Environmental Variation at Non–Native Ecological Regions Exacerbated *Dalbergia sissoo* Dieback Outbreaks in Pakistan

*Asif Javed Muhammad – Assistant Professor (Ph.D.) (Affiliated with the Department of Forestry and Range Management, University of Agriculture Faisalabad, Faisalabad, Pakistan)

Atif Ali – Ph.D. (Affiliated with the Department of Forestry and Range Management, University of Agriculture Faisalabad, Faisalabad, Pakistan)

Nauman Ghafoor – M.Phil. (Affiliated with the Department of Forestry and Range Management, University of Agriculture Faisalabad, Faisalabad, Pakistan)

Izhar Ul Haq – M.Phil. (Affiliated with the Department of Forestry and Range Management, the University of Agriculture Faisalabad, Faisalabad, Pakistan)

Muhammad Bilal Zia – M.Phil. (Affiliated with the Pakistan Forest Institute (PFI), Peshawar Pakistan)

***Corresponding author:**

asifjaved.lincoln@gmail.com

Abstract

Shisham is one of the most important timber species in Pakistan. It is indigenous to the Indo—Pak subcontinent provides income to local people and becomes an important agroforest species. Shisham mortality research has suffered from a false dichotomy of drought vs biotic attack. In this study, the inherent problem associated with the understanding of shisham dieback was addressed by comparing the ecology and soil characteristics of Shisham evolved under high water demand, low salinity, and non–existing waterlogged conditions at its place of origin. Shisham was introduced to semi–arid regions characterized by low water availability, long and frequent droughts, flooding, and salinity thus predisposing shisham to completely new selective factors such as abiotic and biotic stresses that are not known at its place of origin. Shisham dieback is thus a result of prolonged and frequent exposure to abiotic factors in its non–native planting sites. The recent dieback outbreaks were due to water shortage and the lowering of the water table because of different drought episodes. Soil comparison revealed electrical conductivity was higher in diseased than the healthy plants that show high salinity or low moisture conditions in the rhizosphere. These findings further emphasized the importance of the abiotic factors in the shisham dieback in Pakistan. It is concluded that the dieback is mainly caused by abiotic factors such as drought, waterlogging, and salinity. It is therefore suggested that shisham plantations must be established on lands without waterlogging and salinity and drought conditions. Secondly, water availability must be ensured in the plantations by channeling canals through the plantations to ensure water supply as well as to help keep the water table high to maintain healthy shisham plantations.

Keywords: *Dalbergia sissoo., Ecology., Climate change., Dieback., Drought., Salinity., Waterlogging., Abiotic stresses*

Introduction

Dalbergia sissoo locally known as "shisham or Talli" is native to tropical and subtropical Himalayan regions of Pakistan, India, Nepal, Bhutan, Bangladesh, and Afghanistan (Khan and Khan, 2000). Furthermore, it has been introduced to other countries across the globe, particularly in America, Asia, Africa, and Australasia (Asif et al., 2023). Similarly, it was introduced to different ecological regions of Pakistan in Punjab, Sindh, and Khyber Pakhtunkhwa (KPK) in 1880 mainly to meet the needs of fuelwood (Khan and Khan, 2000). In Pakistan, it is one of the most important and widely planted tree species for agroforestry, fuel, lumber, and soil binder. Its wood is widely prized for its remarkable tensile strength, color, texture, and other physio-mechanical attributes (Khan and Khan, 2000). Despite the nativity of the *D. sissoo* in Pakistan, serious issues are expected with plantation establishment and shisham plantation particularly in the non–native regions of Pakistan (Mukhtar et al., 2014). Dieback caused large-scale mortality of shisham in 1998, especially in artificial plantations, roadsides, canals, and farmlands which led to a large-scale eradication of shisham in KPK, Punjab, and Sindh (Asif et al., 2023., Javaid et al., 2004., Mukhtar et al., 2014). Dieback was observed in Pakistan's non–native regions rather than in the Himalayan subtropical riverine valleys, where it originated (Asif et al., 2023). In addition to having salinized and waterlogged soils, these newly established regions have semiarid and dry climates. Widespread dieback epidemics are generally caused by extended drought conditions, which can be attributed to climate change (Asif et al., 2023). Shisham is a subtropical riverine species that thrives in warm, humid climates with high water demands that are met by heavy precipitation or snowmelt. Because of their sloppy nature, the valleys rarely flood, and salinity is not an issue. Shisham evolved at its center of origin under high temperatures, low salinity, low flooding, and high-water availability and was challenged by salinity, waterlogging, low water regimens, high temperatures, and prolonged and frequent droughts (Asif et al., 2023). The main causes of shisham dieback are abiotic factors such as salinity, drought, and flooding whereas fungi are scavengers and secondary pathogens that attack shisham trees compromised due to dieback attack (Asif et al., 2023; Camarero, 2021), Pakistan is the country where droughts occur most frequently, and climate change is making them more frequent and intense. Since these climate anomalies are expected to occur in the future, it is critical to create water management and conservation strategies to guarantee long-term water supplies. Thus, it is critical to understand the ecology and the role of soil characteristics that may play a direct or indirect role in abiotic stresses that eventually will result in the spread of shisham dieback.

Materials and Methods

Field Surveys & Ecology of KPK and Punjab

Field studies were carried out in the summers of 2017 and 2019 in several Pakistani provinces, including Punjab and Khyber Pakhtunkhwa (KPK), which have significant areas under shisham. KPK included shisham from both native and non-native ranges. One of the native ranges of shisham is Besham, the largest town in the Shangla district of KPK. Besham's climate is classified as a Köppen subtropical climate with humid weather. The average yearly temperature and precipitation in Besham are 20.7°C and 842 mm, respectively. Even during the driest months of the year, there is an increase in precipitation. November is the driest month with an average of 18 mm of rain, while August is the wettest month with an average of 138 mm. June has the highest average temperature, coming in at 30.6°C. The coldest month is January, with an average temperature of 8.9ºC. It is located along the Indus River's bank. Natural populations of shisham are abundant in the valley, growing by the sides of the Sindh River. Contrary to Basham the non–native regions of shisham in KPK's include Peshawar, Charsada, Dera Adam Khel, and Kohat. These regions experience extremely hot summers and mild winters. Winter lasts from November to late March, and occasionally into mid-April. Mid-May to mid-September is when summer officially begins. This area is not receiving monsoon rains and the amount of rain is very low. In contrast, winter months typically see higher average rainfall than summer months (Mukhtar et al., 2014).

The climate of Punjab is subtropical desert (Classification, BWh). The province has an annual temperature of 31.01ºC (87.82ºF), which is 10.12% higher than the average for Pakistan. Punjab experiences 47.45 wet days (or 13.0% of the total number of days) and 22.18 mm (0.87

inches) of precipitation on average each year (https://weatherandclimate.com/pakistan/punjab). Salinity has affected around 6.3 million hectares in Pakistan, whereas waterlogging has damaged one million hectares (https://www.envpk.com/waterlogging-and-salinity-in-pakistan/). A survey was conducted in the Punjab province, primarily targeting plantations such as Abbasia in Bahawalpur, Chicha Watni, and Changa Manga as well as Faisalabad, Hafizabad, Gujranwala, Kamokee, Rahwali, Nandipur, and Chichawatni respectively.

Soil Sampling

The soil sampling was carried out mainly from topsoil at a depth of 10 – 20 cm mainly around the *D. sissoo* root zones. Altogether 45 soil samples were collected representing (19) healthy shisham soil samples from Shangla District and twenty-six dieback-infected soil samples from various districts of KPK and Punjab.

Soil Analysis

After each sample was properly labeled, it was brought to the lab for further analysis. The soil analysis was conducted at the Soil Science Laboratory at the Ayoub Research Institute (ARI), Faisalabad, Pakistan, and examined soil parameters such as pH, electrical conductivity (EC), moisture content, organic matter, P, and K content, saturation percentage, and soil type using established techniques (Okalebo et al., 2002).

Data Analysis

All parameters were subjected to a two-way analysis of variance (ANOVA), and the R package "*agricolae*" was used to determine the correlation between various components. The R package "*Hmisc*" was used to compare substantially different treatment means using the Duncan Multiple Range Test (DMRT) (R Core Team, 2022).

Results

A general survey revealed that *D. sissoo* was found in large areas and every district visited both in KPK and Punjab. The shisham was found growing vigorously and without any traces of dieback along the banks of the Sindh River in Besham one of the regions known as the center of shisham origin (Fig. 2). The dieback was mainly found in the areas where shisham was introduced such as Peshawar, Charsada, Dara Adam Khel, and Kohat in KPK, and similar was the case in the Faisalabad, Hafizabad, Gujranwala, Kamokee, Rahwali, Nandipur, and Chichawatni districts of Punjab (Fig. 3). Most of the mortality occurred along the roadsides, and on the canals, and the least was found on farmers' fields (2). There was significant mortality occurred on one side of the canal that was used for transportation as compared to the other side. This could be due to soil compaction inhibiting the root access to water seepage of canal water to the tree rhizosphere thus depriving it of the water. In KPK dead shisham along the canal side was replaced with *Eucalyptus camaldulensis* (Fig. 4 & 5), a species that is known for its high-water demand and deep root system whereas shisham is a very weak competitor and intolerant to shade. On agricultural farm fields mortality rate was generally low however most of the trees were found dead on the side of the water channels where roots were exposed due to flood conditions soil erosion and exposing the roots to pathogens. Most of the artificial plantations such as Changa Manga, and Cheechawatni experience very high losses of shisham due to dieback. Nevertheless, an exception was observed in the Abbasia Plantation situated in Bahawalpur where no shisham dieback incidence was observed although it was present along the roadsides outside the plantation. The water table is kept high by the Melsi Link Canal that runs through the plantation.

Soil Comparison

Soil comparison from dieback infected and healthy shisham trees revealed a significant difference in electrical conductivity (EC), and pH, organic matter, phosphorus, potassium, and saturation percentage did not show any significant difference (Table 1). Comparative analysis of soil samples revealed that the dieback-stricken tree soil had significantly high electrical conductivity (1.40 dS/m) as compared to healthy soil samples. (0.87 dS/m) (Fig. 1). There was no significant difference in soil pH (Table 1). However, the soil pH >8.0 which means it was more alkaline. Soil organic matter was also not significantly different (Table 1). Similar trends were observed for phosphorus, potassium, and saturation percentage.

Correlations among different soil components

EC was not significantly associated with any of the soil parameters taken in this study. However, soil pH was positively associated with organic matter (Table 2). Organic matter was positively associated with soil pH, phosphorus, potassium, and saturation percentage. Phosphorus was also positively correlated with potassium and saturation percentage. Saturation percentage was positively associated with organic matter, phosphorus, and potassium and had no relationship with soil pH and electrical conductivity (Table 2).

Discussion

Forest dieback is a complex, long-term phenomenon caused by a variety of stressors, which can result in positive feedback that reduces tree vitality (Manion, 1981). Many of these acute dieback episodes are distinguished by a sharp loss of tree vigour (e.g., shoot death and leaf shedding, epicormic shoot production, loss of fine roots), a decline in growth, and elevated mortality rates, all of which have been linked to rising temperatures (Adams et al., 2009; Asif et al., 2023., Van Mantgem et al., 2009; Williams et al., 2013). Extreme dry spells usually precede dieback episodes, however, there is a lack of knowledge about the cumulative stress that may predispose trees to die in such rare, extreme droughts. Dieback has obvious consequences, it reduces forest cover and productivity locally, alters the carbon and water cycles, and shifts vegetation composition, frequently toward assemblages with more drought-tolerant tree and shrub species, or by hastening successional dynamics (Anderegg et al., 2015; Batllori et al., 2020). Dyaram et al. (2003) investigated the extent and causes of shisham mortality in twenty North Bihar districts. They concluded that the outbreak was due to waterlogged conditions.

Ecology and Shisham Dieback

Dalbergia sissoo grows naturally in India, Pakistan, and Nepal. It can be found up to 1,500 m altitude in the Indo-Gangetic Plain and the Sub-Himalayan tract. It grows indiscriminately alongside roads, streams, and landslides on newly exposed soil. *Dalbergia sissoo* is a widespread tree found near riverbanks in alluvial soils. It prefers well-drained, alluvial sandy or gravelly soil with plenty of rain. Waterlogged and poorly drained clayey soils are avoided by the tree species. It could endure temperatures ranging from 4 to 49 degrees Celsius. *D. sissoo* loves riverine habitats with plenty of sunlight and moisture. Shisham seedlings are intolerant to shade. Annual rainfall in the trees' natural region ranges from 500 to 4500 mm. Survival and early growth are low where rainfall is less than 1000 mm unless groundwater is present. Once established, the trees can withstand up to four months of yearly drought.

In the present survey, shisham stands did not show any dieback mortality along the roadside or along the river Sindh in the Himalayan valleys. This is perhaps due to the regular supply of water and the high-water table maintained in the place of origin. Shisham trees as old as more than 200 years were also found in several villages along the river. Bakshi et al. (1957), during a survey of diseases in sissoo forests, observed that the wilt and other root diseases are absent in the riverbeds, where sissoo grows naturally. There were no signs of waterlogging or salinity in the area. Shisham was first introduced in Punjab in 1886 to meet the need for coal (Khan and Khan, 2000). Subsequently, it was introduced to KPK, Sindh, and recently in Baluchistan. The non–native regions are characterized by floods and salinity. Similarly, droughts are frequent and prolonged. These conditions presented a challenge contrary to the place of origin of shisham. This was clearly evidenced by the widespread mortality of shisham in a six-year-long drought period declared an *El Niño* era from 1996 to 2000 (Asif et al., 2023., Mukhtar et al., 2014). The yearly mean rainfall during this extended period of drought was less than 150 mm coupled with high temperatures (Asif et al., 2023). High evapotranspiration losses caused a lowering of the water table thus resulting in widespread mortality of shisham along the roadsides, canal, and in the plantations. The subsequently increased rainfall resulted in both reduction and rejuvenation of dieback-infected trees (Fig. 5). The effect of climate anomalies such as droughts and waterlogging in the occurrence of dieback in trees is now well-established (Anderegg et al., 2019., Asif et al., 2023., Cannon et al., 2019., Seidl et al., 2017., Senf et al., 2018., Sommerfeld et al., 2018).

D. sissoo is also vulnerable to prolonged waterlogging because it did not evolve in such conditions in its native habitat. Waterlogged conditions will thus damage and expose the roots to soil or water-based fungi such as *Fusarium solani* and *Fusarium oxysporum*. Sissoo plantations in the Piplee Block of the Bareilly Forest Division experienced up to 30% mortality, while sissoo mixed plantations in the Ganganagar Patiain Tarai and Bhabar Forest Divisions experienced 100% mortality. The water table was always found to be between 2 and 3 metres deep. The depth of the water table appeared to be related to the age at which mortality set in. Mortality began at 10 - 12 years of age in places where the water table was 2 - 3 m deep, 12 - 14 years in places where the water table was slightly lower and 5 - 6 years in places where it was within 2 m. When the roots encounter the water table, the plants appear to become more susceptible to *Fusarium solani* infection and eventually die (Bakshi 1957).

D. sissoo Mortality on Roadside

Shisham is a dominant species planted along the roadsides due to excellent soil binding abilities and shallow root systems. The shisham along the roadside depends mainly on rainfall for its water needs. However, prolonged droughts resulted in low rainfall and high temperatures that increased the evapotranspiration losses causing a lowering of the water table. Similarly, soil compaction on roadsides inhibits root growth and water permeability thus restricting access to possible available water sources. Soil compaction can also cause waterlogging during wet spells and drought during dry spells, limiting root development. Poor rooting inhibits plant growth on compacted soils and increases the risk of trees being blown over during storm events (https://www.forestresearch.gov.uk/). Drought and waterlogging both cause root injury and increase the accessibility of soil fungi such as *Fusarium solani* and *Fusarium oxysporum* to the xylem vessels, causing dieback. Droughts with increased duration and intensity result in shisham mortality along the roadsides.

D. sissoo Mortality on Canals

D. sissoo mortality along the canal side could be due to one of the three factors i.e., waterlogging, low water table due to droughts, and soil compaction. Shisham trees that were growing on the canal bank had roots submerged into water thus exposing to the fungal spore in the water or in the rhizosphere. Secondly, *D. sissoo* was found dead on the canal side used for transportation due to soil compaction and healthy shisham trees were observed on the other side with loose soil rhizosphere. The compact soil makes a barrier for both water seepage and accessibility of the shisham roots to the water source. Low water table due to prolonged droughts further exacerbated the incidence of dieback. The dead shisham trees were replaced by *Eucalyptus camaldulensis*, a fast-growing tree with a very deep root system that is preferred for its use on waterlogged and saline soils. This would further cause a lowering of the water table and offer significant competition to both healthy and diseased shisham trees. According to Bajwa et al. (2003), the canal banks had the highest mortality rate of 75-80 percent. It reveals that high soil moisture content correlates with disease incidence and severity. Water seepage from the canal into the surrounding areas causes waterlogging of the soil. According to other researchers, high soil moisture levels exacerbate the severity of this disease (Sharma et al., 2000; Keerio, 2001). Drought and waterlogging both create an ideal environment for disease attack and severity. Keerio (2006) conducted a survey of all shisham-producing districts, non – native regions for shisham in Sindh, including Ghotki, Sukhur, Khairpur, Naushahro Feroze, Nawabshah, Sanghar, and Hyderabad, confirmed that the primary causes of shisham tree drying/dying were waterlogging and drought, which created stress conditions and made the trees susceptible to dieback disease.

D. sissoo Mortality on Agriculture Farmlands

D. sissoo is the most preferred and commonly grown species on agricultural lands. The least damage by dieback was observed on the agricultural lands (Bajwa et al., 2003., Mukhtar et al., 2014). It could be due to the availability of water by using tubewell irrigation and maintaining the water table, during prolonged drought conditions when canal water would be in short supply. The dying shisham trees that were planted on the watercourses experienced root exposure and damage due to waterlogged conditions because of soil erosion, providing an opportunity for the fungi to infect xylem vessels.

D. sissoo **Mortality in Plantation**

D. sissoo was introduced from nativity to several plantations in Punjab, KPK, and Sindh to meet the local industrial needs. Shisham dieback was reported from all the plantations where most of the plantations suffered high mortality rates. Nevertheless, the lone exception to this was the Abbassia plantation situated in Bahawalpur a southernmost city with a desert-like climate that had reported the lowest dieback incidence (Mukhtar et al., 2014). The main factor that set it apart from other plantations was the Melsi link canal that runs through the plantation to ensure a continuous supply of water and at the same time helps maintain the water table to mitigate evapotranspiration losses. On the other hand, large-scale shisham mortality has been observed from the Changa Manga and Cheechawatni plantations. These plantations are known as irrigated plantations, yet water is only available for two to three months of the year. This resulted in water shortage and the lowering of the water table resulted in large-scale shisham mortality. Bakhshi et al. (1972) reported similar findings based on a 110-ha sissoo plantation that was raised in Karnal Forest Division (Haryana) from 1952 to 1960 and irrigated until 1963. Irrigation was done through shallow channels, which resulted in the formation of the superficial root system. After 1963, irrigation was discontinued in nine of eleven coupes. After three years, mortality started in all nine coupes where irrigation was stopped. There was no mortality rate in the remaining two coupes that were kept irrigated. The trees had dried up due to a lack of water, and the superficial root system was unable to draw water from the low water table in Haryana's deficit rainfall areas.

D. sissoo **Dieback & Pathogens**

Even though *Fusarium solani* is consistently isolated from dying roots and has emerged as the most likely organism responsible for dieback, no single causal agent has been identified in the case of shisham dieback (Pathan et al. 2007). Fungi that can cause wilt and/or root rot on diseased trees include *F. oxysporum*, *Ceratocystis fimbriata*, *Curvularia lunata*, and *Ganoderma lucidum* (Pathan et al. 2007; Rajput et al. 2008; Poussio et al. 2010). *Fusarium solani* and *Ceratocyctis fimibriata* are two of the most common pathogens found in dieback-infected trees. There are however failed pathogenicity accounts available where these pathogens failed to produce dieback symptoms under normal moisture conditions (Asif et al., 2023). Bashyal et al., (2002) made similar observations for six months after fungal inoculation and failed to find any dieback symptoms stating that fungal endophytes were not the primary cause of shisham dieback. The plants appeared healthy during monsoon and showed no dieback symptoms probably due to the availability of water. They concluded that physiological factors such as drought rather than fungal infections play a primary role in sissoo dieback, and the fungal pathogens are the secondary agents in causing shisham dieback (Manandhar and Shreeshta., 2000., Bashyal et al., 2002). Furthermore, most of the fungi that were isolated from dieback-infected trees are facultative parasites mainly associated with wounds, and on hosts weakened by unfavourable conditions require damaged roots due to stress conditions for successful entry into the xylem vessels (Manandhar and Shreeshta., 2000., Bashyal et al., 2002).

Drought and dry soil conditions damage the sissoo roots and provide an opening for the fungi to access the xylem vessel through negative pull where their mycelium or spore is sucked into the vessel. Mycelium and spores enter wounds and move through the xylem in water-conducting cells and into ray parenchyma cells. The fungal growth clogged the xylem vessel and stopped the upward movement of the water-soluble nutrients. *Fusarium solani* is a soil-borne fungus that is present in all soils globally. The pathogen moves upward to stem through the roots. Similarly, the mode of entry might be adapted by *C. fimbriata* which eventually invades the host xylem vessel. The fungus causes dark reddish-brown to purple to deep-brown or black staining in the xylem. This staining may extend several meters from the roots, up the trunk of the tree, and into branches.

Dieback has very specific phenotypic symptoms where the leaf starts shedding from the top canopy and then it proceeds to the lower parts of the canopy. We observed that initially, the infection occurred in one or two xylem vessels and then it progressed with subsequent losses of canopy. The first leaves to disappear are those that are exposed to sunlight, photosynthetically active, and have a high transpiration rate thus causing negative pressure in the respective xylem vessel that pulls the fungal mycelium and spore in the vessel. Subsequently, once the xylem vessel is clogged results in the loss of top canopy cover. This process proceeds with the infection of other xylem vessels and loss of canopy cover till most of the canopy is gone if drought conditions persist. However, if moisture becomes available sissoo tree resumes normal growth by using available healthy xylem vessels.

Fungi once gain entry inside the xylem vessel start using mobile carbohydrate sources. Sissoo plant must partition and use the available mobile carbohydrate sources for different internal processes. This will expend the mobile carbohydrate sources fast if droughts prolong, as the photosynthetic activity has been stopped due to stomatal closure. Once sissoo runs out of its mobile carbohydrate sources, the next available sources are in the form of structural cellular carbohydrates present in the cell wall (McDowell et al., 2008; Sala et al., 2010; McDowell, 2011). This is the point where *Fusarium solani* dominates other fungi as it has the potential to utilize cellulose from the cell wall by secreting cellulase enzymes. This could be a major reason that *Fusarium solani* was considered the main pathogen as it was always present in the dieback infected plant tissues both dead and alive. Once the cellular structure is damaged and wood tissues become soft the insect-like termites invade these tissues and the tree reaches no return point due to significant internal damage.

We believe that a false dichotomy of drought vs. biotic attack has hampered shisham mortality research (McDowell et al., 2013). Tree mortality is caused by pathogens, and it is well known that drought can predispose shisham to insect and fungal pathogen attacks (Asif et al., 2023; Gaylord et al., 2013). A recent meta-analysis (Jactel et al., 2012) investigated the interaction between drought stress and damage caused by forest pests and pathogens, and the relationship between tree physiological status and disease development has previously prompted several reviews (Boyer, 1995). Models of drought-induced mortality have also included biological agents (McDowell et al., 2008, 2011). Previous research, on the other hand, has not fully recognized the diversity of trophic interactions that microorganisms establish with host trees, and how this diversity has direct implications in terms of the physiological mechanisms that lead to mortality. Pathogen-produced metabolites can cause tree mortality directly, but pathogens can also disrupt the xylem and phloem of infected hosts, affecting their C economy through the consumption of C reserves and the induction of C-expensive defences. If abiotic stress conditions persist, this chain of events will eventually lead to tree death.

Soil and *D. sissoo* Dieback

Soil is the most important component of a terrestrial ecosystem that supports life because it transports various ecosystem products and services such as water regulation, flood protection, carbon storage, and soil fertility, all of which have an impact on human welfare (Neina, 2019). Apart from electrical conductivity, no soil metrics measured in this study revealed a significant difference between healthy and ill shisham trees. Soil electrical conductivity affects plant nutrient availability (Cruz et al., 2018). Because soil salinity is related to electrical conductivity, salinity is commonly used to calculate EC (Hardie and Doyle, 2012). The significant difference in electrical conductivity between healthy and diseased shisham trees is associated with stress conditions like salinity and drought. The electrical conductivity (EC) of a solution indicates its salt content and electrolyte concentration. The nutrient solution's EC is proportional to the number of ions available to plants in the root zone (Nemali and van Iersel, 2004). Higher EC slows nutrient uptake by increasing the osmotic pressure of the nutrient solution, wastes nutrients, and increases nutrient discharge into the environment, resulting in pollution. Lower EC may have a negative impact on plant health and yield (Signor et al., 2016).

Negi and colleagues (1999) studied sissoo mortality in Haryana, Uttar Pradesh, and Bihar. Northern districts of Bihar, such as Gopalganj, Siwan, and Muzaffarpur, were particularly hard hit, according to the report. They discovered that the pH of the soil in the affected areas ranged from 7.5 to 9.7, whereas the pH in healthy areas was near neutral. Chemical analysis of plants in sick areas revealed lower potassium and phosphorus concentrations in the leaves when compared to healthy areas. They came to the conclusion that poor nutrient uptake by roots in sick areas. Soil microbial biomasses, as well as bacterial and fungal communities, are more abundant in soils with higher electrical conductivity than in soils with optimal electrical conductivity. High levels of electrical conductivity in soil have also been proposed to promote pathogen growth, which supports our findings (Fang et al., 2023., Lee et al., 2011).

SUMMARY

Shisham is one of Pakistan's most important native species, playing a major role in industry, climate, and agroforestry, as well as providing an important resource for residents. Shisham dieback caused widespread mortality in non-native populations when compared to native populations. The dieback is linked to climatic abnormalities such as drought, salt, and waterlogging, which are widespread in non-native areas of Pakistan. Soil comparisons of infected and healthy shisham trees revealed a substantial difference in electrical conductivity, indicating the presence of stress factors such as salt or low moisture in diseased plants. As climate change has become a major concern for Pakistan, it is critical that shisham plantations be planted in locations with abundant water.

Table 1. Comparison of soil characteristics for healthy and dieback diseased shisham rhizosphere.

SOV	DF	SS	MS	F*calc*
EC	1	3.203	3.203	191.2***
Residuals	44	0.737	0.017	
pH	1	0.002	0.002	0.431^{N-S}
Residuals	44	0.269	0.006	
Organic Matter (OM)	1	0.002	0.002	0.28^{N-S}
Residuals	44	0.339	0.007	
Potassium (K)	1	21	20.8	0.023^{N-S}
Phosphorus (P)	1	0.14	0.14	0.181^{N-S}
Residuals	44	33.30	0.757	
Saturation Percentage	1	0.03	0.03	0.005^{N-S}
Residuals	44	274.04	6.24	

Table 2. Correlations between different soil components.

Soil Component	EC (dS/m)	Soil pH	Organic matter (%)	Phosphorus (ppm)	Potassium (ppm)	Saturation percentage (%)
EC (dS/m)	1.00	-0.12	-0.09	0.03	0.16	0.12
Soil pH	-0.12	1.00	0.29*	0.13	0.05	0.01
Organic matter (%)	-0.09	0.29*	1.00	0.72**	0.44**	0.44**
Phosphorus (ppm)	0.03	0.13	0.72**	1.00	0.83**	0.72**
Potassium (ppm)	0.16	0.05	0.44**	0.83**	1.00	0.80**
Saturation percentage (%)	0.12	0.01	0.44**	0.72**	0.80**	1.00

* Significantly different at <0.05 *** High significantly different at <0.01 ^{NS} Non-significant

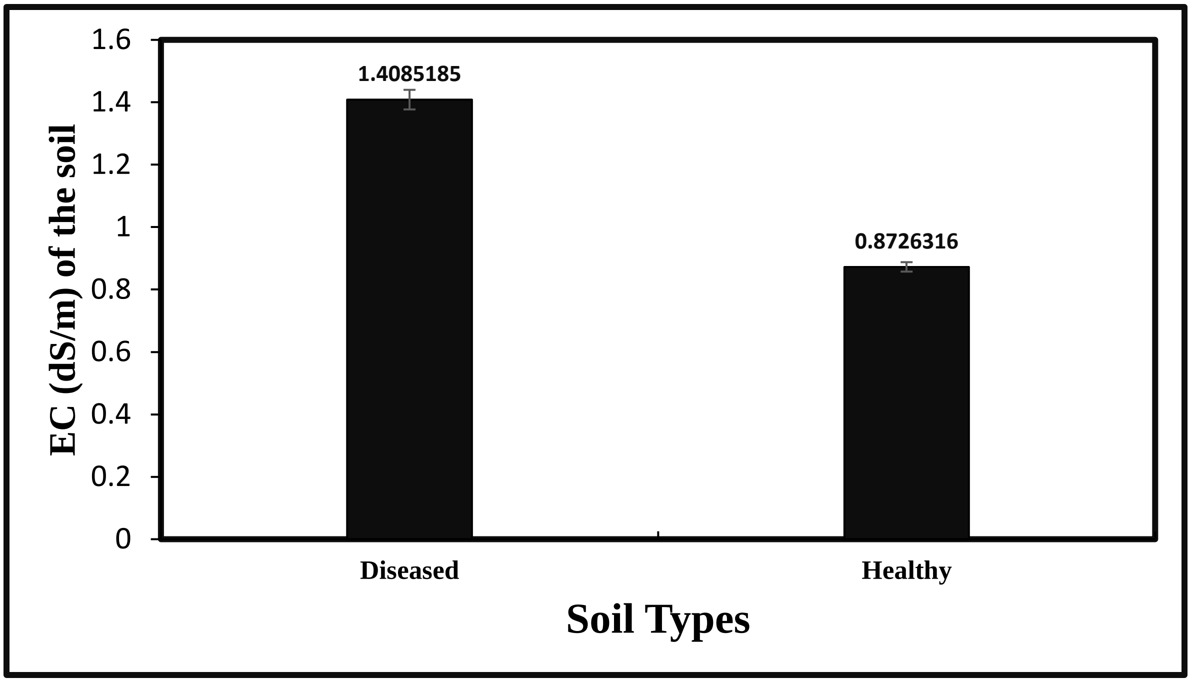

Figure 1. Comparison of diseased and healthy soil samples for EC (dS/m)

Figure 2. Healthy *Dalbergia* sissoo plantation along the Sindh River in Basham, KPK.

Figure 3. Dieback-infected *Dalbergia sissoo* plants along the canal were replaced with *Eucalyptus camalldulensis* in Bannu, KPK.

Figure 4. Dieback infected dead trees on roadside in Gujranwala, Pakistan.

Figure 5. Effects of climate change on shisham dieback incidence. Shisham tree in 2017 showed advanced dieback symptoms due to low rainfall and the same tree revived with a filled canopy due to increased rainfalls after 2017.

Acknowledgment

Dr. Muhammad Asif Javed (P.I.) also would like to thank Professor Dr. Iqrar Ahmad Khan (T.I.) for providing a laboratory facility at the Center for Agriculture Security (CAS), UAF, and for his insight and unwavering support. The work was supported by a combined grant (No. 965) form USAID and Punjab Agriculture Research Board (PARB), Pakistan.

References

1. Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J.C., Breshears, D.D., Zou, C.B., Troch, P.A. and Huxman, T.E., 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings Of National Academy Of Sciences*, *106*(17), pp.7063-7066.

2. Anderegg, W.R., Anderegg, L.D., Kerr, K. L. and Trugman, A.T., 2019. Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. *Global Change Biology*, 25(11), pp.3793-3802.

3. Asif Javed Muhammad, Izhar Ul Haq, Nauman Ghafoor, and Fazal Ur Rehman. 2023. Climate Change Exacerbated *Dalbergia sissoo* Dieback Under Water Stress and *Ceratocystis fimbriata* Infection. *Agri Res & Tech: Open Access J.;* 27 (4): 556376. DOI: 10.19080/ARTOAJ.2023.27.556376.

4. Bajwa, R, Javid, A. and Shah, M. B. M., 2003. Extent of Shisham (*Dalbergia sissoo* Roxb.) declines in Sialkot, Gujranwala, Lahore, and Sargodha Districts. *Mycopathology*, 1,1–5.

5. Bakshi, B. K., Reddy, M. A. R., Puri, Y. N. and Singh, S., 1972. Forest disease survey (Final Technical Report). *Forest Pathology*, 1: 17.

6. Bakshi, B. K., Reddy, M. A. R. and Singh, S., 1972. Ganoderma root rot in Khair (*Acacia catechu* Wild) in reforestation stand. *European Journal of Forest Pathology*, 6: 30-38.

7. Bakshi, B. K., 1957. Wilt disease of shisham *(Dalbergia sissoo* Roxb.). IV. The effect of soil moisture on the growth and survival of *Fusarium solani* in laboratory. *Indian Forester* 83(8): 505-512.

8. Bakshi, B. K., Arora, K. K., and Singh, S., 1957. Root disease of shisham *(Dalbergia sissoo).* V. Incidence of disease in relation to soil pH and soil texture. *Indian Forester* 83(9): 555-558.

9. Bashyal, B. P., Joshi, S. and Shrestha, S., 2002. Role of fungal endophytes on dieback of Dalbergia sissoo. *Nepal Journal of Science and Technology*, 4(1), 45-50

10. Batllori. E., Lloret, F., Aakala, T., Anderegg, W. R., Aynekulu, E., Bendixsen, D. P., Bentouati A., Bigler C., Burk C. J., Camarero J. J. and Colangelo, M., 2020. Forest and woodland replacement patterns following drought-related mortality. *Proceedings of the National Academy of Sciences*, *117*(47), pp.29720-29729.

11. Boyer, J. S., 1995. Biochemical and biophysical aspects of water deficits and the predisposition to disease. *Annual Review of Phytopathology*, *33*(1), pp.251-274.

12. Camarero, J. J., 2021. The drought–dieback–death conundrum in trees and forests. *Plant Ecology & Diversity*, *14*(1-2), pp.1-12.

13. Cannon, J. B., Henderson, S. K., Bailey, M. H. and Peterson, C.J., 2019. Interactions between wind and fire disturbance in forests: Competing amplifying and buffering effects. *Forest Ecology and Management*, *436*, pp.117-128.

14. Cruz, J. L., Coelho, E. F., Coelho Filho, M. A. and Santos, A. A. D., 2018. Salinity reduces nutrient absorption and efficiency of their utilization in cassava plants. *Ciência Rural*, 48.

15. Dayaram, J., Kumar, M., Sharma, S. and Chaturvedi, O. P., 2003. Shisham mortality in Bihar: extent and causes. *Indian Phytopathology*, 56: 384-387.

16. Dayaram, M. K., Sharma, S. and Chaturvedi, O. P., 2003. Shisham mortality in Bihar extent and causes. *Indian Phytopathology*, *56*(4), pp.384-387.

17. Fang, L. L., Liu, Y.J., Wang, Z.H., Lu, X.Y., Li, J.H. and Yang, C.X., 2023. Electrical Conductivity and pH Are Two of the Main Factors Influencing the Composition of Arbuscular Mycorrhizal Fungal Communities in the Vegetation Succession Series of Songnen Saline-Alkali Grassland. *Journal of Fungi*, *9*(9), p.870.

18. Gaylord, M. L., Kolb, T. E., Pockman, W.T., Plaut, J. A., Yepez, E. A., Macalady, A. K., Pangle, R. E. and McDowell, N.G., 2013. Drought predisposes piñon–juniper woodlands to insect attacks and mortality. *New Phytologist*, *198*(2), pp.567-578.

19. Hardie, M. and Doyle, R., 2012. Measuring soil salinity. Plant salt tolerance: *Methods and Protocols*, pp.415-425.

20. Jactel, H., Petit, J., Desprez-Loustau, M. L., Delzon, S., Piou, D., Battisti, A. and Koricheva, J., 2012. Drought effects damage by forest insects and pathogens: a meta-analysis. *Global Change Biology*, *18*(1), pp.267-276.

21. Javaid, A., Bajwa, R. and Anjum, T., 2004. Identification of some more phenotypes of Shisham (*Dalbergia sissoo* Roxb.) and their response to dieback and wilt diseases. University of the Punjab, Quaid-e-Azam Campus, Lahore, Pakistan, 2(2), pp.55-59.

22. Keerio, G. R., 2006. Report on dying and drying of shisham in Sindh. In: Proceeding, 3rd National Seminar, Shisham Dieback, May 11, 2006. Punjab Forestry Research Institute, Faisalabad, Pakistan, pp:107-109.

23. Khan, M. M. and Khan, M. H., 2000. Die-back of *Dalbergia sissoo* in Pakistan. *Journal of Forestry of Pakistan.*, (18), pp.51-56.

24. Lee, Y. H., Ahn, B. K. and Sonn, Y.K., 2011. Effects of electrical conductivity on the soil microbial community in a controlled horticultural land for strawberry cultivation. *Korean Journal of Soil Science and Fertilizer*, 44(5), pp.830-835.

25. Manadhar, G. and Shrestha, S. K., 2000. Fungi associated with dieback of sissoo. In: Proc. of the Sub-Regional seminar on dieback of sissoo (*Dalbergia sissoo* Roxb.), Katmandu, Nepal, 25-28 April 2000. Pp 27-30.

26. *Manion, P.D., 1981. Tree disease concepts. Prentice-Hall, Inc..*

27. McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G. and Yepez, E.A., 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New phytologist*, *178*(4), pp.719-739.

28. McDowell, N.G., 2011. Mechanisms linking drought, hydraulics, carbon metabolism, and vegetation mortality. *Plant Physiology*, *155*(3), pp.1051-1059.

29. McDowell, N.G., Ryan, M.G., Zeppel, M.J. and Tissue, D.T., 2013. Improving our knowledge of drought-induced forest mortality through experiments, observations, and modeling. *New Phytologist*, *200*(2), pp.289-293.

30. Mukhtar, I., Bajwa, R., Nasim, G. and Hafeez, F.Y., 2014. Evaluation of genetic diversity among phytopathogenic isolates of *Fusarium solani* complex causing shisham dieback disease in Pakistan. *J Anim. Plant Sci*., 24, 1724, 1728.

31. Negi, J. D. S., Pokhriyal, T. C., Sharma, S. D. and Bhandari, R. S., 1999. Shisham mortality in India – A case study. Unpublished report. Leslie, John F.; Summerell, Brett A. (2006). *The Fusarium Laboratory Manual*. Ames: Blackwell. pp. 250–254. ISBN 978-0813819198.

32. Neina, D., 2019. The role of soil pH in plant nutrition and soil remediation. *Applied And Environmental Soil Science*, 2019, pp.1-9.

33. Nemali, K. S. and van Iersel, M.W., 2004. Light intensity and fertilizer concentration: I. Estimating optimal fertilizer concentrations from water-use efficiency of wax begonia. *HortScience*, *39*(6), pp.1287-1292.

34. Park Williams, A., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., Swetnam, T. W., Rauscher, S. A., Seager, R., Grissino-Mayer, H. D. and Dean, J. S., 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, *3*(3), pp.292-297.

35. Pathan, M. A., N. A., Rajput, Jiskani, M. M. and Wagan. K. H., 2007. Studies on the intensity of shisham dieback in Sindh and the impact of seed-borne fungi on seed germination. *Pak. J. Agri. Eng*., 23(2): 12-17.

36. Poussio, G. B., Kazmi, M. R., Akem, C. and Fateh, F. S., 2010. First record of Ceratocystis fimbriata associated with shisham (Dalbergia sissoo) decline in Pakistan. *Australasian Plant Disease Notes*, *5*(1), pp.63-65.

37. R Core Team, (2022). R: A Language and Environment for Statistical Computing. *R Foundation for Statistical Computing*, Vienna, Austria. https://www.R-project.org/.

38. Rajput, N.A., Pathan, M.A., Rajput, A.Q., Jiskani, M.M., Lodhi, A.M., Rajput, S.A. and Khaskhali, M.I., 2010. Isolation of fungi associated with shisham trees and their effect on seed germination and seedling mortality. *Pak. J. Bot*, *42*(1), pp.369-374.

39. Sala, A., Piper, F. and Hoch, G., 2010. Physiological mechanisms of drought-induced tree mortality are far from being resolved. *The New Phytologist*, *186*(2), pp.274-281.

40. Samarakoon, U. C., Weerasinghe, P. A. and Weerakkody, W. A. P., 2006. Effect of electrical conductivity [EC] of the nutrient solution on nutrient uptake, growth, and yield of leaf lettuce (*Lactuca sativa* L.) in stationary culture. *Tropical Agricultural Research*, *18*, p.13.

41. Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J. and Lexer, M. J., 2017. Forest disturbances under climate change. *Nature Climate Change,* 7(6), pp.395-402.

42. Senf, C., Pflugmacher, D., Zhiqiang, Y., Sebald, J., Knorn, J., Neumann, M., Hostert, P. and Seidl, R., 2018. Canopy mortality has doubled in Europe's temperate forests over the last three decades. *Nature Communications,* 9:(1), p.4978.

43. Sharma, M. K., Singaland, R. M. and Pokhriyal, T. C., 2000. *Dalbergia sissoo* Roxb. in India. In: Proc. of the Sub-Regional seminar on dieback of sissoo (*Dalbergia sissoo* Roxb.), Katmandu, Nepal, 25-28 April 2000. pp. 5-16.

44. Sommerfeld, A., Senf, C., Buma, B., D'Amato, A.W., Després, T., Díaz-Hormazábal, I., Fraver, S., Frelich, L.E., Gutiérrez, Á.G., Hart, S.J. and Harvey, B. J., 2018. Patterns and drivers of recent disturbances across the temperate forest biome. *Nature Communications*, 9(1), p.4355.

45. Van Mantgem, P. J., Stephenson, N. L., Byrne, J. C., Daniels, L. D., Franklin, J. F., Fulé, P. Z., Harmon, M. E., Larson, A. J., Smith, J. M., Taylor, A. H. and Veblen, T. T., 2009. Widespread increase of tree mortality rates in the western United States. *Science*, *323*(5913), pp.521-524.