

A century-old regeneration problem of *Shorea robusta* Gaertn. F. in south Asia: SWOT analysis (Review)

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ABSTRACT *Shorea robusta* Gaertn. F. a commercially and ecologically important forestry species of south Asia, is facing serious regeneration problem since last century, the continuously diminishing natural regeneration is associated with numerous abiotic and biotic factors, like edaphic, micro-climatic, physiological, genetic, anthropogenic, pathogens, insect-pests, etc. Following a good seed year and timely commencement of monsoon, Sal seeds germinate readily, and thousands of seedlings cover the forest floor. Subsequently, these get afflicted with dieback syndrome impeding shoot growth. Regular fire incidences during hot and dry season further aggravates the problem. Among biotic factors, *Hoplocerambyx spinicornis*, *Cylindrocladum floridanum* and *Inonotus shoreae* causes severe heartwood decay, blight and dieback leading to mortality. Moreover, overexploitation, illegal felling, grazing, etc., have severely depleted the Sal forest. This review systematically explores the factors contributing to regeneration problem in *S. robusta* and opines appropriate silvicultural operations and management strategies for the conservation of Sal forests through SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. We emphasized on the ecological aspects, soil characteristics, micro-climatic factors and importance of associated species to develop sustainable management regimes. Highlighting all facets of Sal regeneration problem and SWOT assessment, we suggest comprehensive weaknesses and threat perceptions to formulate strategies to seal the gaps.

KEYWORDS: Sal, natural regeneration, south Asia, SWOT analysis, micro-climatic factors.

Introduction

In the current scenario of global climatic change, the future of forest conservation and its sustainable management inevitably leads to sound regeneration of the species. By definition “regeneration is the process of silvigenesis by which the trees and forests survives and perpetuate” (Bhuyan et al. 2003). Natural regeneration is a process in which forests are restocked and enriched by *in situ* germination of seeds from the existing genetic base. Forest wealth always depends on the regeneration potential of a species and their status in composing forest stand with space and time (Barker and Kirkpatrick 1994, Adhikari et al. 2017). Considerably, the vertical stratification of a species in a forest conveys its regeneration behaviour, and the presence of seedlings and saplings is an indicator of the regeneration capability (Forest Research 2020). *Shorea robusta* (Gaertn. F., Family-Dipterocarpaceae, Vern: Sal), one of the economically important tree species, is facing the century long regeneration problem in south Asia. This species is deciduous in dry climate and evergreen in wet climate, sub-tropical, light demanding; but, never completely sheds all of its leaves. Natural stands of Sal lie between 20–32° N latitude and 75–95° E longitude (Gautam and Devoe 2006), with elevation ranged from 100–1,500 m (Jackson 1994, Paudyal 2012). This species is moderate to slow growing with fully grown matured trees ranging from 30–50 m in height (Chitale and Behera 2012). Sal forests occurs gregariously on the southern slopes of the Himalayas, distributed in India, Nepal and

Bangladesh (Orwa et al. 2009), south China and in Khanabarti river at Khurkurey Banjang near the Utararay mining site of Bhutan (Gyaltshen et al. 2014). The sub-tropical dominating Sal forests cover about 0.12 million ha in Bangladesh (Alam et al. 2008), 1.4 million ha in Nepal (Rautiainen 1999), and 10.57 million ha in India (Rathore 2000). In India, Sal forest lies in the Himalayan foothill belt in Kangra region of Himachal Pradesh, and northwestern region in Uttarakhand in Uttar Pradesh, Bihar, Jharkhand, and foothills of northwest Bengal in northcentral region; extends up to the Assam valley (including Meghalaya and Tripura) in the northeastern Himalayas; Madhya Pradesh, Chhattisgarh, and Orissa in central region (Orwa et al. 2009, Adhikari et al. 2017). The Sal forest occupies about 13.6%, 2.2% and 8.9% of the total geographical area covered by Siwaliks, Gangetic plains and central India, respectively (ISFR 2015). Though, geographically the enlisted areas of Sal forest distribution are there, but no map clearly revealed the *S. robusta* distribution pattern in south Asia. In recent years, Remote Sensing and Geographical Information System (RS & GIS) technology significantly gain importance, along with species modeling tools. One such Global Positioning System (GPS) and model-based technology is Maximum Entropy Distribution (Maxent), significantly used for prediction and forecasting the distribution (Bhandari et al. 2020), which is required to be explored for this species.

Importantly, *S. robusta* has been overlooked for centuries despite its extensive distribution and wide range of socio-economic importance. It is a major first category tree species for commercial

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timber and production to earn revenue (Gautam et al. 2006), excellent source of construction material, tannin, gum and oil, besides being used as fodder and fuel wood (Jackson 1994, Timilsina et al. 2007, Chitale and Behera 2012, Adhikari et al. 2017). This species also has pharmacological properties, such as analgesic, antipyretic, anti-inflammatory, antioxidant activities etc., which also signifies its medicinal importance (Soni et al. 2013). Unfortunately, the last three decades witnessed enormous anthropogenic pressure on the Sal forests that led to habitat destruction, fragmentation of the native range and the regeneration problem. For instance, massive deforestation activity to use the wood as railway sleepers, ship-building and other purposes etc., have seriously affected the Sal forests dynamics (Chitale and Behera 2012). Earlier, the natural regeneration of Sal was classified into two distinct phases *viz.* recruitment and establishment (Puri 1960). As determined by Rautiainen and Suoheimo (1997), the natural regeneration problem is due to the dieback phenomenon, which is usually associated with the recruitment phase where conversion of seedlings into saplings gets hampered. The living root system produces continuous sprouting in a periodic manner till the establishment of an enhanced rootstock occurs. However, the seedlings which recover from die-back tend to form “large whippy” or “small woody” pattern. Other reasons being the short viability of seeds, soil properties, canopy opening, sunlight availability, and interaction with the associated species. All these instabilities are enhanced due to the cumulative effect of rapid urbanization and climate change (Adhikari et al. 2017). For instance, Uttarakhand state forest department (India) revealed the effects of climate change causing early flowering and reduced seed setting, hampering the natural regeneration of Sal forest (Kumar 2018). Importantly, the forest fires coupled with the ill-effects of climate change affect the vigour of Sal shoots and their susceptibility to diseases (Ganguly 2019). Hence, the problem of regeneration is a major obstacle in maximizing the potential of Sal forests and extraction of resources in a sustainable manner. Quietly evident, as there are various studies being done on Sal forests with regard to its structure, diversity and regeneration; but they are localized and zone specific. With these facts, we undertook an extensive literature survey regarding the problems of Sal forest regeneration in south Asia and observed a lack of future directives towards proper silvicultural management of Sal forests. Further, it is observed that there is a huge lacuna in diversity specific research and modern approaches towards enumeration of Sal populations. These serious issues could possibly be evaluated by using Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T), i.e., SWOT analysis. Being a participatory tool, SWOT is widely applied in strategic decision support mechanism and sustainable management in corpo-

rate businesses regime. In the early 80s, SWOT gained official recognition by FAO as an important tool for gathering, synthesising and analysing qualitative forest related information (Kazana et al. 2015). A wide range of SWOT applications have been already reported on *Fynbos* (small belt of natural shrubland or heathland vegetation located in the Western Cape and Eastern Cape provinces) industry in South Africa (Coetzee and Middelmann 1997); forest sector development in Australia, Finland, Philippines, Wales, and other countries (Kurttila et al. 2000, Piggitt 2003, Harrison and Herbohn 2004, Suh and Emtage 2004, Wong 2005); and water resource management (Diamantopoulou and Voudouris 2008, Diputacion de Granada 2011). More specifically, SWOT attempts to: (i) identify the most important internal and external factors for sustainable management assessment and monitoring according to four groups *viz.* strengths, weaknesses, opportunities and threats; (ii) identify alternative forest management strategies based on the internal and external factors; and (iii) use of SWOT analyzed factors to prioritise the alternatives.

In this review, we provide an overview of the work done on the regeneration problem faced by Sal forests in relation to the management perspective through SWOT analysis. This could be used in the future sustainability of *S. robusta* as well as other forestry tree species through an integrated approach like k-means clustering or the TOPSIS (Kazana et al. 2015). The key objectives outlined in this review are: (i) to reveal the current distribution scenario of *S. robusta* in south Asia through Maxent model; (ii) to elaborate all the contributing factors affecting the natural regeneration of Sal forest; (iii) to explicate the effective management prospective on the regeneration potential of *S. robusta*; and finally (iv) to evaluate the possible mitigation measures and forecast the future scenarios using SWOT analysis. Overall, this review highlights the regeneration problem of Sal forest along with its past and present management initiatives, and recommends future management priorities.

Distribution status of *S. robusta* in south Asia

In the present study, the potential distribution of *S. robusta* in south Asia was determined through Maxent modeling (Version 3.4.1; Phillips et al. 2006), which generates an estimate of probability of presence in the range of 0–1, i.e., from lowest to highest likelihood of occurrence. The parameters, such as species geo-coordinates (latitude and longitude, 118 in Nos.), bioclimatic (19 in Nos.), categorical variable (elevation) and weather variable (wind) were used for prediction. The geo-coordinates used in the present study were derived from primary as well as secondary data-sets, with former obtained through field-based sampling in state of Uttarakhand (India), while later were derived from various sources,

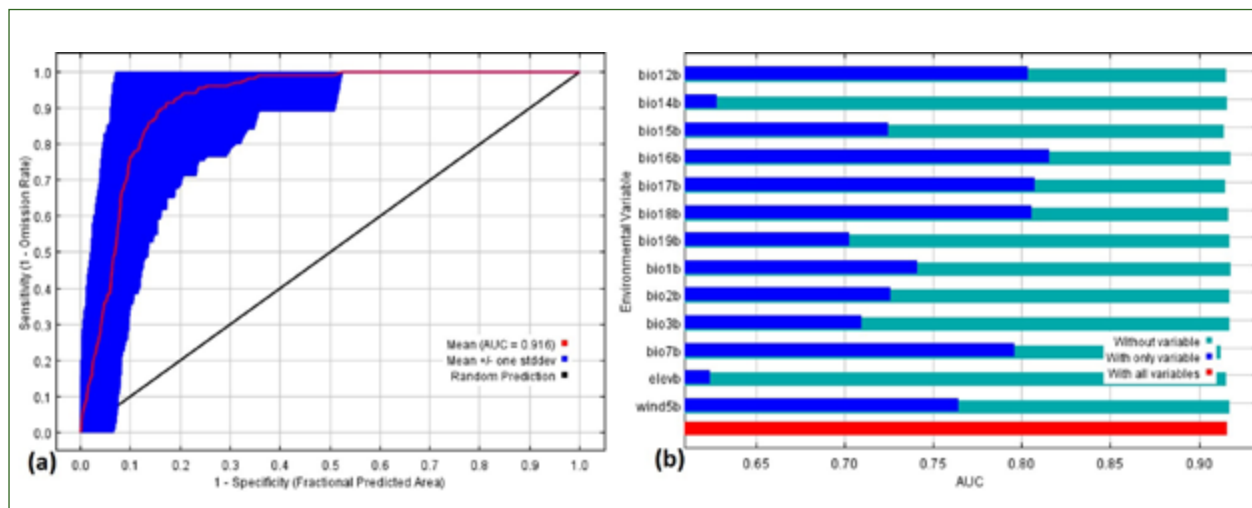
viz. Global Biodiversity Information Portal (GBIF) (<https://www.gbif.org>), National Forest Library Information Centre (NFLIC) and Botany Division of Forest Research Institute (FRI), Dehradun, and Northern Regional Centre Botanical Survey of India (BSI), Dehradun. The bioclimatic data were derived from WorldClim Version 1.4 (1960-1990) dataset (<https://www.worldclim.org/data/worldclim21.html>) with 30 seconds (~1 km²) spatial resolution. Specifically, for weather variable, wind layers were taken for the months of March, April and May as these are the flowering months of *S. robusta*, which is a wind pollinated species (Atluri et al. 2004). Further, the multicollinearity test was performed using the Pearson Correlation Coefficient (r) in the statistical software R (Version 3.5.1; <https://cran.r-project.org/bin/windows/base/>) to examine the cross-correlation among these variables (Supplementary Table 1). The variables with cross-correlation coefficient value greater than ± 0.80 were excluded. Consequently, out of the 23 environmental variables, only 13 were selected to run the Maxent model (Supplementary Table 2). Importantly, the variables were chosen based on their ecological relevance to Sal forests distribution and other Species Distribution Model (SDM) studies (Bradie and Leung 2017, Pearson 2007). In modelling, a total of 118 geo-coordinates were used, out of them 70% were used for estimating and predicting the distribution, and rest were used for the validation of the model. Then the model was allowed to run for 100 replicates for prediction mapping (Flore et al. 2012).

Eventually, the performance of the Maxent model was evaluated by Area Under 'Receiver Operating Characteristic (ROC)' Curve whose values ranged from 0 to 1, and the model with highest Area Under Curve (AUC) value was considered as the best performer. It describes the relationship between the proportion of correctly predicted observed presences, i.e. sensitivity, and the proportion of incor-

rectly predicted observed absences, i.e., 1-specificity (Chitale and Behera 2012). The AUC provides a single measure of model performance independent of any particular choice of threshold. In our case, the Maxent model output as revealed by ROC curve was depicted in red line and blue wavy-pattern (Fig. 1a). The red line shows the fit of the model to the training data; whereas the blue wavy-pattern indicates the fit of the model to the testing data, and is the real test of the model predictive power. The area in the uppermost left region provides the most useful discrimination in terms of accuracy of training set modelled for the prediction. The average test AUC for the replicate runs was 0.916 ± 0.079 , which indicates better performance of the model for test data, and best fit with the bioclimatic variables used under the Maxent model in south Asia as compared to the study conducted on *S. robusta* (AUC: 0.897) in India by Deb et al. (2017a). The categorized models with AUC value > 0.9 are considered as highly accurate for prediction modeling (Swets 1988). Other studies on tropical forestry species, such as *Tectona grandis* L.F. in tropical Asia (AUC: 0.844 ± 0.051) and *Dipterocarpus alatus* Roxb. ex Don. in Thailand (AUC: 0.904), revealed the significance of AUC value in the outcome of prediction modelling (Deb et al. 2017b, Kamyono and Asanok 2020).

The outcome of the model depends on the Jackknife test as it checks the influence and contribution of each variables used in prediction modeling (Phillips et al. 2006, Stohlgren et al. 2010, Babar et al. 2012). The current prediction had a probability range from 0 to 1, which were re-grouped and those with value > 0.7 were used to determine the current distribution range of *S. robusta*. Based upon Jackknife test, percentage contribution and permutation importance, the environmental variables, namely precipitation of wettest quarter (bio16b), precipitation of driest quarter (bio17b), and annual temperature range (bio7b) appeared to provide most useful infor-

Figure 1 - Maxent model output for *S. robusta* (a) The ROC curve evaluated the model performances and the average test AUC for replicate runs is 0.916 ± 0.079 ; (b) The Jackknife test determine the relative importance and contribution of environmental variables.

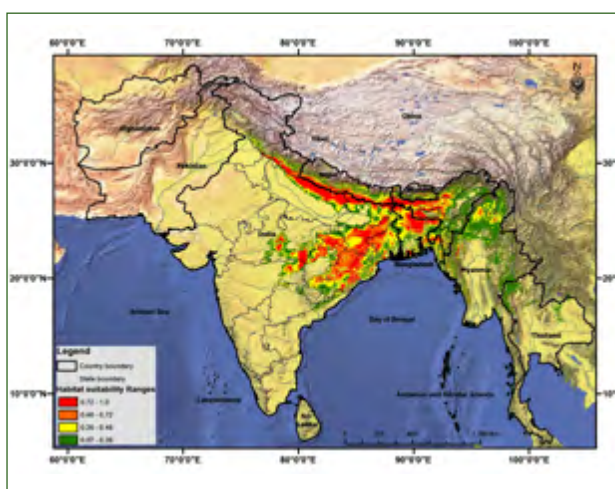


mation for predicting the distribution of *S. robusta* (Fig. 1b). The model has shown probable distribution of Sal in northern with few patches in central and northeastern India, Nepal, Bhutan, Bangladesh, and few scattered patches in Myanmar and Thailand (Fig. 2 and Supplementary Fig. 1), which also confirms the probable distribution as explained by Alam et al. (2008) and Chitale and Behera (2012).

Natural regeneration problem of *S. robusta*

Under tropical forest management, status of Sal regeneration seems to be a widely discussed problem, but the efforts initiated yet are not sufficient

Figure 2 - Eco-distribution map of *S. robusta* in south Asia developed using Maxent modeling.



and have not been very successful. This issue involves two major prospects, i.e., recruitment and establishment of seedlings. Problem regarding regeneration are different and varied with the distribution range of the Sal forests types. Many studies reported regeneration potential, which ranged from poor (Giri et al. 1999, Garkoti et al. 2003) to good (Tiwari et al. 2010, Sapkota et al. 2009b, Chaubey and Sharma 2013). However, significant difference was observed in the regeneration potential of Sal forest maintained in different conditions, such as protected and unprotected forests, natural and managed forests, similar regions or adjoining areas, etc. (Deshpande 2015, Awasthi et al. 2015).

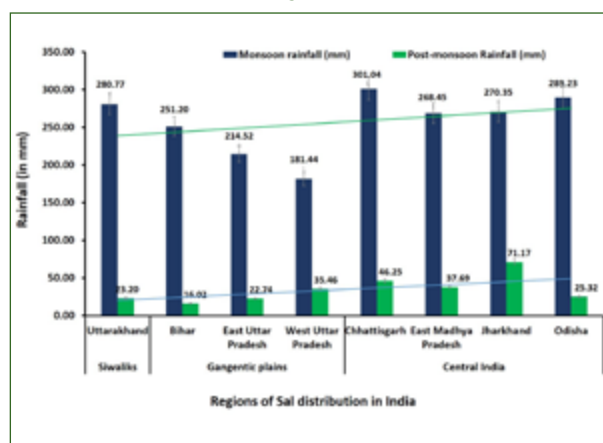
Importantly, adequate seed supply is the key and prerequisite to successful natural regeneration of Sal forest. The factors affecting the germination are the combination of good seed year and timely initiation of monsoon. It has been observed that *S. robusta* produce sufficient amount of seeds during a good seed year (Tewari 1995), but its recruitment and establishment is poor. This issue is diversified at different places according to numerous reasons, such as climatic (humidity, temperature, light intensity, span of light receiving hours, precipitation, rainfall and wind), edaphic (depth, aeration, moisture level, nutrients and erosion), seed (sensitivity, short viability and dispersal), biotic (wildlife, insect-pests, disease,

grazing animals), abiotic (forest fire, over browsing and water scarcity), and anthropogenic disturbances (Tyagi et al. 2011). Under natural conditions, the seeds of *S. robusta* are short lived (Khare et al. 1987) and lose viability within 10 days after maturity (Purohit et al. 1982). “Monograph on Sal” by Tewari (1995) also suggest that there should be no disturbance in the site during the short coincidence period of seed fall and rainfall.

Additionally, hydro-meteorological anomalies also reduces the regeneration success of seedlings, though optimum rainfall required for germination is 1,200–1,500 mm. For instance, in the areas of Siwalik and foothills of the Himalayas, regeneration decreases during the post-monsoon dry periods (Garkoti et al. 2003). Similarly, Gangetic plains and central India also experience long dry spells after monsoon, hence a similar regeneration problem might be present there. Considering all these facts, we have taken rainfall data during monsoon and post-monsoon seasons for the areas of Sal distribution in India from period 1920–2017 through India Meteorological Department (IMD) website (IMD 2020; <https://imd.gov.in/>). Average rainfall was evaluated for the monsoonal (June–September) and post-monsoonal (October–November) months over the period of 98 years. Additionally, the average rainfall over all the months (January–December) was also derived for the same period. The differences between the monsoonal and post-monsoon average rainfall is shown in Figure 3 and average rainfall distribution pattern for all 12 months is shown in Supplementary Figure 2. The pattern revealed that there is a heavy drop in rainfall (significant decline in the amount of rainfall i.e., 86.49%) between monsoon and post-monsoon seasons. Further, throughout the year for over the period, average rainfall patterns also showed steep decline during the post-monsoon months.

Importantly, the post-monsoonal season corresponds to the establishment period of *S. robusta*

Figure 3 - Comparison between monsoonal (June–September) and post-monsoon months (October–November) rainfall pattern from 1920–2017 in meteorological subdivisions corresponding to regions of *S. robusta* distribution in India. (Source: IMD 2020; www.imd.gov.in).



seedlings, but due to reduced rainfall the seedlings might suffer in the region of Siwaliks, Gangetic plains and central India. However, in localities where the moisture is retained after the monsoon recedes, successful regeneration was observed.

It can be concluded here, that dry conditions affect the regeneration and moisture deficiency can be an important cause for reduced *S. robusta* establishment in south Asia. Contrarily, hilly localities have satisfactory natural regeneration because of the appropriate moisture, adequate soil drainage and light conditions (Tiwari et al. 2010, Sapkota et al. 2009c). A large number of seeds germinate to form saplings annually, which further develop into seedlings, but fail to establish due to several factors as discussed below:

Dieback problem

Sal root system remains alive and continues to send up new shoots each year until, eventually a very strong root stock develops, producing a shoot which continue to grow and develops as a tree (Troup 1921). Dieback is a phenomenon often linked to the recruitment phase. It is a common disease symptom, especially of woody plants, characterized by the progressive death of twigs, branches, and shoots, starting at tips. All trees are susceptible to dieback, a condition where trees die or decline in canopy health prematurely and often rapidly (www.cottoninfo.com.au). Often, this condition is a response to negative stress occurring within arise by several stresses, viz., attack of nematodes, root borers (*Pammene theristhis*), heartwood borers (*Hoplocerambyx spinicornis*), defoliators (*Lymantria mathura* and *Ascotis impenrata*), stem canker (*Macrophoma shoreae*), thread blight (*Polyporus* sp.), horse-hair blight (*Marasmius gordipes*), root and collar rot (*Xylaria tuberosa* and *X. polymorpha*), etc. (Bagchee 1953, Tewari 1995, Rahman et al. 2010). The seedlings recover from dieback year after year for a considerable period. This indicates that in spite of the recruitment of new seedlings being satisfactory, it may take 30 to 60 years for the establishment of new generation under irregular systems (Rautiainen et al. 1997). Unflinching, the germination of seeds is less difficult as compared to secure its persistence and establishment within an equitable period. Further, it is difficult to enumerate the exact factors and their extent of damage, which ultimately results in the dieback of seedlings at a specific locality. For instance, the seedlings show less tolerance to low temperature resulting into frost injury (Sahu et al. 2005). Similarly, high temperature causes heat injury, which is fatal and leads to dieback. Substantially, the establishment of seedlings is better in light than in shade; and an adequate amount of light arrest the dieback (Hole 1921).

Hence, manipulation in the canopy density and structure provides proper establishment of

the seedlings, as it is directly correlated with the moisture retention capacity of soil and weed growth.

Edaphic factors

Several studies have documented soil moisture, especially at the seedling stage (Gautam et al. 2014), nutrient availability, aeration, and soil erosion, as the major edaphic factors affecting natural renaissance of Sal forest. The understory of Sal forests observed to be quite scanty and dominated by shrubs, such as *Flemingia strobilifera* (L.) W. T. Aiton, *Indigofera pulchella* Robx. and *Clerodendrum viscosum* Vent. (Timilsina et al. 2007), which are the indicators of fertile soil for regeneration (Troup 1986). Importantly, in tropical and subtropical forests, particularly in foothills of the Central Himalayas - alluvial soils is geologically spread to form 'Bhabar' and 'Terai' regions. The Bhabar area has a high-water table terrain and slopes towards the plains; whereas, the Terai is the alluvial plain area below the Bhabar-land (Mishra et al. 2000). In Bhabar soil, which is boulder and well drained, the recruitment of *S. robusta* takes place freely, whereas establishment is problematic (Tewari 1995). But in Terai soil, both recruitment and establishment of the seedlings are difficult. An earlier study on the agronomic practices i.e., weeding and their effect, suggested that the ideal light conditions would be synchronized with these cultural operations for better growth and establishment of the seedlings (Qureshi et al. 1968). Some studies also revealed the effect of root competition on natural regeneration, where trenching and weeding are recommended before the growth peaks of the seedlings (Bhatnagar 1959). Poor aeration, dispersed condition of soil during monsoon, high magnesium, soil hardness during dry periods, inadequate moisture and topography are the major limiting factors for successful natural regeneration (Sharma et al. 1985). The correlation analysis of the physico-chemical properties of soil with the floristic composition of the shrub layer, revealed negative correlation between pH and soil properties, and acidic soils are favourable for the healthy regeneration of Sal forests (Deshpande 2015).

Overall, these studies suggested that edaphic factors are the major determinant for healthier regeneration in Sal forests, provided that the optimum pH, nutrient availability and good aeration with appropriate moisture are concurrently available in the root zone of the soil.

Microclimatic features

The effect of microclimatic factors on Sal regeneration is well documented. Factors, such as low temperature, high diurnal variation in air, light intensity, drought, frost, and soil temperature during winter season were found responsible to affect the natural regeneration (Rautiainen and Suoheimo 1997, Sapkota et al. 2009c, Deshpande 2015, Mishra and Garkoti 2015). In India, reduced regeneration

in Sal forest was linked to abiotic factors (Sharma et al. 1985), and the effect of variation in the light intensity revealed that the revival is quite dependent on illumination ferocity conditions throughout the year (Tyagi et al. 2011). Considerably, the tree canopy density is directly related to the light intensity, which is a major factor affecting the regeneration (Adhikari et al. 2017). Similarly, regeneration study conducted in Nepal revealed better regeneration in the areas where direct photosynthetically active radiation hits the surface rather than dense canopy obstructing the light (Sapkota et al. 2009b). Other works also revealed that the poor light conditions were responsible for the reduced growth and survival of the seedlings in Nepal (Qureshi et al. 1968, Awasthi et al. 2015). Overall, the bio-climatic studies support the fact that *S. robusta* is a light demanding species and entrance of complete overhead light from the earliest stages of its establishment is needed for optimum growth except under dry conditions, where shade is required to conserve the moisture and protection from frost (Tewari 1995).

Physiological determinants and ecological constraints

Physiological factors, such as ratio of O_2 to CO_2 are critical in regeneration point of view (Griffith et al. 1943). An earlier study on the assessment of plant and soil water potentials, leaf conductance, osmotic and elastic adjustment, and xylem conductance revealed prolonged drought season succeeding monsoon rain is the main cause of seedlings dieback in Doon valley, India (Garkoti et al. 2003). One of the physical factors, altitude also governs the renaissance of Sal forests in *Terai* and hills. Precisely, altitudinal gradient causes variations in temperature, relative humidity, rainfall and wind movements, which are important factors affecting Sal regeneration (Sapkota et al. 2009c). Under ecological suitability of the ground biomass, the removal of top soil and litter also results into considerable decline in the seed bank and replenishment of the nutrients in Sal forest (Verma and Sharma 1978).

Associated Species

Shorea robusta is a climatic climax species in the tropical and sub-tropical areas of south Asia, particularly in Sal forest dominated communities in India, and thus, found in association with various species of trees, shrubs and herbs (Chauhan et al. 2001). Previously, studies were conducted to quantify the association of *S. robusta* with other species, where the shrub and herb layers were found to be the most reliable indicators. There is an appreciable competition between *S. robusta* seedlings with herbs and shrubs, and further between the seedlings and larger trees, where the former effect being much more pronounced (Seth and Bhatnagar 1960). For instance, the regeneration of different communities

in Sal forests, namely *Sal-Terminalia-Moghania*, *Sal-Lagerstroemia-Pogostemon* and *Sal-Syzygium-Randia-Ageratum* showed good regeneration status, whereas reduced regeneration was observed in *Sal-Ougeinia-Colebrookea* community (Bhatnagar 1960). Noteworthily, the growth and nutrient uptake of the seedlings showed the competition between Sal and its associates. *Moghania chappar* (Benth) Kuntze and *Murraya koenigii* (L.) Spreng. were found to be the good indicators, while *C. viscosum* and *Syzygium cumini* (L.) Skeels. as bad associates suppressing the growth and nutrients uptake (Srivastava 1972). Although, the majority of studies explained the association of Sal with other species, but the positive and negative impact of a few species are contradicted in some research work. Taking an example, the study conducted on the Sal forests in Doon valley (India) highlighted that *C. viscosum* had adverse effects on Sal regeneration due to high moisture requirement; and other fast-growing invaders, such as *S. cumini*, *Mallotus philippensis* (Lam.) Muell. Arg. and *Maca-ranga auriculata* (Merr.) Airy Shaw hamper the Sal regeneration (Pande 1999). In contrast, it was also reported that *M. philippensis*, *M. koenigii* and *C. viscosum* are the strong and positive indicators of Sal regeneration, whereas negative impacts were shown by *Adhatoda vasica* and *Pogostemon plectranthoides* (Gautam et al. 2007).

However, common impetus of all these studies suggest that the future research work will be utmost importance for knowing—how different species impact Sal regeneration?

Anthropogenic factors

Habitat fragmentation led by human activities (firewood collection, gathering of seeds, lopping, and harvesting) affects the forest ecosystem by changing the species composition, density and stand structure; thus, support the perpetuation of some species at the cost of losing others (McKinney 2002, Deshpande 2015). For instance, over-exploitation and excessive human disturbances in Bangladesh have converted the thickly stocked Sal forests into a depleted area with scattered trees (Dey 1995, Rahmann et al. 2010). Earlier, it was reported that more than 60% of these forests were densely stocked in late 1970s. However, after few decades the area under tree cover was reported as 36% in 1985, while only 10% remained in 1990s (Haque 2007). Similar cases of Sal forest depletion have been recorded in the other countries, namely Bhutan, India and Nepal (Acharya et al. 2011, Islam et al. 2012). Other consequences of demographic load are the illegal felling of trees. It has been estimated that around 25,101 ha (12%) of Sal forest area of Madhupur, Bangladesh were felled during 1990s (Gain 2005). Also, illegal cutting of Sal forest due to iron ore mining in the state of Jharkhand (India) has been a major problem in last few decades (Singh 2018). Additionally, poaching, expanding

‘cultural expansion’, growing livestock, and severe encroachment have contributed significantly to a decline in Sal forest cover over the decades. Grazing by the domesticated animals tends to harden the upper crust of soil and decline the vegetation emergence. Another aspect that must be taken into account for the regeneration problem is the replacement of natural Sal stands with commercial cash crop plantations. The Madhupur Sal forest stated above again serves as an example in which out of 18,623.48 ha, 3,157.89 ha were utilized for rubber plantations (Gain 2005).

As snowballing human population is likely to lurk very existence of the fringe Sal forest areas, which actually necessitate less anthropogenic disturbances and more attention in order to conserve species richness and maintain sound regeneration.

Insect-pests and diseases

Incidences of biotic problems severely affect the regeneration capacity of the growing stock in any forest ecosystem (Malmstrom and Raffa 2000). Till date, approximately 346 insects-pests have been recorded on Sal with around 155 being associated with living trees, a majority of which are defoliators (Roychoudhury 2015). Importantly, Sal borer (*H. spinicornis*) is a silent killer, an oligophagous insect that feeds chiefly on *S. robusta* heartwood (Roychoudhury et al. 2018), whose infestation can be easily noticed with presence of saw dust at the tree base. It causes heavy damage to standing trees as well as in freshly felled timber (Joshi et al. 2002) due to the kairomonal activity of the Sal sap (Kulkarni et al. 2004). Trees of all age class are affected by this borer above the girth of 20 cm (Bhandari and Singh 1988), particularly girth class of 91–150 cm are the most preferred (Beeson 1941) with maximum mortality was recorded between 121–150 cm, causing major economic loss to the timber industry (Roychoudhury et al. 2004). Thus, management of the borer is crucial in successful regeneration of Sal forests as its fatal attack causes slow withering of branches from the tree top (Utkarsh 1998). Periodical surveillance should be undertaken to identify the areas of borer attacks (Roychoudhury et al. 2017) and various management techniques, such as trap tree operations and removal of infested individuals should be used (Bhandari and Rawat 2001). Under this method, beetles of Sal heartwood borer get attracted and then collected effectively. Importantly, isolation, identification, synthesis and formulation of chemical compounds from Sal trees are required to be used as traps. These techniques will be used to control major insect-pests of Sal forest and open-up new frontiers in forest management of other biotic-organisms (Pandey et al. 2020).

Besides insect-pests, the fungal diseases, such as leaf spots and blight caused by *Cylindrocladium floridanum* (now *Calonectria floridanum*) and *Cy. scoparium* (now *Ca. scoparium*) seriously hamper

the foliage growth of *S. robusta* trees in natural forest, mostly reported from India (Mehrotra 2001). In the states of Chhattisgarh and Madhya Pradesh, root-rot disease in dry and wet Sal forest caused by *Inonotus shoreae* (Wakef.) Ryvarden (formerly *Polyporus shoreae*) has been reported which resulted into top dying leads to death (dieback) of the trees (Jamaluddin 1991). Similar case was reported in north Bengal and Assam, where dying trees became windthrown owing to root decay. The fungus infects through healthy roots, causing decay in the bark and sapwood, while heartwood remains unaffected (Bakshi et al. 1959).

Therefore, considering the severe impact of biotic agents, an integrated insect-pests and diseases management is crucial and critical for enhancing the potential of Sal forests and must be taken into account in every conservation program.

Forest fires

The forest fire, which is often used to clear the surface area of weeds and unwanted seedlings, generate drier conditions and should be avoided in areas of Sal forests with low rainfall (Gautam and Devoe 2006). Although, fire has positive effect on new flush of regeneration but is hostile to the existing saplings (Maithani et al. 1989). The loss of nutrients from the top soil due to forest fire in the tropical forest is detrimental to the seedling growth. Due to increased extraction pressure, the areas close to the road sides as well as nearby villages are devoid of saplings, and the conditions get aggravated by the frequent occurrence of fire incidences (Adhikari et al. 2017). Subsequently, the surfacing of grasses and herbs after the fire-effect attracts wild-life, which ultimately results into the destruction of the seedlings. Therefore, these incidences should be managed in a proper way for better Sal regeneration (Malla et al. 2018). To sum up, undesirable impacts on Sal forest regeneration may be avoided or reduced through distinct strategies based on controlled forest fire.

Management prospective of the Sal regeneration

The problem of natural regeneration could be addressed by proper management of the Sal dominated forest areas or through artificially assisted regeneration. As envisioned from the results of various research work, the majority advocated the proper management techniques or good silvicultural methods to increase the regeneration. Given these facts on natural and artificial regeneration, we elaborated our discussion under two sub-sections:

Silvicultural management of the natural forest

In case of natural stands, proper silvicultural management has been suggested as effective means to improve the regeneration (Tab. 1). In Nepal, the

implementation of timber production forestry was advocated, as there was abundant natural regeneration and seedling establishment in Sal forests (Sah 2000). Further community managed *Bhabar* low-land and *Hill* Sal forests have been studied for tree diversity and regeneration, where overall regeneration of both the types of forests was found to be satisfactory (Sapkota et al. 2009a). Similarly, the emergence of 6,126 seedlings ha⁻¹ of *S. robusta* in a community forest also revealed satisfactory regeneration (Paudyal 2012). In India, management and conservation of forests is administered by forests department of the respective state through working plans. It includes forest inventories which are prepared for extensive surveys, species mapping, management operations and recording of data on regenerated areas of forest. Other than these, various silvicultural and protective measures like invasive plan management, thinning, pollarding, fire management, community participation, etc., could be easily conducted in the natural forests. (Shah and Joshi 2008, Sinha and Upadhyaya 2012). For instance, *S. robusta* regenerated and augur well in the *Tera-Bhabar* of Sohagi Barwa Wildlife Sanctuary, which provided good management prescriptions for the planted forest (Chauhan et al. 2010). Further, plantation forests are helpful to fulfil the fuel wood needs of society besides reducing pressure on the natural forests (Webb and Sah 2003). In other studies, Irregular Shelter Wood System (ISWS) was suggested as a better silvicultural management tool in Sal forests (Awasthi et al. 2015, Subedi et al. 2018). Further, increase in regeneration as well as decrease in plant diversity was observed by implementing ISWS in the managed stands when compared

to the unmanaged ones (Awasthi et al. 2015). Complementary to these observations, the diversity and structure of a protected Assisted Natural Regeneration (ANR) plot located in the Kalsi Forest Division (Uttarakhand, India) of moist Sal forest were compared with the adjacent unprotected Sal forest. The findings showed lesser value of Importance Value Index (IVI) in ANR than the latter, which revealed the ANR and urbanization-impact on the natural regeneration of *S. robusta* trees in Doon valley. This study also suggested that the biotic, abiotic and other man-made disturbances like forest fire should be strictly controlled for the sustainable development and maintenance of stand structure in both ANR plots as well as unprotected Sal forest (Srivastava et al. 2016). However, in a case study in Chakrata Forest Division (Uttarakhand, India), silvicultural management of fir and spruce was done in 1898, but regeneration was not successful, while the cleared area remained opened and vacant which was then named 'Howard's Folly' (Uttarakhand Forest Department 2020). It suggested that before operating the direct removal of trees from natural forest, experimental and preliminary level of scientific procedure must be followed.

Agronomically, decent weeding practices and avoiding water logged conditions could get the satisfactory results of regeneration even in the degraded areas, as these may be considered as other relevant factors, which affect the rejuvenation of Sal forests (Malla and Acharya 2018). Importantly, efforts are required to manage the dieback, which is a major contributory factor affecting the establishment of seedlings and is not caused by the inherent tendencies, but by the faulty growing conditions (Rautainen

Table 1 - Reasons for unsatisfactory Sal regeneration and methods to overcome.

Sl. No.	Reasons for unsatisfactory regeneration	Management techniques	References
1.	Improper soil working techniques	Standardization of the game proof fence, maintaining reasonable balance between shrub and grasses, retention of middle storey species etc.	Hole (1921)
2.	Root competition	Trenching and weeding	Bhatnagar (1959)
3.	High pH of soil and imbalance of micronutrients: Like Nitrogen (N), Phosphorus (P) and Potassium (K).	Maintaining the optimum sub- soil pH (4.5-5.5) Providing high level of N and K, low level of P.	Bhatnagar (1965)
4.	Coarse texture and excessive boulder soil with moisture deficiency or clayey soil with high moisture.	Amelioration of structure and promotion of drainage. Thinning and weeding	Yadav (1966)
5.	Absence of adequate light	Thinning of upper canopy.	Seth (1967)
6.	Associate species which suppress regeneration by nutrient competition.	Removal of these species once their indicator value has been reached. Increase availability of Nitrogen in soil using fertilizers or suitable silvicultural techniques.	Srivastava (1972)
7.	Short period of seed viability	Synchronization of seed fall with the advent of rainy season. Vegetative propagation.	Singh et al. (1987)

and Suoheimo 1997). Therefore, providing quality sites for seedlings germination are important, as *S. robusta* requires moist conditions along with optimum photoperiod. The factors, such as anthropogenic pressure, forest fire, weeds, water logging, etc., could be controlled by the proper management of Sal forest, besides artificially providing the natural growing conditions in nurseries and *ex situ* plots.

Artificial regeneration

Many studies conducted during 19th–20th century advocated various management methods (including artificial means and silvicultural techniques) as mandatory for improvement of unsatisfactory regeneration status of Sal (Tab.1). Artificial regeneration methods include seed germination using nursery techniques, macropropagation (vegetative propagation), and micropropagation (tissue culture/in vitro methods). Prominently, the seeds of *S. robusta* are categorized as true recalcitrant as they are very sensitive towards desiccation and loose viability if dehydrated below 37% (Parkhey et al. 2012). Therefore, the moisture content and storage temperature are the key factors affecting viability of *S. robusta* seeds, when stored. The viability could be enhanced by storing the seeds at temperatures between 13.5 °C and 23.5 °C (Purohit et al. 1982). The seed loses viability when they are stored at low temperature (Tompsett 1985) or high temperature (Khare et al. 1987). The rapid loss in seed moisture at higher (33–36 °C) and near freezing (5 °C) temperatures seems to be the primary cause of loss in viability (Purohit et al. 1982). This is a serious problem which explains low success of *S. robusta* in artificial seed germination, as they are difficult to store. Additionally, seed germination and seedling survival also depend upon seed size, age of mother tree and orientation of seed in soil (Pattanaik et al. 2015). For instance, in Simlipal Biosphere Reserve (Odisha, India), germination and survival of *S. robusta* seeds were recorded to be higher for large sized seeds fallen on soil in inverted position from young parent trees. In contradiction to these works, Amam (1970) describes direct sowing method and conducted successful experimental work on planting of nursery grown seedlings of *S. robusta* in Bangladesh and India. Recently, a traditional regeneration protocol was developed for the germination of *S. robusta* seeds with the help of community participation. Under this protocol, the seeds were sown artificially, and the termite mound soil was used to cover the pits. Soil moisture was retained by keeping fallen Sal leaves over the plot. Germination percentage of 84–96% was recorded with enhanced seed viability up to 14 days (Agrawal et al. 2018). These studies concluded that, various artificial methods of regeneration with direct seed sowing have been successful up to some extent; but needs investigation with proper incorporation of

the advanced technology in seed science discipline (e.g., seed priming, synthetic seed, seed quality enhancement, etc.) under the silvicultural research management programmes.

Secondly, an important artificial regeneration method is vegetative propagation, which offers a unique opportunity to avoid the problem of recalcitrant seeds predominant in tropical tree species (Gbadamosi and Oni 2005). There are very few studies related to macropropagation or nursery techniques successfully tried and tested for *S. robusta* and are mentioned here: Tewari (1995) in his “Monograph of *Shorea robusta*” suggested successful adoption of various artificial methods, such as direct sowing, poly-pot planting, basket planting, pre-sprouted stump planting, entire container planting and air-layering. Further, Pande (1960) described various techniques for nursery raisings, transplanting and stumpings in Sal, where ball-transplant (process where root balls with surrounding soil are wrapped in burlap for transport to the planting sites) reported to be more successful than ordinary transplants or stumps method. However, there are attempts to propagate *S. robusta* through cutting or air-layering, which proved to be failed (Kadambi and Dabral 1954); though Chaudhari (1963) indicates the possibility of air-layering by suggesting few adjustments like selection of branch and rooting medium (hormone/s).

Another technique used in artificial regeneration is micropropagation (in vitro propagation) method, which is an important alternative to conventional propagation for a wide range of plant species including *S. robusta*. A benefit of micropropagation over the conventional methods is the production of large number of true-to-type planting material in short time and space. A reproducible protocol for mass multiplication from nodal explant has been developed in *S. robusta*. The study concluded Woody Plant Medium (WPM) with 1.0 mg L⁻¹ BAP + 0.5 mg L⁻¹ NAA is the best medium for shoot initiation and proliferation (Singh et al. 2014). The findings could be highly useful in species where natural regeneration fails completely or for propagation of threatened and endangered species declared by the International Union for Conservation of Nature (IUCN). Specifically, Kumar et al. (2018) successfully multiplied important Sal cultivars by resolving the challenges associated with in vitro selection procedure, helping to improve breeding methodologies. In other study on Sal, survival and growth was measured for the plantlets developed from seeds or in vitro methods. Results revealed that the performance of the seedlings was superior than the plantlets raised through in vitro methods, which indicated collection and sowing of seeds at proper maturation time is more important (Roy 2006).

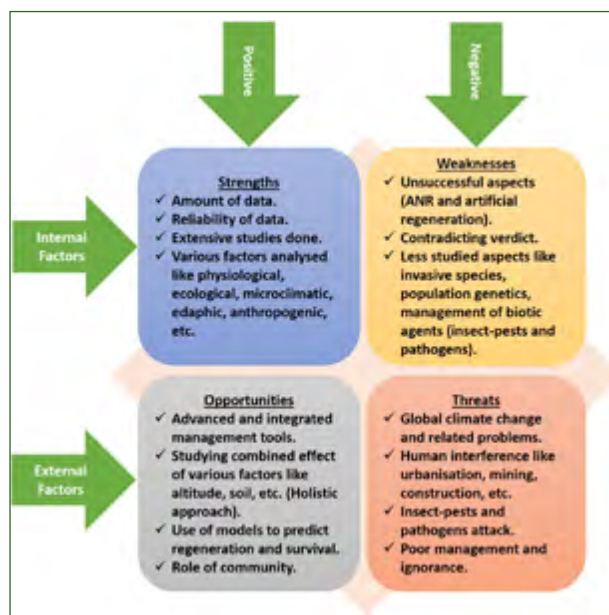
Decisively, all these studies have given a vast overview on the management of Sal forests to ensu-

re its better regeneration and explained numerous techniques largely used in the various regions across different nations. However, most of these techniques are of limited applications and confined to special situations. A wholesome viewpoint to safeguard the management forthcomings through SWOT analysis is explained in the next section.

Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis

The SWOT analysis comprises to identify Strengths, Weaknesses, Opportunities and Threats, for the strategic planning and management of a project / upcoming plan (Gurel and Tat 2017). Strengths and Weaknesses are the internal factors, whereas, Opportunities and Threats are the external factors affecting the project. It would help the investigator in creating the sound objectives and identifying the research goals. Herein, the SWOT analysis is used to discuss the available research work on *S. robusta* regeneration and to describe the less studied aspects (Fig. 4). Sal, being an economically and ecologically important tree species of tropical forests, has attracted people across the globe, such as silviculturist, ecologists, researchers, academicians, students, wildlife enthusiasts, foresters, tourists, etc. Study conducted on the Sal forests in south Asia depicted the health status, sustainability, *S. robusta* regeneration problem, and mitigation measures. In this review, adequate information on the Sal regeneration is gathered to depict the positive (Strengths) and negative (Weaknesses) factors of the previous research work; and further research requirement to fulfil the gaps with key discussion on the future prospects (Opportunities) and the associated problems (Threats)

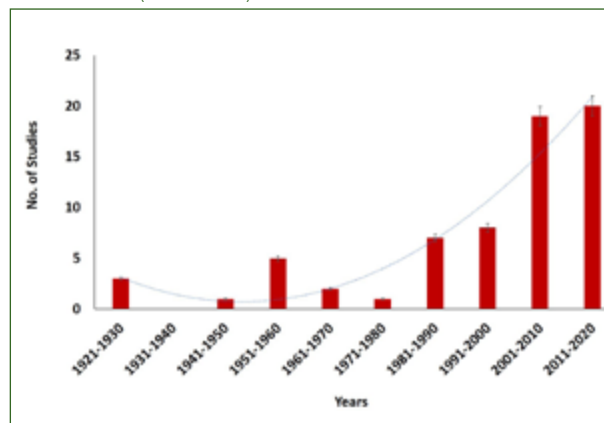
Figure 4 - SWOT analysis.



Strengths

Numerous studies (66 in Nos.) on Sal forest regeneration was conducted during early nineteenth century to present era (especially in the last two decades; 2001–2020) and generated plethora of chronological data on this species (Fig. 5). In the global scenario, forest management attention seems now to have been generally graduated from management for a single objective (regeneration of *S. robusta* in this regard) to a sustainable ecosystem approach, where whole forest is taken as a unit (Hausler and Scherer-Lorenzen 2001, Sayer et al. 2007). This is an attempt to incorporate principle of equity in forest resource utilization (Young 1992) with subsequent participation of different stakeholders for the conservation and management of the natural forest resources. A similar approach in case of Sal forest could yield much more sustainable management in solving the regeneration problem. Many studies analysed and depicted the major contributory factors like soil, physiology, microclimate, ecology, biotic, etc., which have been associated directly or indirectly to the regeneration problem of Sal. As most of the research work associated with Sal forest is on the regeneration status, causes of failure, silvicultural and physio-climatic justification to the problem, but the actual solution is yet to be unearthed.

Figure 5 - Quantified the century old status on the regeneration studies of Sal (1921-2020).



Weaknesses

Various aspects on Sal forest regeneration have been less studied or not found successful. One of the major weaknesses could be the ineffectiveness of the artificial regeneration methods, for instance ANR. Another problem was the association of *S. robusta* with other species viz., *C. viscosum*, as some studies referred to it as a good indicator, while a few others directed it as a bad associate for regeneration. This contradiction should be removed by conducting the detailed study on the association of *C. viscosum* with *S. robusta*. Another factor that got attention recently is the effect of invasive species namely, *Lantana camara* and *Phoenix sylvestris*; which are less studied in association of regeneration problem

faced by Sal forest. Further, due importance should be given to the statistical based sampling designs, which not only minimizes the errors but also generate authentic data for analysing the problem and future course of action. Importantly, research on the population genetics and tree improvement prospects is completely lacking for species which is very essential to formulate future strategies for conservation, management and sustainable utilization. Although, few regional reports on the genetic diversity of Sal is available from Nepal (Pandey et al. 2009) and Odisha, India (Surabhi et al. 2017); but in context to overall distribution of Sal in the countries *viz.* Bangladesh, Bhutan, India, Myanmar, the research is lagging and need to be statistically augmented.

Zenith of *S. robusta* representing the tropical forest might be in the verge of decline, as suggested by the ecological hypothesis. Globally, all-over South America, as in tropical Africa and Asia, the forest is retreating and a man-made landscape taking the place of the climax plant communities (Richards 1971). Thus, the role of conservation genetics seems to be much crucial to understand the missing link for the survival and existence of the species in this oriental region of the earth.

Opportunities

Opportunities include fulfilment of the current research gaps on the regeneration problem of Sal forests which have been studied in a fragmented way, besides drafting the future prospects and policy regimes for the sustainable maintenance of these biodiversity reservoirs. The weaknesses being discussed earlier can be converted into opportunities using several new conservation and management tools. Hence, an integrated management tool– Restoration Opportunities Assessment Methodology (ROAM) is worth mentioning here. It is a planning and decision-support methodology for identifying forest landscape restoration opportunities and strategies (including ANR) based on the conditions, objectives and resources available. The ROAM framework is adaptable, non-prescriptive, landscape specific and manifests itself in a bottom-up approach. It may also help to ensure that ANR is a part of the optimal balance of ecological and development benefits for the targeted landscapes (Chokkalingam et al. 2018). Importantly, *Taungya* system, sacred groves and ANR are some methods that would be improved using mass awareness of the situation by including community participation approach into the conservation measures (Niyogi 2018). Secondly, population genetic analysis through the use of molecular markers, such as Simple Sequence Repeats (SSR), Single Nucleotide Polymorphisms (SNP), Genotype-based Sequencing (GBS), etc., should be used to decipher the level of genetic diversity within and between the populations of *S. robusta* existing in south Asia.

We hypothesized that there might be areas with good regeneration and have superior genetic material, which will be required to be introduced into the areas having low level of genetic diversity. Thus, the selection of plus trees, provenance testing, creation of *in situ* and *ex situ* seed and clonal orchards, germplasm and field gene banks, will required to be strategized and implemented (Kedharnath 1984, Ruotsalainen 2014). Tertiary, there are various modeling techniques to predict tree survival and regeneration, which could be helpful to mitigate the regeneration problem of Sal forests. For example, some of these models have been used for regeneration prediction for several different species such as *Pinus sylvestris* L. (Pukkala and Kolstrom 1992), *Picea abies* (L.) Karst. (Kupferschmid et al. 2006), along with some general models for tree survival were also illustrated across the globe (Rose et al. 2006). Other aspects, such as altitudinal variations on Sal regeneration and community management of Sal forests can also be explored in detail. The impacts of associated species, soil, and other ecological parameters produce combined effect on the regeneration of Sal forest. Thus, combined correlation analysis of different factors would be highly valuable to understand and overcome the problem of Sal regeneration. Seed is one of the most important aspect in every species of production forestry and therefore seed parameters like germination, viability, dormancy, seed treatment, etc., must be deeply studied. Research gaps on seeds viability and seed anomalies (wing arrangement pattern, number of wings, wing size) were documented in the Shivalik region (Uttarakhand, India), and further needs to be explored. For instance, the increased number of wings in seeds have been attributed to areas with higher temperature ranges throughout the year and appeared to be an adaptation towards better innate seed dispersal mechanism of *S. robusta*. This selective advantage of phenotypic plasticity could be critical in knowing the natural regeneration mechanism and helps in enhancing the revival process of Sal seedlings at incipient stage (Sharma et al. 2019).

Furthermore, studies revealing molecular diagnosis to identify the biotic agents associated with the major diseases and insect-pests problem in the gregariously distributed Sal forests are not significantly conducted, and therefore need to be thoroughly examined. Importantly, while considering microorganisms into account, Tapwal et al. (2015) studies that the mycorrhizal associations significantly enhance the growth of *S. robusta* seedlings, where in ectomycorrhizal association provided the highest growth rate. Therefore, regeneration work should be taken into consideration with the possibility of using dual inoculations (both seed/seedlings and mycorrhiza/*Trichoderma*) of regeneration areas for better survival and growth rates. All these suggestive measures will help to overcome the regeneration problem.

Threats

Threats basically are the external factors which pose disadvantages to the research hypothesis and tried to be mitigated during the review. For example, the role of climate change on the regeneration of any species is very important; and if not managed properly, could cause a serious threat on the regeneration by many ways, namely advent of invasive species, change in species composition and structure, alteration in phenology, habitat loss and decline in quality of the gene pool. Unavailability of the genetic material i.e., germplasm resources for future research programs and non-incorporation of new ideas could also pose menaces. Another major threat being the inadequacy of the edaphic conditions which retards growth to a large extent. Usually, soil health is focused in agricultural studies, but similar status of woodland must be taken into account at the early stages of species regeneration in forest. Proper soil testing and subsequent nutrient percolation must be realized in the regenerated sapling areas with moisture retainment strategies (like mulching) to mitigate manageable threats, such as inadequacy of nutrients and moisture, surface dryness, etc. Additionally, disturbances occurring in forest areas often alters the environmental conditions by changing light availability and soil conditions (Fredericksen and Mostacedo 2000). These turbulences also influence the processes that either augment or decrease the ecological functioning of a Sal forest community (Sagar et al. 2003). Further, upsurge of land-based resources coupled with the commercial allure of Sal timber by the anthropogenic threats seem to be an imminent problem in the upcoming decades. Both natural and human caused instabilities, have significant level of influence on forest dynamics and diversity of *S. robusta* at local and regional scales (Ramirez-Marcial et al. 2001). These repercussions might be significantly enhanced by the biology of specific species (such as their life history traits, physiology and behaviour), which also influences the post-disturbance forest regeneration process (Lawes et al. 2007). Hence, proper policy must be formulated and implemented to safe-guard and fortify these areas, and research should be redirected towards conservation focused projects with keeping in mind the global call for sustainable development, which has been emphasized in the Brundtland report (United Nations 1987). Lastly and importantly, protocols required to be developed for integrated insect-pest and pathogens management systems (IIPPMS) in *S. robusta*. For instance, University of California Agricultural and Natural Resources (UCANR 2006), USA have developed robust protocols for IPM systems in case of short rotation species like eucalypts. Similar standard IIPPMS protocols should be developed for Sal insect-pests and pathogens, such as *H. spinicornis* (heart-wood borer), *P. theristhis* (root borer), *L. mathura*, *A. imparata* (defoliators), *I. shoreae*, *M.*

gordipes (horse-hair blight), *Xylaria tuberosa*, etc., which are directly or indirectly associated with die-back and other fatality conditions (Bagchee 1953). Such threats must again be addressed in a sustainable manner keeping in mind the ecological importance of these many biotic agents. Hence, appropriate methods and scientific-knowledge-base is obligatory to converge these threats into opportunities, which required a robust framework of collective research focused towards addressing the key issues and providing sustainable alternatives to them.

Conclusion

Appropriate regeneration status always remains a key essence for the sustainable forest management, but the disturbances cause turmoil of the forest area as a whole. In general, natural regeneration of a species determine the health status and classify the forest conditions, i.e., more the regeneration of a species, better the forest condition, and *vice versa*. Aiming towards the natural regeneration problem of *S. robusta* in south Asia, the foremost essence of this review is that collaborative research on regeneration for the proper management of Sal forests is required to reduce the adverse effects of the factors discussed in section 3. This review showed the distribution of Sal forest which is confined to south Asia (Fig. 2), where the world's one-fourth populations (24.89%) resides (Worldometer 2020). It means, there is heavy demographic load on the natural forests and Forest Genetic Resources (FGRs) of these geographical areas. Thus, to ensure its sustainable existence, immediate attention for its conservation and management is required (Agrawal et al. 2018). We invoke strict implementation of the policy decision with proper investigative mechanism put in place for combating the decline of this magnificent species. Conclusively, "Regeneration of Sal in India-A Symposium (1953)" advised mixed forest and broken canopy for the proper management of Sal forest wealth, which depends on the regeneration potential. The silvicultural operations, such as thinning at regular interval may be helpful to decrease excessive canopy and provide efficient light conditions for *S. robusta* seedlings and saplings. In accordance to that, studies highlighted in this review also suggested Irregular Shelter Wood System (ISWS) as the better silvicultural management tool in Sal forests. Research works done in natural and plantation Sal forests in a whole suggest that natural stands tend to have lesser IVI and density in shrub and herbaceous layers and subsequently show inadequate regeneration capacity (Srivastava and Vasishta 2017). Though ANR plots protect the regeneration area from wild animals but are easily accessible to the domesticated cattles, thereby reducing the efficiency of the system.

The regeneration of *S. robusta* depends on numerous factors, which might be considered for the better growth and development of Sal forest. Being an important timber yielding species, new and better silvicultural techniques should be developed along with continuous research programmes focusing on population genetics, tree improvement, association biology, phenology, ecological drifts, etc. The SWOT analysis specified in this paper, reveal the gaps and opportunities to work on new frontiers, which would be helpful for the sustainable management of Sal forest regimes in south Asia.

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