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Research Article

Stay on trails: Detrimental effects of recreational activities on soil compaction and infiltration

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Abstract

Bromo Tengger Semeru National Park (BTS-NP) in East Java, Indonesia showcases a breathtaking volcanic landscape and cultural allure, drawing hundreds of thousands of domestic and international visitors. Recreational activities involving human and animal trampling and motorized-vehicle traffic caused soil disturbance along their networks of paths, trails, or roads, potentially having a detrimental long-term effect on the tourism industry and environmental services provided by the national parks. However, the extent of the impact of these disturbances on soil properties remains unclear. This study assessed the impact of different disturbance intensities, consisting of undisturbed locations as a control (zone 1), low to medium- (zone 2), and high- (zone 3) disturbance intensities on five different BTS-NP tourism hotspots, including Entrance Wonokitri (EW), Whispering Sand (WS), Parking Temple (PT), Teletubbies Hill (TH), and Entrance Bromo Stairs (EB), on soil properties, including soil compaction represented by soil penetration resistance, and soil infiltration. This study revealed that the higher severity impact of recreational activities on soil compaction was parallel with higher disturbance intensity, particularly in EW and TH. In these particular locations, higher soil compaction is significantly linked to lower soil infiltration, thus needing extra attention and protection. Meanwhile, in WS, PT, and EB, soil infiltration was more controlled by the establishment of a cemented topsoil layer consisting of mixed sand, sulfur, and water. Better management strategies, such as the use of proper trails and road infrastructures, particularly on EW and TH, might be relevant to minimize the impact of recreational activities on these ecologically, economically, and culturally important areas.

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Introduction

National parks are established with the primary goal of preserving both natural and cultural resources (Dudley, 2008). However, their integrity is jeopardized by human activities, such as the (un)intended introduction of non-native species and the increasing intensity of recreational and tourism activities (Wolf et al., 2019). The latter contributes to direct monetary benefits for the national park manager. But, at the same time, it also results in persistent and escalating challenges in protecting nature from human-induced ecosystem degradation, including in Bromo Tengger Semeru National Park in Indonesia. Recently, Bromo Tengger Semeru National Park (BTS-NP) in Indonesia was acclaimed as one of the World's Most

Beautiful National Parks in the world by Bounce travel agency, which is based in San Francisco, California, United States (https://usebounce.com/blog/beautiful-national-parks). Located in East Java, Indonesia, BTS-NP showcases a breathtaking natural landscape, predominantly defined by its dynamic active volcanic scenery. Beyond its natural allure, the national park has evolved into a prominent destination for cultural and spiritual tourism in the last decade, drawing visitors from both domestic and international spheres. Contributing to Indonesia's government vision to make Indonesia as world-class destination for tourism, with their determined target to introduce the "New 10 Bali" to the world community, consisting of Toba Lake, Tanjung Lesung, Tanjung Kelayang, Borobudur Temple, Pulau Seribu, Wakatobi, Mandalika, Morotai, Labuhan Bajo, and Mt. Bromo (Firdaus et al., 2022). The Tengger Caldera, a remarkable element of BTS-NP, featuring the well-known active volcano of Mt. Bromo, stands as an iconic focal point within the national park. With an estimated annual visitation exceeding hundreds of thousands of tourist per year and even reaching over a thousand visitors per day during special occasions like Upacara Yadnya Kasada (a customary ceremony to praise gods and ancestry), involving more than 300 four-wheel-drive (4WD) vehicle and hundreds of motorcycles, the site's popularity underscores its significance. Unfortunately, the large influx of visitors, particularly instances of visitors venturing outside of designated trails or routes, has caused harmful effects on the fragile natural ecosystems of the national park. Irresponsible visitor's behavior often leads to the establishment of new and unauthorized complex networks of illegal paths, trails, or roads, including those created by human and animal foot tramplings, mountain bikes, and motorized-vehicle traffic, contributing to an array of ecological disturbances and degradation (Figure 1).

Figure 1. Between 2018 and 2023, the irresponsible behavior of visitors going off-trails has resulted in the establishment of new complex networks of illegal paths, trails, and roads (as observed in aerial images captured from Google Earth).

This unfavorable condition is exacerbated by the absence of fixed fences or elevated walkways specially designed to protect nature from trespassers, thereby posing a significant threat to the sustainability of the ecosystem. The disturbances induced by recreational activities have caused disruptions in soils properties in the form of soil compaction, erosion, and water pollution, as well as vegetation biodiversity loss and disturbance to wildlife populations, which potentially have a detrimental long-term effect on the tourism industry and environmental services provided by this ecosystem (Webb, 2002; Lei, 2004; Hill and Pickering, 2006; Ouren et al., 2007; Pickering and Hill, 2007; Mingyu et al., 2009; Lucas-Borja et al., 2011; McNearny et al., 2012; Ballantyne and Pickering, 2015a; Hakim and Miyakawa, 2018; dos Santos Pereira et al., 2022). Hence, it becomes a crucial subject for ecological impact study. Beyond the detrimental impact on vegetation cover that is visually visible in the park (as shown in Figure 1), the ongoing disturbances are also suspected to contribute to the increased frequency of flash floods in the Tengger Caldera area (Figure 2).

Figure 2. Flash flood frequently occur inside the Tengger Caldera, leaving visitors trapped after heavy rainfall.

The Public speculated that these unfortunate events were caused by the soil compaction due to applied pressure or loading, which could reduce soil porosity and soil infiltration, and consequently disrupting the water balance of the region. Soil surface crusting and compaction reduce soil pore connectivity, inhibiting soil infiltration and increasing the potential of surface runoff up to 50% of the total rainfall (dos Santos Pereira et al., 2022). Surface runoff occurs when the infiltration rate is lower than the precipitation rate (hortonian overland flow). This unfavorable condition is also linked to the decline in the clean water supply for the nearby community, considering that this area potentially serves as one of the catchment areas for local springs (Sukojo, 2003). Yet, a direct field measurement and assessment of the specific impact of tourism-related activities on soil quality, especially soil compaction and infiltration, has not been conducted.

This research aimed to address this knowledge gap by examining whether varying disturbance intensities, as consequences of recreational activities, result in differing impacts on soil compaction and water infiltration. This study hypothesized that the disturbance induced by recreational activities involving human and animal tramplings, and motorized-vehicle traffic, leads to soil compaction and slower water infiltration.

Materials and Methods

Study area

The study was conducted within the Tengger Caldera, located in East Java, Indonesia (Figure 3). The Tengger Caldera is part of the Bromo Tengger Semeru National Park (S 7°51′-8°11′; E 112°47′-103°10′; 750–3676 m a.s.l), which has an annual precipitation average of 6,600 mm and temperature ranges from 3°C to 22°C.

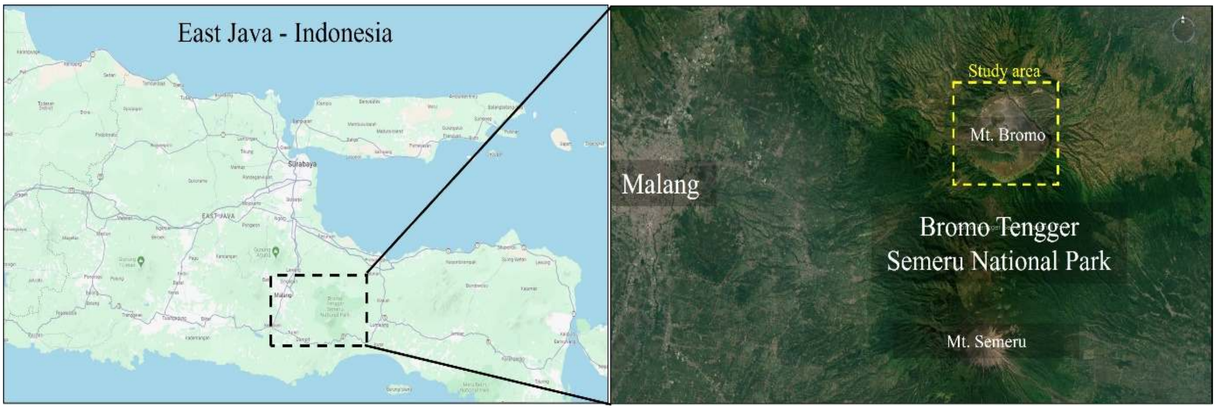

Figure 3. The Tengger Caldera is situated in the proximity of Mt. Bromo, within The Bromo Tengger Semeru National Park in East Java, Indonesia (map captured from Google Maps).

The Tengger Caldera area is characterized by two distinct types of parental materials such as Tengger Volcanic Sand (Qvs) and Bromo Volcanic Rock (Qvb). Qvs comprised of volcanic sand, bombs, and pumice, while Qvb consisted of volcanic breccia, lava, tuff, tuff breccia, and lahar. Differentiating these materials in the field can be challenging, particularly due to the overlapping deposits from Mount Bromo's regular eruptions. The Tengger Mountains, with their rich volcanic history starting around 1.4 million years ago, form the Bromo-Tengger Complex, characterized by multiple volcanic bodies and a series of calderas, culminating in the active Bromo volcanic cone. The Tengger Caldera, surrounding stratovolcanoes and cinder cones, features areas with varying slopes: flat terrains with 0-3% slopes at locations like Teletubbies Hill (TH) and the Parking area close to the Temple (PT), and more inclined areas with 3-8% slopes at Whispering Sand (WS) and Entrance Wonokitri (EW), while the slopes at the lower flanks of Bromo Stairs (EB) are steeper, between 15-25%. This landscape is covered with loose sand deposits from eruptions, highlighting the area's complex geological dynamics and the historical significance of Bromo's eruptions, which have shaped the landscape and occasionally impacted local agriculture.

The Tengger Caldera is exceptionally important for the region's recreational industries, with many local people depending on tourism-related activities for their livelihoods. Local natural attractions include the infamous Mt. Bromo (2329 masl), Whispering Sand ("pasir berbisik"), Savanna, and Teletubbies hill. For cultural attraction, there is a Hindu Temple, 'Pura Luhur Ponten' which organizes the annual Yadnya Kasada Ceremony to praise the gods and ancestry, attracting thousands of visitors during this activity. During this ceremony, Tenggerese people climb up to the Mt. Bromo crater to make offering of fruit, rice, vegetables, flowers, and sacrificial livestock such as goats and chickens to the mountain gods by throwing them into the Mt. Bromo crater.

Field measurements were conducted during the dry season of 2018 in the inner plains of the high and steep cliff of Tengger Caldera, which spans around 5290 hectares and is renowned as the 'Sea of Sand' ("lautan pasir"). This location was selected due to its status as a prominent tourism 'hotspot' within BTS-NP. The soil in the study area, characterized by poor soil structure development, primarily consists of thin layers of coarse to fine-size sand particles, indicating the frequent deposition of volcanic ash from Mt. Bromo eruptions. Additionally, some parts of the area also show signs of sulfur deposition on the soil.

The Sea of Sand and Savanna ecosystems are typified by the prevalence of densely packed *Imperata cylindrica*, complemented by other herbs and shrubs genera such as Panicum, Pennisetum, and Andropogon, as well as several woody trees including Casuarina, Acacia and Pine (Ayunin, 2010; Hakim and Soemarno, 2017), These herbaceous species undergo flourishing growth during the rainy season. Notably, certain herbs in this ecosystem exhibit ephemeral characteristics, completing their life cycle in less than a month, while non-ephemeral herbs persevere through the dry season in the form of tubers (Sukojo, 2003). Annual forest fires are also an important factor affecting the ecosystem dynamics in this area.

Site selection and research approach

The selection of observation points was based on two primary factors. Firstly, the selected locations were determined based on pre-identified tourism hotspots within the Tengger Caldera (Figure 4), including 1) Entrance to the Tengger Caldera from the Wonokitri district (EW), 2) Whispering Sand (WS), 3) Parking area close to the temple (PT), 4) Teletubbies Hill (TH) or Lembah Watangan, and 5) Entrance to Mt. Bromo crater stairs (EB).

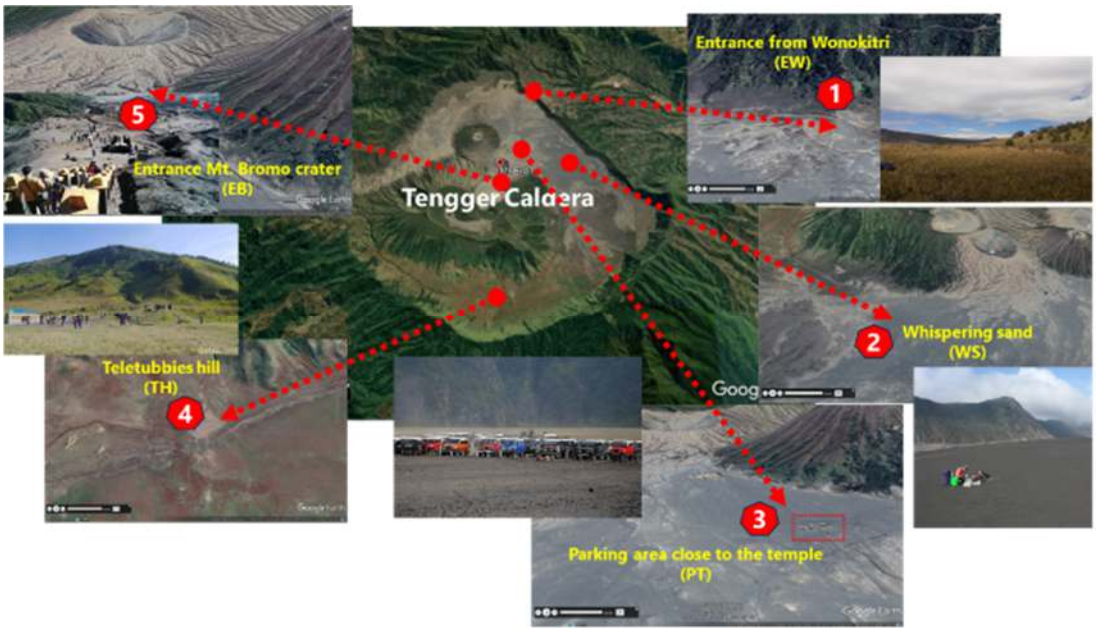

Figure 4. Site selection for field measurements was determined based on pre-identified tourism hotspots within the Tengger Caldera, including (1) the Entrance to Tengger Caldera from Wonokitri (EW), (2) Whispering sand (WS), (3) Main parking area close to the temple (PT), (4) Teletubbies hill or Lembah Watagan (TH), and (5) Entrance to Mt. Bromo Crater (EB).

The entrance to the Tengger Caldera from the Wonokitri Village (EW)

This area is situated beneath the steep ring of the Tengger Caldera near Wonokitri Village. This area serves as the entry point for all tourist vehicles, including horses, mountain bikes, motorbikes, and 4WD cars, into the Tengger Caldera area. Characterized by relatively flat terrain, the area features short vegetation, predominantly in the form of grass and shrubs. The soil type in this location is identified as Entisols, with an additional characteristic of initial development toward Andisols. At the topsoil, a layer of consolidated volcanic ash and sand exists. Furthermore, pumice rocks intermixed with coarse sand were identified at various points within the area (Figure 5a).

The whispering sand (WS)

The whispering sand ("pasir berbisik") is an area that is dominated by layers of coarse and fine sand resulting from repeated deposits of pyroclastic materials ejected during Mt. Bromo eruptions (Figure 5b). Within the soil profile, solid layers consisting of compacted fine sand (tuff) are prevalent. Vegetation is nearly absent in this section, with only scattered patches of grass and shrubs observed at certain points.

The parking area close to the temple (PT)

The PT serves as the primary trail and road access and parking facility for all motorized vehicles visiting the Temple, Mt. Batok, and the Mt. Bromo crater. The soil layers in this Entisol consist of coarse pyroclastic materials, tuff, pumice, sand, and ash deposited from frequent Mt. Bromo eruptions, which have undergone consolidation (Figure 5c). Comparable to the conditions observed in WS, no vegetation is present in this area except for small patches of grass or shrubs.

The teletubbies hill (TH)

Teletubbies hill, also locally known as Lembah Watangan, is a hilly area covered with grass and shrub vegetation, along with scattered trees at specific locations. This area is regularly visited by tourists due to the picturesque beauty of its green, hilly landscape. Inevitably, numerous illegal paths, trails, and roads have been formed by irresponsible visitors, causing disturbance to the ecosystem. Located to the east and relatively distant from the Mt. Bromo Crater, this area receives fewer deposits of pyroclastic materials from Mt. Bromo eruptions compared to the WS and PT areas. The Entisol soil layer in this area has undergone further pedogenesis processes (towards Andisol soil types) compared to other locations, featuring thicker soil horizons with a range of coarse to fine sand materials (Figure 5d). The presence of vegetation also influences soil pedogenesis processes. Soil organic carbon from vegetation litter and root development, directly and indirectly, supports the formation of soil aggregates and macropores.

The entrance to Mt. Bromo crater stairs (EB)

This is the most frequently visited area within the Tengger Caldera. The observation point was situated directly below the stairs leading to the Mt. Bromo Crater. The terrain is relatively undulating, and in the topsoil, a layer of hard yet fragile soil with a reddish-white coloration was found, resulting from the cementation of a mixture of water, sand, ash, and sulfur (Figure 5e). The Entisol here receives frequent depositions of pyroclastic materials from Mt. Bromo eruptions. Vegetation, in the form of scattered grass and shrubs, was present only at certain locations.

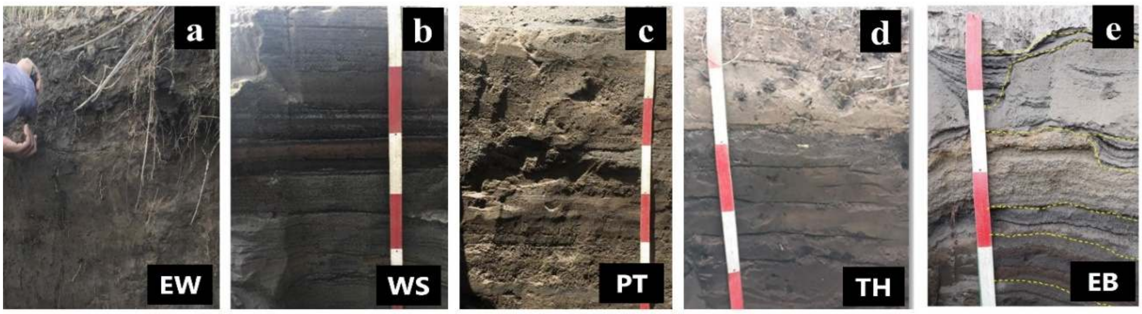

Figure 5. Soil profiles of (a) Entrance Wonokitri (EW), (b) Whispering Sand (WS), (c) Parking area Temple (PT), (d) Teletubbies Hill (TH), and (e) Entrance Mt. Bromo stairs (EB).

The second factor pertains to the intensity of disturbances, categorized as follows: Zone 1: undisturbed/natural condition (distance of >100 m from the main paths, trails, or roads); Zone 2: low-medium intensity disturbance (within the distance of 50-100 m from main paths, trails, or roads); and Zone 3: high-intensity disturbance (inside main paths, trails, or roads), caused by human and animals tramplings, mountain bikes, and motorized-vehicles traffic. The schematic diagram of different disturbance intensity zonation is shown in Figure 6.

Field data collection

Two and three replicate plots, each comprising five locations and three zones (a total of 30 and 45 measurement points), were established to study the effects of soil disturbances on soil compaction and soil infiltration, respectively, in different tourist hotspots inside the Tengger Caldera.

Soil compaction was assessed through the soil penetration resistance indicator using a hand penetrometer (Adedokun et al., 2023). A hand penetrometer with a 15 cm rod length was horizontally pressed into the soil layers to measure the force of compaction (MPa) necessary for full penetration. Soil penetration resistance was measured at 0, 20, 40, 60, 80, and 100 cm soil depths, with three measurement points for each layer (Figure 7). All measurements were conducted under the field capacity soil moisture conditions.

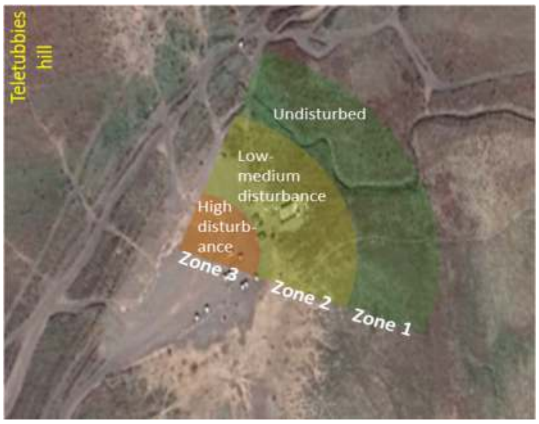

Figure 6. The disturbance intensity zonation at Teletubbies hill: zone 1 (undisturbed), zone 2 (low-medium disturbance intensity), and zone 3 (high disturbance intensity).

Figure 7. Soil penetration resistance measured with a hand penetrometer at six different soil depths of 0, 20, 40, 60, 80, and 100 cm.

Soil infiltration was measured using a double-ring infiltrometer following the falling head method (Figure 8). The infiltrometer rings were inserted 15 cm into the soil and filled with water. The speed of water infiltration was then measured until the infiltration rate reached a constant value (approximately 1-2 hours) (Saputra et al., 2020). Soil infiltration was expressed in water volume per ground surface and per unit of time (cm h^{-1}). Quasi-steady state infiltrability was subsequently estimated by means of curve fitting to Horton's equation using SigmaPlot 14.5 edition (Saputra et al., 2022).

Statistical analysis

To evaluate the effect of disturbance intensities and sampling locations (tourist hotspots) on soil compaction (represented by soil penetration resistance) and soil infiltration, This study used two-way ANOVAs, followed by Tukey's HSD (honestly significant difference) post-hoc tests. Statistical differences were declared significant at $\alpha = 0.05$ level. All the combinations of two-way interaction was included since it improved the model fit that was decided based on the Akaike Information Criterion (AIC) value. Linear regressions were performed to explore the relation between soil penetration resistance and quasi-steady state soil infiltration. All statistical analyses were performed in R 4.2.3 (R-Core-Team, 2023).

Figure 8. Soil infiltration was measured using a double-ring infiltrometer following the falling head method.

Results

Effect of disturbance intensity on soil penetration resistance

Generally, soil penetration resistance (representing soil compaction) increased with soil depth, as observed in the undisturbed area (zone 1). However, disturbances from tourist activities altered the pattern and led to a higher soil penetration resistance, particularly in the first 0-40 cm soil depth. A clear pattern of increased soil penetration resistance was observed with the increases of disturbance intensities, and the magnitude of the impact differed among locations (Figure 9).

The most noticeable negative impact was particularly evident in EW and TH. In EW, the average soil penetration resistance increased from 1.3 MPa in zone 1 to 2.3 and 4.1 MPa in zones 2 and 3, respectively. A similar pattern was observed in TH, where the average soil penetration resistance increased from 1.6 MPa in zone 1 to 1.8 and 2.6 MPa in zones 2 and 3, respectively. Meanwhile, in WS, PT and EB, an interesting pattern emerged. The low to medium intensity disturbance in zone 2 displayed lower soil penetration resistance compared to the undisturbed (zone 1) and high-intensity disturbance (zone 3), indicating that human and animal tramplings in this particular location slightly reduced the soil penetration resistance. However, the high intensity disturbance (zone 3) in PT and EB increased the soil penetration resistance.

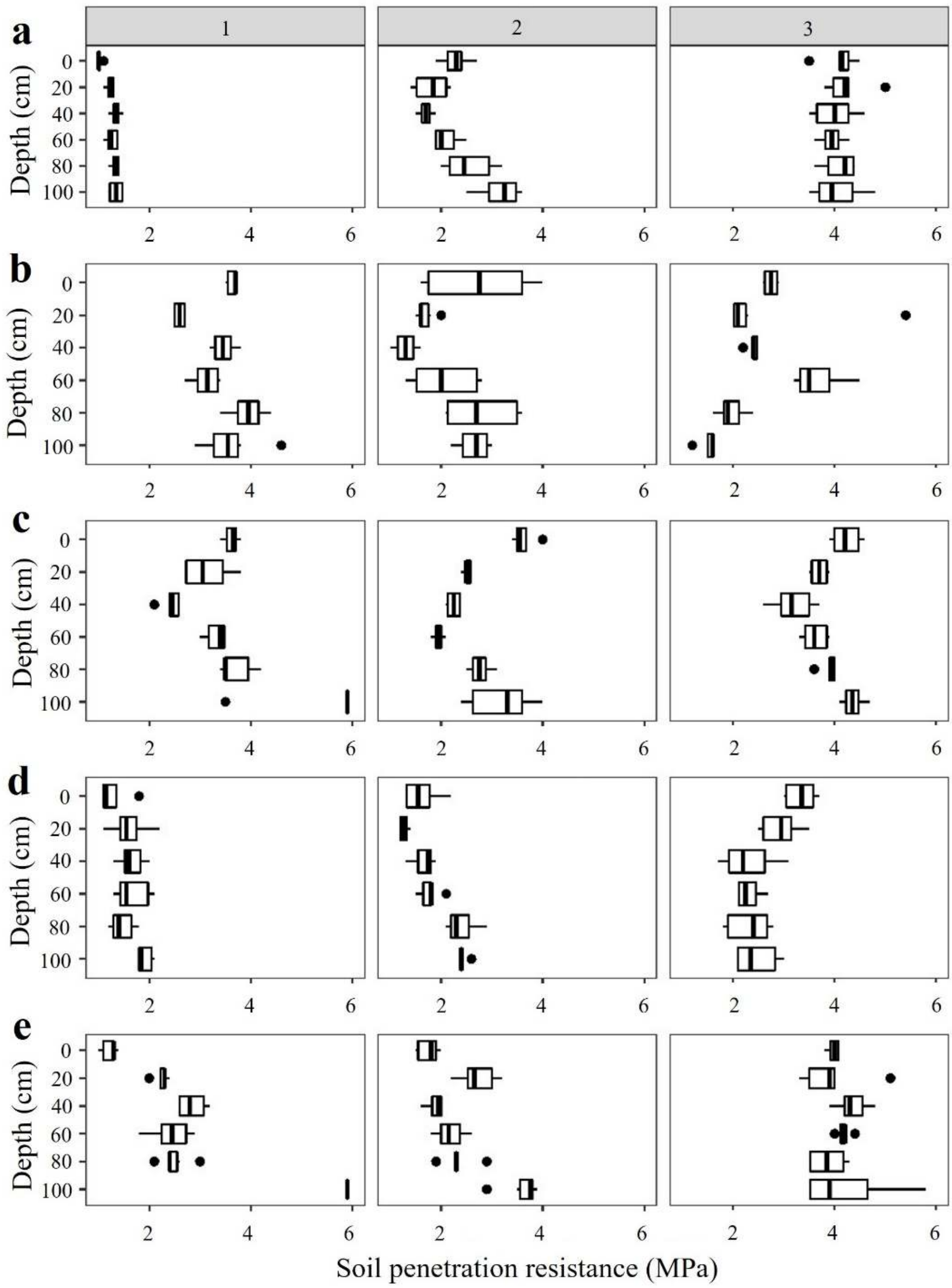

Figure 9. Soil penetration time resistance boxplot distribution across Entrance Wonokitri (a), whispering sand (b), parking temple (c), teletubbies hill (d), and entrance Bromo stairs (d); undistrubed/natural condition (zone 1), low-medium intensity disturbance (zone 2), and high intensity disturbance (zone 3).

Effects of disturbance intensity on soil infiltration

While its impact on other locations was insignificant, soil disturbance in TH and EW drastically reduced soil infiltration (Figure 10). In TH and EW, high intensity disturbance in the main trails (zone 3) contributed to 25- and 6.5 times lower soil infiltration than in undisturbed conditions (zone 1), respectively. Meanwhile, low to medium disturbance intensity (zone 2) only marginally reduced soil infiltration. Excluding WS, apparently, the minimum threshold of soil infiltration rate in all locations was less than 4 cm h^{-1}, as indicated through the infiltration rate values in the highly disturbed zone. Simple regression analysis indicated that higher soil penetration resistance was significantly linked to lower soil infiltration (R^2= 0.36, p<0.001). However, the small coefficient determination (R^2) value indicated that there were other confounding factors affecting lower soil infiltration (Figure 11).

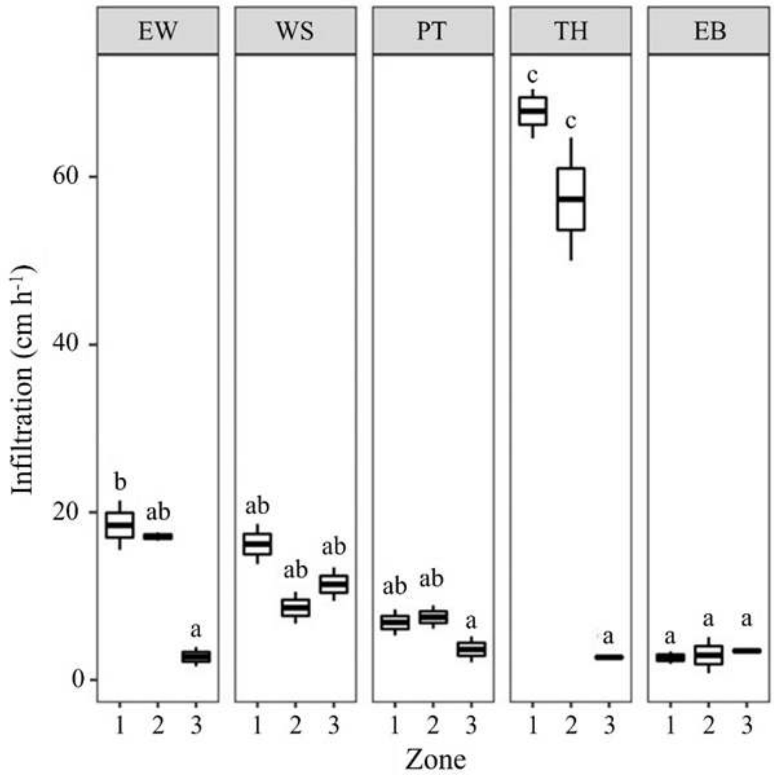

Figure 10. Soil infiltration rate in various locations and three different zones (EW=Entrance Wonokitri, WS=Whispering Sand, PT=Parking Temple, TH=Teletubies Hill, and EB=Entrance Bromo Stairs; Undistrubed/natural condition (zone 1), low-medium intensity disturbance (zone 2), and high intensity disturbance (zone 3). Different letters indicate significant differences between locations and zones ($p \leq 0.05$).

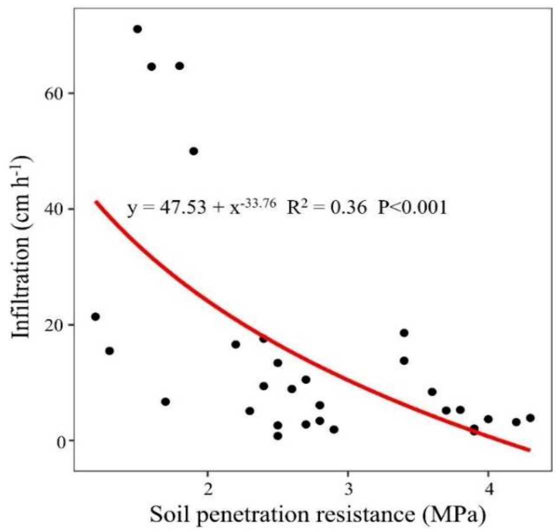

Figure 11. Relationships between soil penetration resistance (as an indicator for soil compaction) and soil infiltration rate within all locations and zones

Discussion

Tourism activities partly contributed to the soil compaction and lower soil infiltration

This study showed how human and animal tramplings, mountain biking, and motorized-vehicle traffic, as part of recreational activities, have contributed to soil compaction as indicated by increases in soil penetration resistance. As a result, soil infiltration, which is known to be an important ecosystem service provided by this ecosystem, has declined, most prominently on the more developed soil of EW and TH. The soil infiltration reduction in these two locations (EW and TH) is significantly related to the increase in soil penetration resistance, as the direct impact of higher disturbance intensity from recreational activities. A similar result was reported by Lei (2004), who found that human recreational activities significantly increased soil compaction and bulk density, and reduced soil porosity. Other recreational activities, such as campsite also significantly increased soil compaction by 37% compared to the control soil (Adedokun et al., 2023). Meanwhile, Webb (2002), through his research in the sand-dominated soil texture of the Mojave Desert, found that large-scale military maneuvers in the past, involving human trampling to tank traffic, caused soil compaction and required decades to centuries for recovery.

EW and TH are situated relatively far from Mt. Bromo, and thus have less ecological disturbance frequency from Mt. Bromo eruption than other locations. This favourable condition, supported by the vegetation living above it, allows the soil pedogenesis process in these areas further advanced, as indicated by its more developed soil structure. Developed soil structure, indicated by the abundance of soil macropores, facilitates faster soil infiltration (Saputra et al., 2022). However, the established soil macroporosity in this particular location was not sufficiently supported by stronger soil aggregate stability. Consequently, the soil macropores were relatively easy to collapse by disturbances from tramplings and vehicle traffic, thus reducing soil permeability (Cambi et al., 2015). By comparing the infiltration data between zones, this study found an indication that the disturbance originating from human and animal tramplings in zone 2 was insignificantly different from the undisturbed condition. Yet, when the disturbance originated from all possible disturbance sources (humans, animals, and motorized vehicles), the impact was prominent. However, the effect of human and animal tramplings could slowly increase over time relative to motorized vehicle traffic, as reported by Lei (2004) through their research in the Coleogyne shrubland of Kyle Canyon in southern Nevada.

In WS, PT and EB, where the soil was less developed, the disturbance from recreational activities affects the soil penetration resistance but does not directly impact the infiltration rate. There was no significant soil infiltration difference between undisturbed and disturbed soil in this particular area. The plausible explanation for that was that the infiltration rate was highly controlled by the existence of infiltration-inhibited a hard and semi-impermeable layer that developed from the mix of water, sand, and sulfur that covered the soil surface (author pers. obs.). These processes were less likely to occur in EW and TH, given their location relatively far from Mt. Bromo, than WS, PT, and EB. The relative distance to Mt. Bromo determined the level and frequency of direct ecological disturbance from pyroclastic materials deposition during the eruption. The difference in frequency of disturbance is transformed into different soil pedogenetic processes such as soil aggregate and macropore development. The existence of vegetation in EW and TH might also contributed to preventing that layer to form.

Management implications

Despite growing visible evidence (such as the frequent flash flood and loss of vegetation canopy cover) that tourism activities are having an adverse impact on this special ecosystem, the public and national park management continues to extensively use Tengger Caldera for recreational activities. The increasing number of tourists in the area, including irresponsible visitors, could result in more ecosystem disturbances and consequently present an increasing management challenge. However, given its important source of income for the government, and particularly the local community, the closure of this nature-based tourism is not realistic. In the BTS-NP area, management plans prioritize the protection and conservation of the natural ecosystem heritage. Current management has already limited access for visitors to visit remote or sensitive areas. Additionally, during the Yadya Kasada Ceremony, all motorized vehicles are prohibited from entering the Tengger Caldera, allowing the ecosystem to recover. However, these practices seem insufficient to halt the decline in ecosystem quality and services. It is imperative for the BTS-NP manager to educate local stakeholders and visitors about the ecological consequences of soil compaction and reduced soil infiltration on the landscape water cycle. With this knowledge, they may be more likely to voluntarily minimize soil disturbances by staying within established paths, trails, and roads. Collaboration between national parks managers and local communities might also help clarify differing stakeholder aspirations and intentions in regard to future tourism activities development (Newsome et al., 2016).

Volcanic soils developed on ashes and other pyroclastic materials are friable and have low densities, thus intrinsically susceptible to soil compaction (Cambi et al., 2015). As the most susceptible locations to soil disturbance within the other, EW and TH require extra protection or even total restriction for tourists to access outside the designated paths, trails, or roads. Further spatial segregation (Wolf et al., 2019), such as the use of trails infrastructures of raised walkways constructed from steel or wooden slats that successfully implemented in the Australian Alps (Hill and Pickering, 2006; Ballantyne and Pickering, 2015a; Ballantyne and Pickering, 2015b), might be relevance to minimize the impact of recreational activities on ecosystem degradation. Prioritizing protection against severe vegetation cover loss, as a negative impact of recreational activities, is also crucial (Mingyu et al., 2009; Ballantyne and Pickering, 2015b; Jägerbrand and Alatalo, 2015; Feng et al., 2019; Barros et al., 2020).

Research limitations and future works

This current field research survey approach is unable to separate the impact of human and animal trampling, mountain biking, and motorized vehicles on soil properties. However, these results can serve as scientific evidence and an early warning of ecosystem degradation affected by the tourism-related activities in this particular area. Further systematic research and experiments involving different disturbance origins and intensity levels of humans, animals, mountain bikes, and motorized-vehicle (motorbiked and 4WD cars), covering both wet and dry seasons (Mingyu et al., 2009) are urgently needed to compare their specific impacts on soil properties and its other ecological functions. This comprehensive information could be useful for the national park manager to develop more effective management strategies for protecting these economically, ecologically, and culturally important areas.

Conclusion

In conclusion, this study demonstrates the significant impact of recreational activities on soil properties within the study area. These activities, involving human and animal trampling, and motorized vehicle traffic, have resulted in soil compaction, evident from increased soil penetration resistance, with varying degrees of compaction depending on the severity of disturbances. The correlation between soil penetration resistance and lower soil infiltration highlights the complex interplay between soil properties affected by recreational activities. Among all tourism hotspots, Entrance Wonokitri (EW) and Teletubbies Hill (TH) emerged as the most vulnerable locations to soil disturbance, highlighting the need for enhanced protection measures in these areas. To mitigate these impacts, implementing appropriate trails and road infrastructures is recommended.

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