Understanding the impact of climatological shifts on forest-fire frequency and intensity in Simlipal Biosphere Reserve, Odisha, India

The Simlipal Biosphere Reserve is the second largest biosphere reserve in Asia occupying an area of 5569 km^2, located between 20°17′–22°34′N and 85°40′–87°10′E in Mayurbhanj district, Odisha, India. The Reserve houses 42 species of mammals, including the melanistic tiger (*Panthera tigris*), 29 species of reptiles, 231 species of avian fauna, 12 species of amphibians and more than 3000 floral species, including 94 species of orchids. The six main forest types in the Reserve are northern tropical moist deciduous forests, dry deciduous hill forests, northern tropical semi-evergreen forests, high-level sal forests, grasslands and savannah[1].

The lack of industrialization in the district has helped maintain the ecological stability of the region. However, the only source of ecological vulnerability is forest fire as evidenced by the recent wildfire which lasted for over two weeks and affected over one-third of the total area under the Reserve. Forest fires in the Simlipal landscape are not new. The transition phase between autumn and summer aggravates the chances of forest fire as the largely dominating deciduous vegetation results in a forest floor occupied by dense and dry leaf litter which is highly combustible, facilitating an ideal condition for natural forest fires[2]. These sporadic events behave like controlled fire, replenishing the essential soil nutrients and promoting regeneration of primary floral species[3]. However, 2021 marked a destructive wildfire causing large-scale biodiversity as well as timber loss. Edaphic factors, geological conditions and climatic parameters maintain the thin line between a controlled fire and a wildfire[4]. Any shift in climatic conditions of a region imposes magnified effects on the size, intensity, frequency and severity of forest fires in that region. Elevated temperature and long dry spells lead to extreme changes in the ecosystem, significantly degrading the forest habitat[5]. Essential factors which contribute to wildfires include vegetation stress, tree mortality, drought, disease outbreak and accumulation of combustible matter[6,7]. Climatological shifts as characterized by changes in temperature, humidity, rainfall and wind velocity combined with fuel accumulation magnify an annual controlled fire into a destructive wildfire. A study in North America underlined the rapid increase in the number of fire hotspots with increase in temperature and decrease in humidity[8]. Similar studies in southern Australia indicated the direct relationship of wild fire intensity with mean annual temperature and relative humidity[9].

We obtained the annual number of fire points based on Moderate Resolution Imaging Spectroradiometer (MODIS) data of Odisha from 2012 to 2021 (refs 10, 11). The data were transformed to make them suitable for comparison. We also obtained the annual mean temperature (°C) and mean relative humidity (%) of the study landscape for the same time period[12]. We compared the obtained datasets using Pearson's correlation and the resultant correlation coefficient was found to be 0.92, indicating a strong positive correlation between fire points and annual mean temperature. Similarly, correlation was tested for a number of fire points and relative humidity, wherein the value of r was –0.88, indicating a strong negative correlation. Thus, with increase in temperature and decrease in relative humidity, the number of fire points was found to increase (Figure 1).

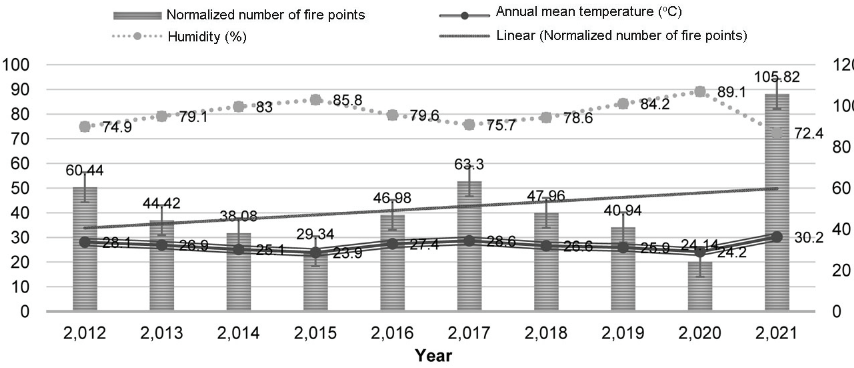

Figure 1. The number of fire points (data-transformed), annual mean temperature (°C) and relative humidity (%) of Odisha, India from 2012 to 2021. Data source: Number of fire points have been obtained from Mallapur[10] and Berrick[11]. The relative humidity and annual mean temperature data are obtained from Bikos[12].

Given the consistency in the number of forest fires occurring every year in the Simlipal landscape, the Forest Department may adopt modern techniques to reduce the chances of fire and minimize losses in case of an accidental outbreak. An important measure is to build fire-fighting reservoirs like underground cisterns or natural water reservoirs within or near the forested areas, since water is the primary means to fight forest fires. The functionality and accessibility of these reservoirs can be checked from time to time. The Forest Department uses fire-fighting maps at a scale of 1 : 50,000 using the Universal Transverse Mercator (UTM) geographic coordinate system. However, with advancements in satellite technology and aerial photography, more detailed district maps at a scale of 1 : 25,000 or 1 : 10,000 may be used[13]. Such maps would highlight all significant elements such as water reservoirs, fire breaks and fire lines. An example of such maps is in the Forest Rescue Service of Rhineland, Germany, wherein forest maps at a scale of 1 : 25,000 are being used. Lastly, detailed emergency and deployment plans can be effective to control fire outbreaks. In general, reduction in wildfire-induced losses is only possible through consideration of the overall climatic scenario of the country[14]. With the alarming rate of increase in global warming, the number of naturally occurring forest-fire incidences will keep increasing. As a preventive measure, the combustible content of Simlipal and similar landscapes can be cleared at regular time intervals, especially during the long, dry summers. This is because accumulation of leaf litter on the forest floor increases fuel load and aggravates the fire intensity.

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Frullania bolanderi Austin (Marchantiophyta: Jubulaceae), a rare, disjunct liverwort in the Himalaya

Genus *Frullania* is represented in India with 72 taxa, including 63 from the Eastern Himalayan localities[1], thus constituting an important part of the Indian bryoflora. During a recent exploration in Tawang district, Arunachal Pradesh, India, few plants of *Frullania* were identified as *Frullania bolanderi* Austin. This species has its main distribution in boreal North America[2–5] and Europe[6], while in Asia it has been reported from a few localities in Japan[6,7] and Russia[8–13]. The species thus shows a trans-oceanic disjunct distribution between North America and Europe[5]. A report of the species from Caucasus indicated that it may have further southward distribution[14]. Thus the present study from the Himalaya extends its range of distribution further southeastwards, possibly attributed to long-range dispersal mechanism as suggested by Frahm[15]. While discussing the disjunctive distribution of some North American species in Europe, Frahm[16] speculated *Frullania oakesiana* and *F. bolanderi* as possibly holarctic species rather than circumpolar. The current global distribution and the present study from the Himalaya confirm its holarctic distribution as speculated by Frahm[16].

An interesting aspect about *F. bolanderi* disjunction is that sexual reproduction in this species remains unknown, while asexual reproduction usually takes place through unique modified caducous leaves producing leaf gemmae and their *in situ* germination. Long-range dispersal is generally achieved best by spores, whereas vegetative dispersal places the vegetative reproducing structures or diaspores like vegetative propagules, gemmae, etc. close to the parent plant, generally in the same environment[17]. Studlar *et al.*[18] have concluded that some diaspores, including plant fragments, could travel with the help of wind into the atmosphere. Yet the living vegetative propagules, active fragments, gemmae, etc. may or may not be dormant and are least adopted to the conditions of the stratosphere. Pohjamo *et al.*[19] concluded that gemmae, at least the size of spores, can contribute to long-range dispersal. However, it is unclear whether a modified leaf gemmae, as reported in the case of *F. bolanderi*[20] (Figure 1 *e–g*), much larger than the size of spores, can withstand the conditions of long-range dispersal by wind. Further, in Indian plants, frequent *in situ* germination from leaf lobes and leaf lobules has been observed; a condition unsuitable for long-range dispersal through wind. Hence these factors make this case interesting for further studies to understand whether the disjunction of *F. bolanderi* should be attributed to long-range dispersal by wind or some other reason. One possible scenario could be the role of migratory birds. It is well known that migratory birds help in the long-range dispersal of higher plants through epi- or endo-zoochory; however, their role in the long-range dispersal of bryophytes was barely considered till recently, when Lewis *et al.*[21] for the first time provided evidence on the role of epi-zoochory by migrating birds in the long-range dispersal of bryophyte diaspores. Boch *et al.*[22] reported that bryophyte spores and vegetative reproductive structures can withstand ingestion by slugs, hence supporting the endo-zoochory theory. Similarly, endo-zoochory of large bryophyte fragments by water birds has been reported recently[23]. Every year, India hosts a large number of migratory birds from various parts of the globe. A number of birds have been reported to migrate from Europe and Russia to India through the Central Asian flyway. The Siberian crane is an excellent example of a migratory bird which travels annually from Russia to India. In the light of these findings, the dispersal of asexual gemmae of *F. bolanderi* from Europe or Russia to India through migratory birds, though not observed directly in the present study, seems more appropriate than purely by wind. Further studies may provide a new angle to the Himalayan disjunction of bryophytes.

Taxonomic enumeration.

Frullania bolanderi Austin, *Proc. Acad. Nat. Sci. Philadelphia* 21: 226. 1869 (Figure 1).

Plants form reddish-black patches, growing prostrate and closely appressed on bark with some apical, upright flagelliform branches with caducous leaves, small to medium sized, up to 13 mm long, 0.6 mm wide, branching 1–2-pinnate. Stem differentiated into cortex and medulla. Leaves imbricate, incubous, ovate, dorsal lobe 0.19–0.42×0.24–0.56 mm in size, dorsal margin arched, crossing and growing beyond the stem width. Leaf cells thick-walled,