural land, and grasslands is expected, the high pollen accumulation in the evergreen forest region is surprising. It shows the prevailing wind pattern. The laminar airflow from the southwestern area carries pollen in a west-east direction to the evergreen forests that dominate the eastern part of the Columbia Basin. It is the turbulent flow of air that takes this lowland pollen to a higher elevation and contributes to the creation of a transitional zone where a mixture of upland and lowland pollen grains occur. Therefore, this analysis is useful for understanding local wind patterns, pollen grain transport, and potential environmental pollution.

Pines are one of the largest pollen producing plant species on planet. This is confirmed by the density deposition of pine pollen per square kilometer compared to Cheno-Am pollen and by the total quantities of pollen grains in each vegetation zone (Figure 6). The largest densities of pine pollen grains are located in deciduous and evergreen forest areas that are dominated by trees taller than five meters, and there is a relatively small deposition in areas occupied by the Amaranthaceae species. However, there are still large pollen densities of pine pollen in areas that are occupied by grasses and herbs (category 71). In the pasture and grass zone is the density of Cheno-Am pollen naturally high; however, the pine pollen is also relatively high in grass zone.

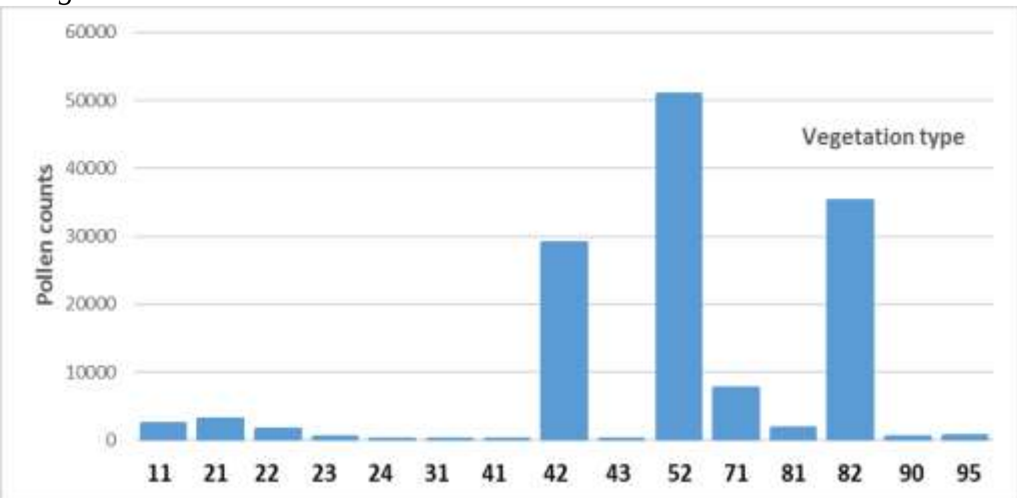
Figure 6. *The Density of Pine Pollen in Vegetation Groups*



The urban areas and open water category receive about the same proportion of total pollen amounts from both groups (upland and lowland). Deciduous forests and mixed forests exhibit the smallest accumulation of pollen from both Cheno-

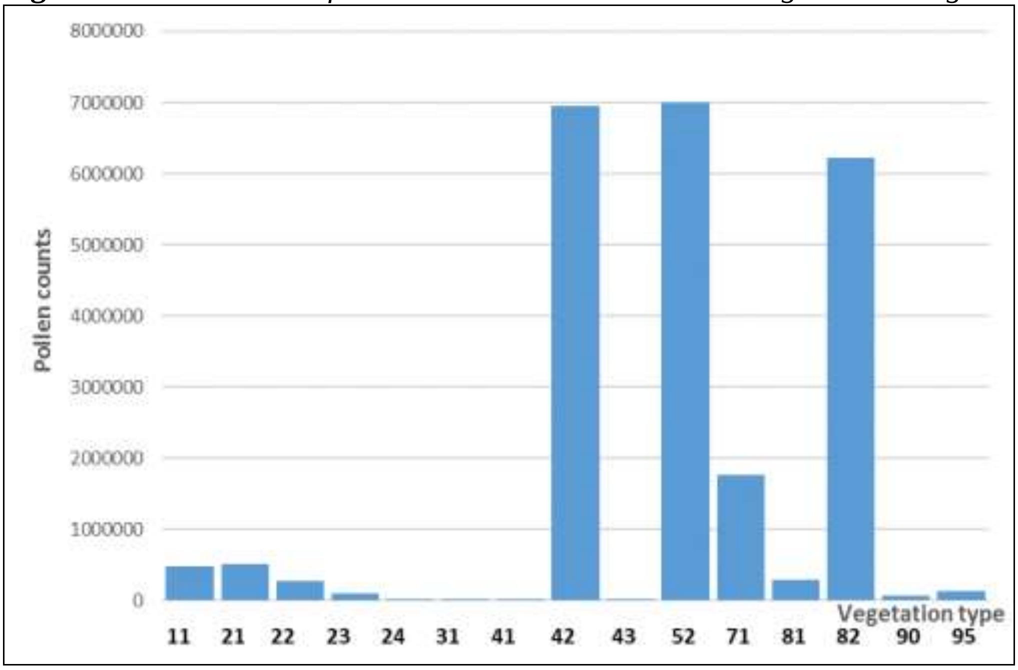
Ams and pine pollen. In the evergreen forest and shrub-scrub vegetation areas we observe an "ecologic pollen swap." This means that co-existence of pine and Cheno-Am pollen is a mirror image of respective source vegetation. In evergreen forest high density of pine pollen coexists with large amount of Cheno-Am pollen whereas in shrub-scrub areas high densities of Cheno-Am pollen coexist with large amount of pine pollen. This ecological "coexistence" between Cheno-Ams and pine pollen is a typical characteristic of the Columbia Basin and perhaps all dry basin ecosystems where geomorphology controls environment. Another interesting characteristic in Columbia Basin is the existence of transitional zone where significant mixing of the upland and lowland pollen grains is taking place. This "mixing" of pollen marks a special lowland-upland boundary where the basin floor is connected to the mountain backdrop. In the Columbia Basin, this boundary is between 400-700 meters in elevation. Finally, both types of pollen grains significantly contribute to agricultural areas where crop vegetation dominates landuse (Figures 7 and 8). This indicates that agriculture is occupying areas that were in the past supplied by pine and shrub-scrubs pollen grains. What used to be a zone of species competition has today been taken over by human activities. Therefore, there is a significant mixing here of naturally occurring pollen with agricultural plants pollen mainly corn, tobacco, cotton and orchards. The woody wetlands and emergent herbaceous wetland areas with perennial vegetation receives only a minimal amount of pollen from the Cheno-Ams and pine species, indicating a similarity in the upland-lowland pollen categories.

Figure 7. *The Total Sum of Amaranthaceae Pollen Grains in Individual Vegetation Categories*



Another important aspect of this study was understanding the pollen accumulation patterns in this specific geomorphic setting (a basin) and the significance of the local bioclimatic influence. The importance of elevation is only implicitly deduced at this point. The elevation increases from the center of the basin to its sides in each direction. The spatial patterns of lowland/upland pollen grains, temperature, and evapotranspiration share clear similarities. Higher elevations in the basin slopes, especially in the eastern part, also show high evapotranspiration values in the same region where coniferous forests with low temperatures are located. In those areas, there is an abundance of upland pollen. In contrast, at the center of the basin, lowland pollen is heavily accumulating in areas with the highest temperatures and lowest evapotranspiration. Agricultural land use and heavily based irrigation is causing the loss of moisture as well as affecting the natural regime of this dry, almost arid ecosystem. Temperature and humidity are also influencing the dehiscence of anthers and the release of pollen grains into the environment. With increasing elevation, the temperature decreases which slows down the microsporangium dehiscence and release of pollen into the atmosphere. This release is delayed by elevation on the slopes of rising mountains and contributes to the seasonal variability of pollen amounts in mountainous ecosystems.

Figure 8. *The Total Sum of Pine Pollen Grains in Individual Vegetation Categories*



Conclusions

The spatial distribution of pollen deposition and accumulation was studied in relationship to temperature, evapotranspiration and geomorphological setting. This study confirmed that pollen is a sensitive component of the natural environment and its dispersion/accumulation in the soil is a function of the natural geomorphology that controls temperature, humidity, underground and surface water flow as well as wind patterns. In addition, the spatial distribution of pollen is also related to its producer sources (vegetation) that varies in elevation as well as geographically (Franklin and Dyrness 1988). The distribution of modern pollen rain with respect to pollen producers can also be used in paleo-environmental work relating to fossil pollen assemblages reflecting the patterns of past vegetation and climatic changes (Minckley and Whitlock 2000). In this work, we determined that depositions and accumulations of pollen grains is a sensitive indicator of many environmental changes such as climate or biosphere. In addition, pollen grain depositions and accumulations mark important breakpoints in the relief that change the character of pollen deposition and therefore the local bioclimatic conditions. Therefore, geomorphology can be an important characteristic causing changes in the natural as well as social aspects of the environment and affects how natural and human systems adapt to life on this planet.

Further investigation is necessary to confirm the existence of a 400-700 meter elevation breakpoint that marks a significant change in the Columbia Basin environment. The study also revealed that especially people with severe pollen allergies should avoid the maximum quantities of pollen grains that fall in the basin area. The match between vegetation and pollen amounts is most noticeable in the basin floor and in the eastern part of the study area. The influence of a southwesterly wind pattern is visible in the spatial pattern of the upland pollen distribution that follows a typical southwest-northeast direction. The amount of pollen gradually changes on the slopes of the mountains where pollen grains are moved in both directions: upwards and downwards. The meeting place forms a special transitional zone of downslope-upslope accumulation and transport. This transitional zone in the Columbia Basin is between 400-700 meters in elevation. The existence of this transitional zone of pollen accumulation from upwards and downwards pollen transport is also mentioned in the Qaidam Basin (Zhao and Herzschuh 2009). It underlines the influence of geomorphic conditions on the biosphere, atmosphere and hydrosphere of the studied area.

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