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UAV Inventory of the Last Remaining Dragon Tree Forest on Earth

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Abstract: The last remaining Dragon Tree Forest on Earth survives on a small plateau (Roqeb di Firmihin) in Socotra Island (Yemen). The Socotran Dragon's Blood Tree (*Dracaena cinnabari* Balf. f.) is endemic to the Socotra Archipelago UNESCO World Heritage Site. Being a culturally important and endangered tree species, its conservation is a priority. Despite this, a complete inventory of the Firmihin *Dracaena* forest (14.9 km^2) has never been attempted before. We applied the use of unmanned aerial vehicles (UAVs) for the first time in conserving the Socotran Dragon's Blood Tree. A pair of UAVs (small drones) were used during field surveys in 2021 to spatially describe individual tree positions, tree density, mortality, and the forest age structure. Aerial images were processed into a single orthophoto image of high spatial resolution (8 cm/pixel) used for detailed analysis. We applied image-enhancement techniques, used object-based classification, and corrected every entry manually during the inventory process. In total 35,542 individual living trees and 2123 uprooted trees were inventoried. The mean age of the forest, based on crown age (derived from crown size) was estimated at an average of ca. 300 years (291.5 years) with some individuals older than 500 years. Our analysis reveals that the trajectory of recent cyclones and the average direction of fallen trees in Firmihin are correlated, suggesting that intensified winds (as a result of global warming) catalyze the decline of the overmature forest. Our study illustrates the use of UAVs in collecting crucial data for the conservation and threat assessment of endangered tree species in Socotra, and regular drone inventories could be applied (e.g., after future cyclone events or landslides) to better evaluate the status of these vulnerable island ecosystems.

Keywords: Socotra; *Dracaena cinnabari*; Firmihin; UAV inventory; conservation

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Citation: Vahalík, P.; Van Damme, K.; Nétek, R.; Habrová, H.; Tulková, J.; Lengálová, K.; Zejdová, L.; Avoiani, E.; Maděra, P. UAV Inventory of the Last Remaining Dragon Tree Forest on Earth. *Forests* **2023**, *14*, 766. https://doi.org/10.3390/f14040766

Academic Editor: Arturo Sanchez-Azofeifa

Received: 28 February 2023
Revised: 14 March 2023
Accepted: 2 April 2023
Published: 8 April 2023

1. Introduction

There are few remaining arborescent Dragon Tree species in the world. Dragon Trees (or Dragon's Blood Trees) of the genus *Dracaena* (Asparagaceae) have a disjunct distribution, including several insular taxa [1]. They are generally considered relicts of Cenozoic (Mid-Oligocene to Miocene) times when Dragon Tree vegetation extended in a continuous vegetation belt between Northern Africa and Southern Europe [2]. Several of these species are extinct or endangered island endemics [1]. The latter endemic insular Dragon Trees group includes *Dracaena cinnabari* Balf. f. from Socotra Island (Yemen).

Dracaena cinnabari, the Socotran Dragon's Blood Tree, was first described in scientific literature by the Scottish naturalist I.B. Balfour [3]. It is a tree of significant cultural importance. The red resin (dragon's blood) derived from this tree is mentioned in early sources, including the Periplus of the Erythrean Sea, an anonymous source from the first century AD [4,5]. Dragon's blood has been intensively harvested and exported from

Socotra Island since ancient times, throughout medieval periods, until the 19th century. It is currently mainly limited to local use [1,6,7]. Although no reliable written sources are known from before the 19th century that would allow us to understand the former abundance and distribution of the Socotran Dragon's Blood Trees, we can speculate that the island was more densely populated by these trees in the past. More recent historical records mention dense *Dracaena* forests in the Socotran mountains [8], where these trees still occur. According to the most recent ecological niche models [9,10], the current occurrence of the island's Dragon's Blood Trees is only 5%, or even less, of its potential distribution in suitable areas. At least a quarter of the land surface of Socotra Island is suitable for the occurrence of the endemic Dragon's Blood Tree [10].

In general, Dragon's Blood Trees are relatively common in Socotra Island, even locally abundant in the granite Haggeher mountains, adjacent limestone plateaus, and in some disjunct areas, from 500 to 1500 m a.s.l., yet absent in the western parts of the island [6,11]. In the higher areas, they form a unique major habitat for the island which harbors a significant number of associated endemic species, the *Dracaena* woodlands, and forests, such as in the Firmihin Plateau. In the last twenty years, considering the importance of conserving these endemic trees, inventories combining field and remote sensing data have improved our knowledge of *Dracaena cinnabari* distribution. Eleven types of habitats were distinguished in Socotra where Dragon's Blood Trees occur [12]. The first remote sensing data evaluated the Dragon's Blood Tree populations on Socotra Island [13], concluding that land cover classes with an occurrence of this tree species comprise a total of 7230 ha. Based on satellite imagery, more than 80,000 dragon's blood trees were counted on Socotra [11] consisting of 20 more or less isolated (some locally abundant) populations, in a total area of occupancy of 51,963 ha; later, Dragon's Blood Trees were estimated to occur in 15 land cover classes [13], the majority of these habitats containing only sparse individual *Dracaena* trees or occurring in open woodlands.

A dense Dragon's Blood Tree forest as a vegetation type occurs in the limestone plateau known as Roqeb di Firmihin [14] which hosts the most abundant population on the island as far as we know [11]. This area has thus attracted the interest of many researchers. The features of many individual trees in Firmihin were measured, and a methodology for general age estimation was developed [14], which was further improved [1,15]. Traditional Dragon's Blood resin harvesting techniques have been described [7] and managed by local inhabitants maintaining traditions for centuries, even perhaps for millennia, used for a wide range of ethnobotanical practices [4]. In addition, practical conservation measures have been studied. The dynamic response of woody vegetation on fencing protection was studied during an enclosure experiment in Firmihin [16]; among other effects, the latter study recorded recovery of the vegetation and natural regeneration of the Dragon's Blood Trees in the absence of grazing. The first detailed field inventory of the Dragon's Blood Tree population in Firmihin was carried out on 107 monitoring circular plots [15] using the methodology of statistic forest inventory and FieldMap software. A few years later, a full-area inventory based on the analysis of remote sensing data was published, combined with some ground truthing [11]. In addition, a few hundred trees in this area were measured, and the relationship between resin harvesting and the vitality of the trees was evaluated [7]. All of these studies have contributed to a better knowledge of an important yet vulnerable insular endemic tree.

Being a national symbol for Yemen and providing a wide range of ecosystem services, the Socotran Dragon's Blood Tree plays a crucial role in the identity of the Socotri people, and it is synonymous with nature conservation in the Socotra Archipelago UNESCO World Heritage Site. The Socotran Dragon's Blood Tree is, however, rapidly declining, and it is estimated to be on a path towards full extinction in a few centuries if no long-term conservation measures are urgently put in place [17]. The species is currently listed as Vulnerable in the IUCN Red List [6], but this status is outdated and in need of reassessment, because recent climate effects were not included. Considering a predicted decline of Dragon's Blood Tree populations in Socotra due to overmaturity, the effects of overgrazing by goats, and climate change-related impacts of cyclones [11], detailed estimates of such relict populations, and the application of new techniques, are vital for future monitoring and formulating conservation strategies on the ground. One of these techniques, now commonly used in forestry for inventories of relatively small areas, is the use of drones (unmanned aerial vehicles or UAV), which have a wide range of applications [18–21]. To our knowledge, results of the use of such advanced methods for the assessment of Dragon's Blood Tree populations around the world have not been published (in general) yet.

This work aims to apply the use of UAV to achieve a high-resolution, up-to-date estimation of the globally unique Dragon's Blood Tree forest in Firmihin, its vulnerability, age structure, and to assess the impacts of recent climate change in Socotra (cyclones). The work aims to serve as a basis for future surveys that are needed in a current global warming scenario and for the management of this unique ecosystem. Furthermore, our study aims to assess the applicability of the technique for the analysis of the distribution and threats of other endangered Dragon's Blood Tree populations in the world.

2. Materials and Methods

2.1. Study Area

Roqeb di Firmihin (referred to as "Firmihin" in this paper), is a limestone plateau surrounded by deep canyons in the center of the island Socotra, the main island of the Socotra Archipelago (Yemen). The canyons create a relatively isolated area just south of the higher granite mountains (Figure 1). The plateau is gently inclined to the south and is covered by a typical karstic surface of an average altitude of 638 m. a.s.l. According to a recent study [11], this small plateau occupies only 2% of the total suitable area currently occupied by the endemic Dragon's Blood Trees of Socotra, yet it hosts more than 40% of the population.

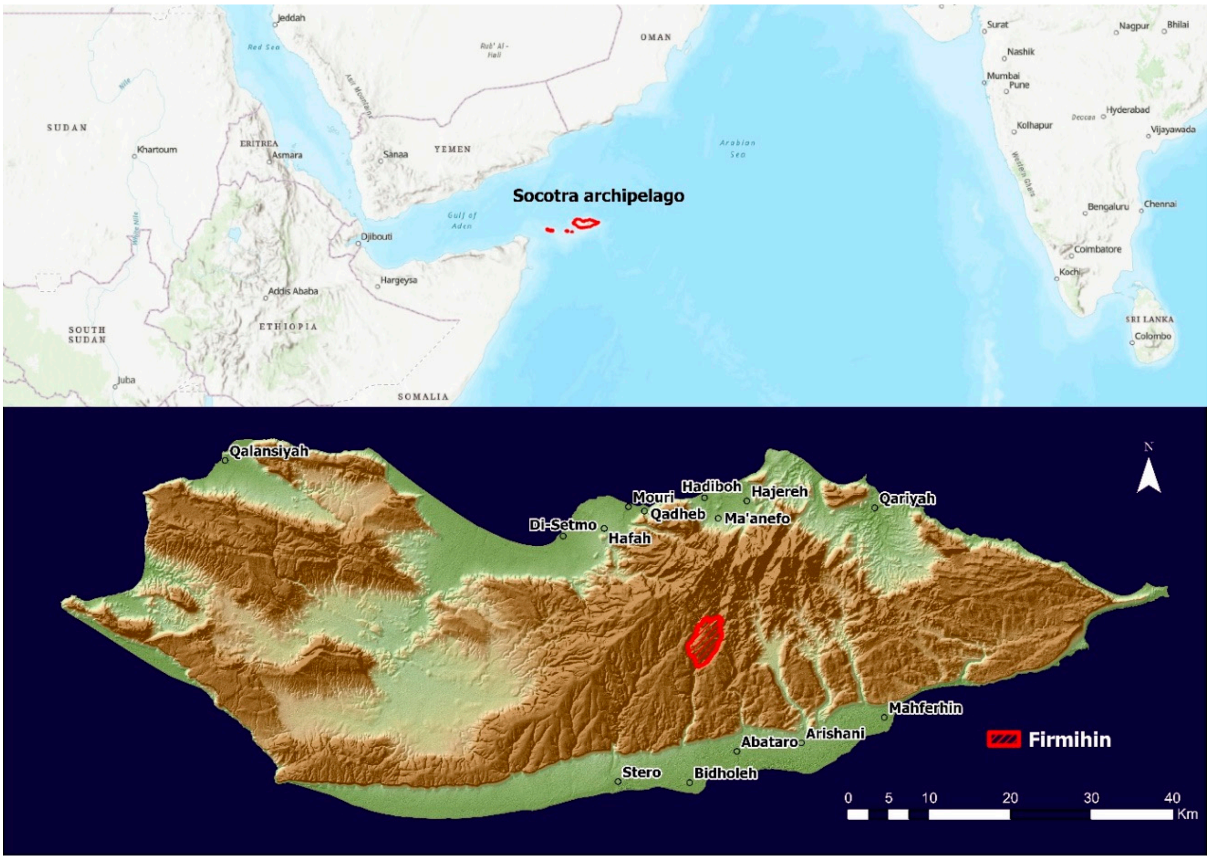

Figure 1. The Socotra Archipelago (Yemen) (**up**) and location of the Firmihin Plateau (in red) in Socotra Island (**below**).

The climate in Socotra is influenced by two monsoon systems: the summer and winter monsoons [22]. The mean monthly air temperature, air humidity, and precipitation for the closest localities in the Shibhon plateau are available [11].

2.2. Field Survey and Aerial Flights

The *Dracaena* forest of Firmihin was inventoried in March 2021 using georeferenced aerial imagery, acquired by the use of tandem drones. Due to the geopolitical instabilities in Yemen, no large UAVs can be applied; therefore, we used the smallest and lightest professional drones available on the market (DJI Mavic Mini^{TM}, Da-Jiang Innovations, Shenzen, China) for which we received official permission from Socotran authorities.

Using two drones, a series of orthophoto images with high spatial resolution was created to cover the entire area of interest (14.9 km^2). Due to the type of drones used and the unavailability of a good bandwidth in the area of interest, all flights were managed "by hand". We used a gravel road that crosses through the Firmihin plateau (dividing it into a western and eastern part) as the main area for homing (i.e., UAV landing and taking off). All flight trajectories were oriented in a W–E and N–S direction. Despite the limited battery life of the individual drones, our approach guaranteed a successful coverage of the entire study area; the collected georeferenced aerial images have minimal overlap (Figure 2). After a series of test flights and an evaluation of test data, all flights were carried out at a height of 350 m a.s.l. to reach a spatial resolution of 8 cm/pixel. Such a high spatial resolution is necessary as it is detailed enough for the successful identification and measurement of individual Dragon Tree crowns. In total, 12 flights were made (Figure 2). There were no missing areas in the assembled orthophoto, thus no corrections were needed.

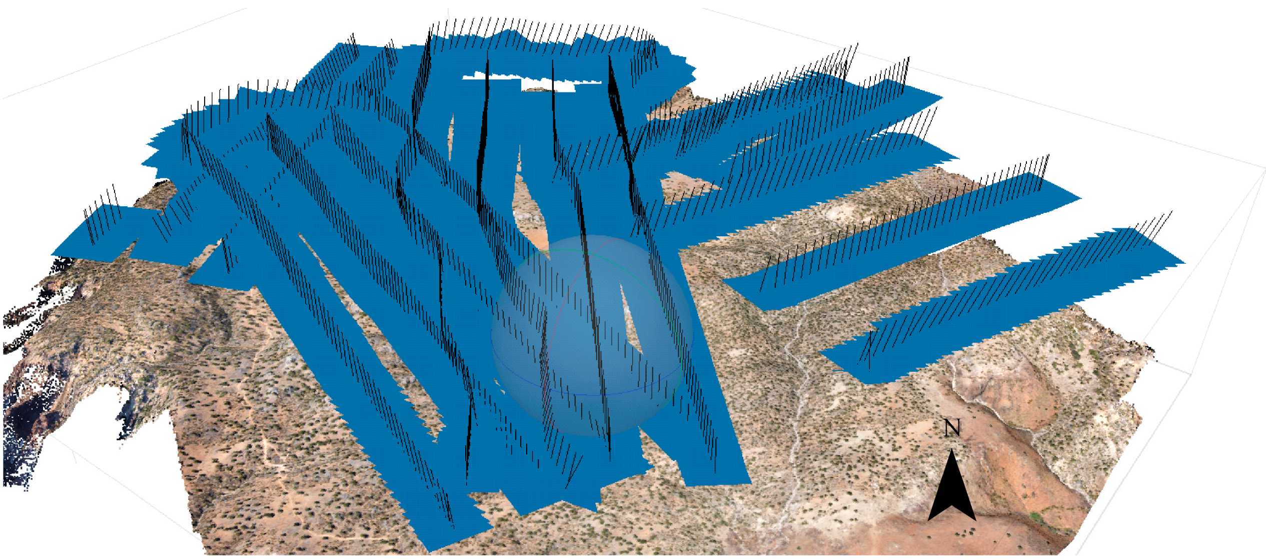

Figure 2. Individual UAV flight trajectories (Firmihin Plateau, Socotra Island, March 2021).

2.3. Data Processing

2.3.1. Processing of Aerial Images

Aerial images were assembled into an orthophoto mosaic using Agisoft Metashape software (Agisoft LLC, St. Petersburg, Russia). In total, 4849 georeferenced photos were produced and processed. The images were aligned into the mosaic using an automated control point identification. A dense point cloud consisting of 32,310,160 points was created and were covered by a mesh and textures to generate a custom digital elevation model (DEM). The textured DEM was processed as a tiled model, which was used to produce the final orthophoto image (Figure 3).

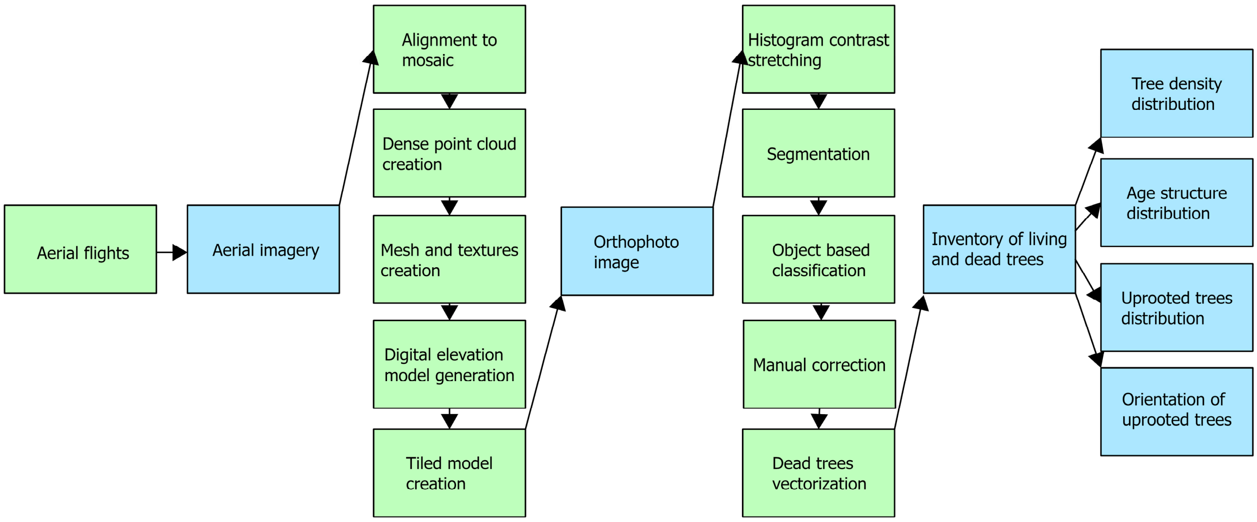

Figure 3. Flowchart describing methodological steps.

2.3.2. Tree Inventory

We used ArcGIS Pro (Esri ver. 3.01) to conduct a detailed tree inventory of the Dragon Tree forest of Firmihin. All crowns of Dragon Trees were vectorized using an object-based classification applied to the orthophoto image. Pre-processing of the data was carried out using histogram contrast stretching, which customizes a contrast stretch of various parts of the studied area by interactively adjusting the histogram. This process eliminates cloud shades affecting the resultant orthophoto image. Segmentation was used to group neighboring pixels that are similar in color and that have certain shape characteristics, as the next step. Finally, object-based classification was used to group neighboring pixels based on the image segmentation as described above. The resultant inventory included automated errors such as potential mutual contact of a few trees growing close to each other, which were misclassified as a single tree. All errors were corrected manually, by visually checking the automated object-based classification and redrawing (vectorizing) the exact crown contour in case of erroneous delineation (Figure 3).

2.3.3. Spatial Age Distribution Analysis

The spatial age distribution of the Firmihin Dragon Tree forest was evaluated based on the tree crown projection areas. *Dracaena* trees do not have growth rings, yet individual ages can be estimated using the number of divisions of branches (branch sections), where branching increases with age results in an expansion of the crown as seen from above (crown projection area); [15] described an approach for *Dracaena cinnabari* age estimation, based on the number of branch sections, and [11] calculated its relation to the crown projection area (i.e., the crown area as projected in orthophotos and satellite images). The equation of the dependency of the crown projection area (CPA) and the number of branch sections (NBS) is as follows [11]:

$$\mathrm{NBS} = (\mathrm{CPA}\hat{}\ (1/3) - 0.868425)/0.106529 \quad (1)$$

Based on this equation and the size of the crowns as estimated from the orthophoto, the number of branch sections was calculated for every single tree, which was then used to extrapolate the age of the trees. The spatial structure of the age distribution of the Firmihin forest was calculated as the average age of the trees per hectare of the area of interest.

The use of two models gives the accuracy of age estimation. The first is the relationship between the crown projection area and the number of branch sections [11], and the second is the relationship between the number of branch sections and the crown age of the tree [15]. Both regressions were published in the original studies including the confidence intervals, and the fit models of both relationships were used for our purposes.

2.3.4. Inventory of Uprooted Trees

The arid weather conditions on the Firmihin plateau significantly slow down the decomposition of uprooted trees. Most of the dead trees are a direct result of extreme weather events when cyclones hit Socotra in November 2015, affecting the Firmihin forest [1]; the remnants of a fallen Dragon Tree will stay on the ground for years. Dead uprooted trees were identifiable from our high spatial resolution orthophoto image (Figure 4). During the process of manual correction of the tree inventory, dead uprooted trees were also vectorized. We manually added a linear vector layer for each dead tree, oriented from the root section to the crown section, to indicate the direction of the fall (Figure 4).

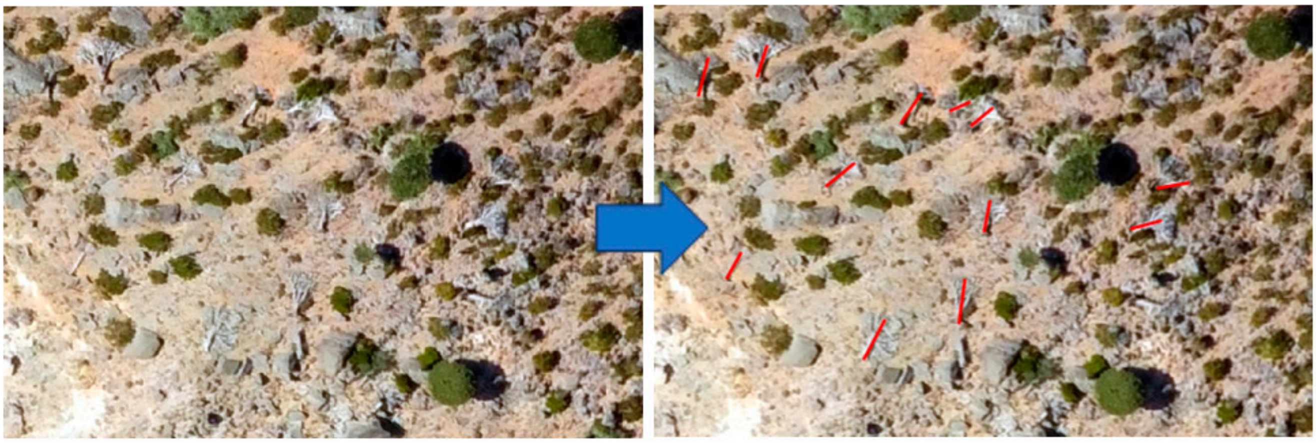

Figure 4. Uprooted *Dracaena* trees in the study area were visually identified and vectorized manually. Red lines indicate the direction of each fallen tree, added as linear vector layers.

The entire study area was divided using a grid with a square size of 1 × 1 hectare. The number of dead trees and their average direction of orientation to the cardinal points were evaluated for every single square of the grid.

3. Results

3.1. Inventory of the Firmihin Forest

The assembled orthophoto image of Firmihin using the DJI Mavic Mini drones had a final spatial resolution of 8 cm/pixel and a size of 12.5 GB. We used this image for an updated and accurate forest inventory. In total, 35,542 individual living *Dracaena* trees were inventoried (Figure 5). When compared to the estimation of the entire population of *Dracaena cinnabari*, reaching ca. 80,000 individuals [1], Firmihin hosts more than 40%.

3.2. Tree Density and Age Structure

The spatial distribution of the *Dracaena* tree density within the entire plateau is variable. Tree density (number of individual trees per hectare) varies, ranging from a few to, maximally, 239 trees/ha. The densest parts of the forest are in the central-eastern section and in a few areas in the southern section of Firmihin (Figure 6).

The Firmihin *Dracaena* forest has an old structure in general (Figures 7 and 8). The spatial variability of the age structure indicates that less dense parts of the forest are older (Figure 7). These parts with the older trees are located in the southeastern and northwestern sections surrounding the road crossing the Firmihin plateau (Figure 7). The largest continuously dense area in the central-eastern section (Figure 6), with ca. 120 to 220 trees/ha, contains the cohorts of the relatively youngest trees, estimated at approximately 150–300 years old (Figure 7).

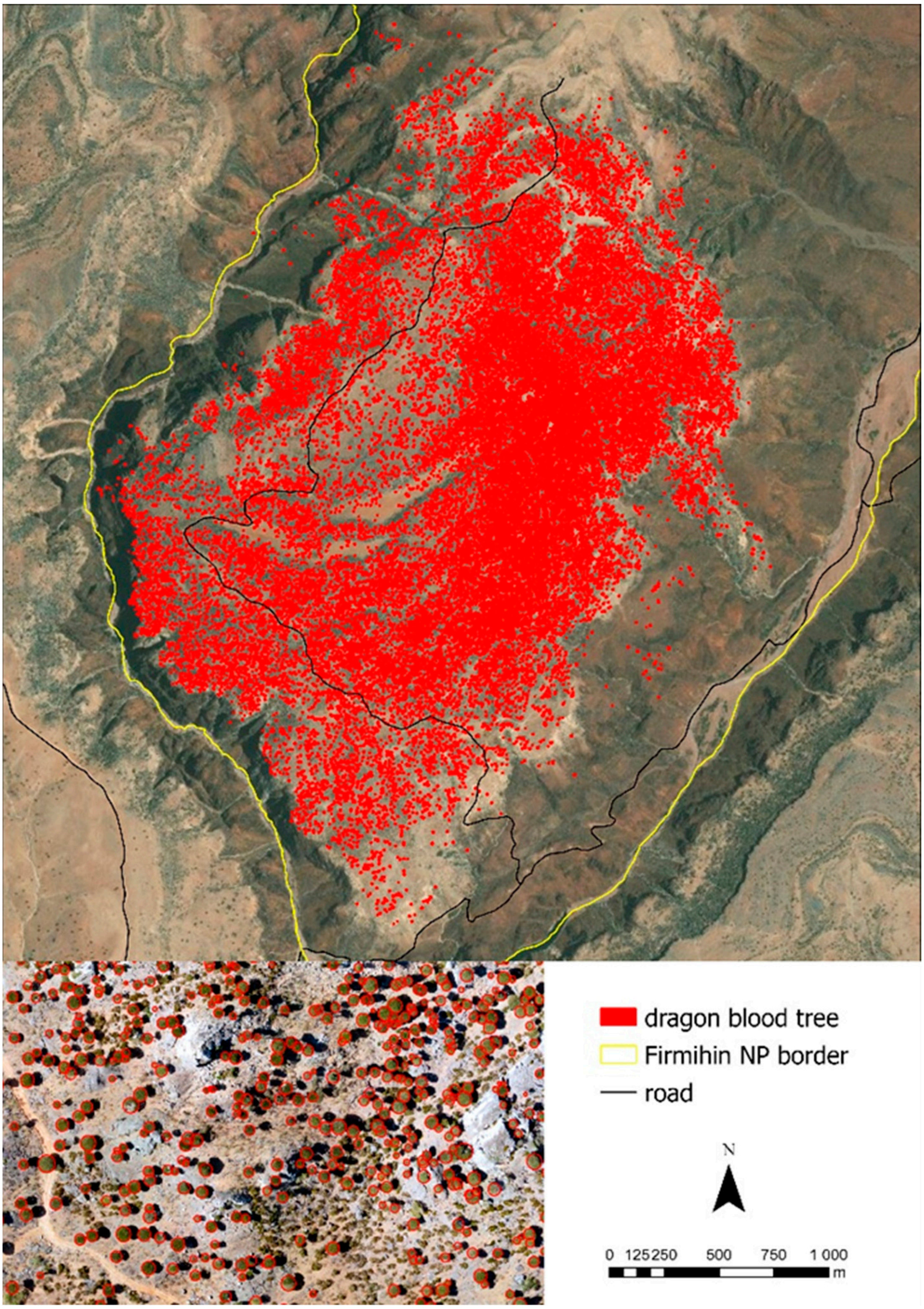

Figure 5. Firmihin forest inventory and detail of a group of inventoried *Dracaena cinnabari* trees showing vectorized crowns, each red dot representing an individual (living) tree.

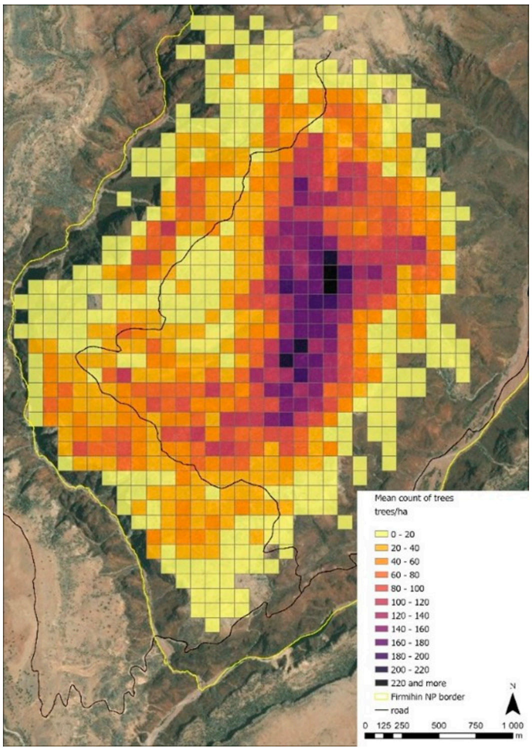

Figure 6. Spatial distribution of *Dracaena* tree density in Firmihin (individual trees/ha).

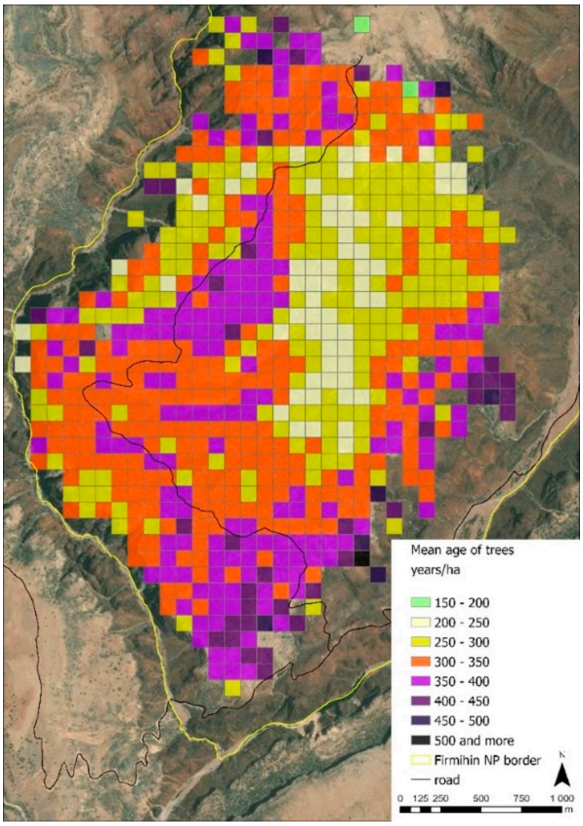

Figure 7. Spatial distribution of *Dracaena* estimated tree ages in Firmihin (tree ages/ha).

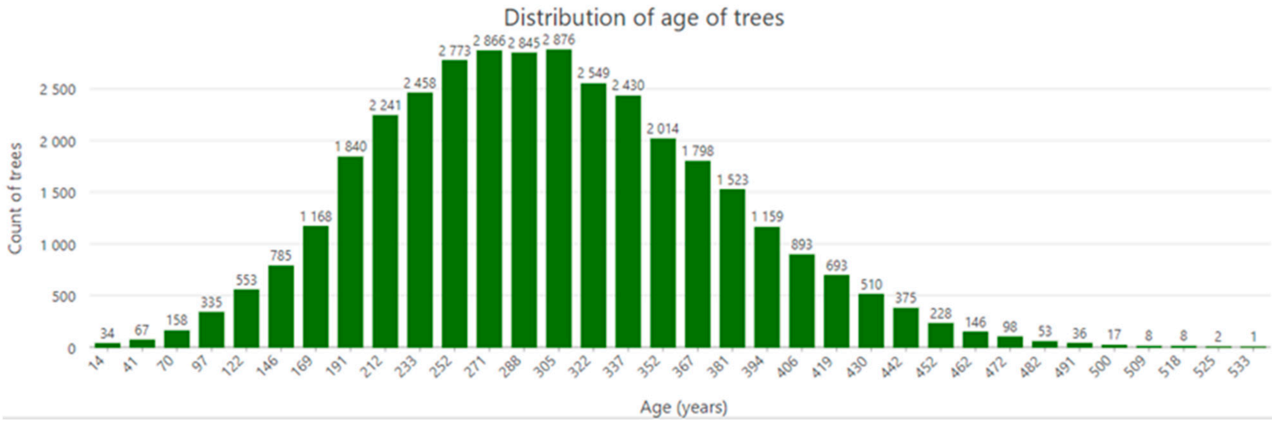

Figure 8. Distribution of estimated *Dracaena* tree ages (calculated on the projected crown sizes) in Firmihin.

Calculation of the age using the tree crowns ranges between 14 years, as a minimum, and 533 years, as a maximum, with an average age of 291.5 years and a median age of 288 years. 60% of all trees range between 200 and 350 years (Figure 8).

3.3. Evaluation of Uprooted Trees

Uprooted trees and their remnants were vectorized on the orthophoto image for the entire Firmihin plateau (Figure 4). In total, 2123 dead trees were vectorized. The highest number of uprooted trees are located at the northwestern and southwestern edges of the forest; the occurrence of dead trees (Figure 9) is less in relatively younger and denser parts of the forest (Figures 7 and 8) in the central-eastern section.

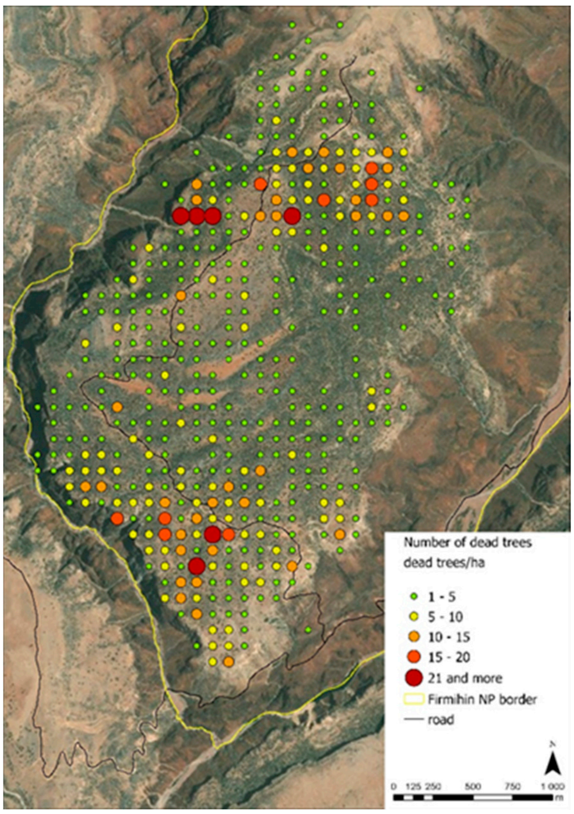

Figure 9. Spatial distribution of the number of uprooted *Dracaena* trees (number of dead trees/ha) in Firmihin, Socotra Island.

Relative to the cardinal points, a generally eastern direction prevails among the fallen trees (Figure 10). In the northern part of the forest, dead trees are oriented in a southeastern direction, and in the southern parts of the forest, they are oriented towards the northeast. In total, uprooted trees have a northeastern, eastern, or southeastern orientation with a range of horizontal angles between 22.5° and 157.5° in 91% of the entire area of Firmihin (Figures 10 and 11).

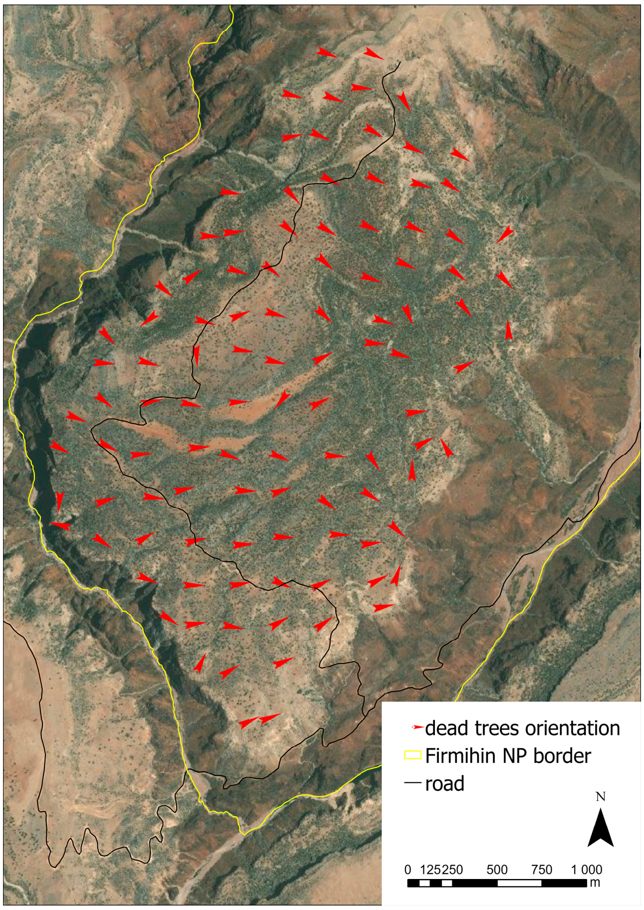

Figure 10. General orientation of uprooted *Dracaena* trees (directions from stem base to crown) in Firmihin, Socotra Island.

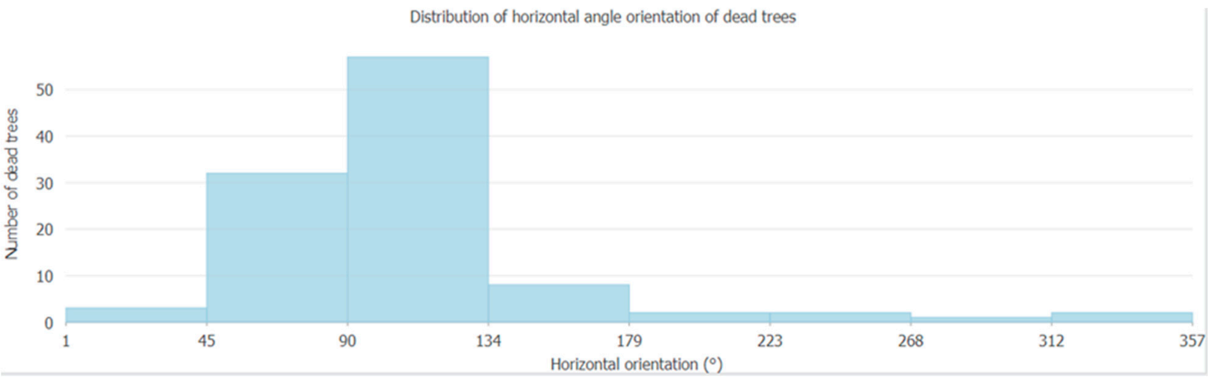

Figure 11. Distribution of the horizontal orientation (in degrees relative to the baseline) of dead *Dracaena* trees in Firmihin, Socotra Island.

4. Discussion

The use of UAVs has a wide range of applications in forestry, including management planning, assessment of forest health, and tree attributes [20,21,23]. Due to the relatively low operational cost and the high resolution, such advanced methods of remote sensing are increasingly used (and useful) in assessing the impacts of resource management and climate change [24]. As the terrestrial ecosystems of Socotra and, in particular, the island's endemic endangered trees are increasingly affected by extreme weather events as a result of global warming [25], modern methods are crucial, as they allow the best possible conservation and management strategies with the most accurate data. Our study does not only allow better insights into the population size of the last Dragon Tree forest on the planet, but it also helps us to understand the age structure of the population using *Dracaena*'s circular canopy (crown) sizes (applying recently published age estimation formulas). In addition, analysis of dead tree directions reveals a link with extreme weather events, such as cyclones, affecting the endemic trees of the Socotran forests and woodlands.

Specifically, using two low-cost UAVs (DJI Mavic mini-drones), we created a highly detailed orthophoto to describe the first complete and highly accurate inventory of *Dracaena cinnabari* trees in the area of interest (Firmihin). We assembled an orthophoto of a resolution of 8 cm/pixel, which allowed us to count 35,542 *Dracaena cinnabari* living individuals and 2123 uprooted trees. Our detailed inventory has allowed us to estimate crown sizes of the individual trees, from which we could calculate the most likely age structure of the forest, revealing an average of 292 years (ranging between 14 and 533 years, and with 60% of the area containing trees of ages between 200 and 350 yrs). For the latter analysis, it is a benefit that *Dracaena* has a highly recognizable, dense circular crown, not easily confused with other tree species in the same area, and that there is a recent system for age estimation based on the size of the canopy. In addition, our detailed analysis of individual uprooted trees revealed a predominantly eastern direction of falling, which we attribute to the impacts of extreme weather events due to global warming (cyclones).

4.1. Previous Inventories

Several inventories in the past applied other methods to estimate the size of the Socotran *Dracaena* forest. In 2010, statistical methods were used to perform the first forest inventory in Firmihin using randomly selected circular plots with a diameter of 25 m [26]. In total, 1992 individual Dragon trees were directly measured inside the predefined sample plots. The database was statistically extrapolated for the entire Firmihin forest with an estimation of 66,054 trees (with 14,500 trees as a 95% error) in total. Although this forest inventory was carried out before the cyclones that affected the forest in 2015, the total number of *Dracaena* trees in the latter study is almost two times our estimation. A more recent inventory used remote sensing analysis of Google Earth and ESRI orthophoto images [11], identifying 32,086 individual *Dracaena* trees in Firmihin, which is very similar to the estimation in our study. These previous estimations provide valuable information about the area of interest; however, the current UAV inventory allowed us to create an orthophoto with a higher resolution in comparison to the Google and ESRI orthophotos (Figure 12). The current results are more accurate, not only in estimating the number of trees, but also allowing some specific tree attributes such as individual crown area estimation and, therefore, the age structure of the forest, and to investigate mortality.

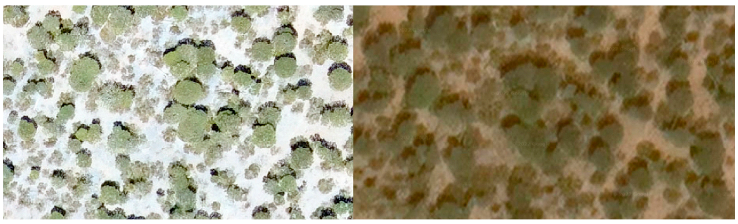

Figure 12. Comparison of UAV orthophoto (**left**) and Google orthophoto (**right**) in (a section of) Firmihin.

Future monitoring, which can be conducted regularly, could apply relatively larger UAVs for more extensive data collection, however, this is not feasible within the current geopolitical context in Yemen (restricted use of drones).

4.2. Population Structure and Natural Regeneration

The Socotran Dragon's Blood Tree is an endangered endemic insular species that is facing multiple threats, and its conservation status needs re-assessment [6,27]. Our study confirms that the overmaturity of the Firmihin *Dracaena* population, which can be attributed to the lack of natural regeneration, as recognized in previous studies, is a major issue. This element is important to consider for future conservation management of the species. We found that the average age of the forest is likely ca. 300 years and that the densest area of the forest contains relatively younger cohorts.

The overmaturity of the Dragon Tree population in Socotra can be mainly attributed to overgrazing by goats, a major threat that counteracts natural regeneration, resulting in a skewed population structure and the aging of the *Dracaena* forest [1,11]. The largely missing younger age classes are well illustrated in our study (Figure 8). The decrease in the occurrence of trees with a crown age below 200 years indicates that the problem with the (lack of) regeneration of the forest has been initiated at least 200 years ago. In other words, about two centuries ago, during the time of major development of this forest, the grazing intensity in the highlands of Socotra must have been considerably lower (i.e., fewer goats and/or better-managed grazing practices). The missing young trees in the area are not an artifact of the remote sensing data (e.g., younger trees could be out of sight from up because they are covered by the crown of another tree); we can confirm the low occurrence or absence of young trees during our regular field surveys. Young *Dracaena* seedlings appear after rains but are destroyed during the subsequent seasonal drought (as soon as grazing intensifies).

The lack of natural regeneration of *Dracaena* on Socotra Island has been mentioned by several authors before [1,11,14,15,28]. Conservation strategies, natural regeneration, and artificial reforestation activities were highlighted as key actions in previous studies [16] and, most recently, [10] as the only solution to protect this unique endemic species. Fencing of Dragon's Tree woodlands to exclude goats can support the occurrence and survival rate of young trees through natural regeneration [16], and artificial regeneration can be used in areas where this species has disappeared [29].

Moreover, harvesting of resin (dragon's blood) affects the health of adult trees [7], but the generally low intensity of this activity in present times has no significant influence on the general population decline. Wounds on the stem are larger and more abundant in woodlands with lower tree density and in matured and overmatured trees. Open woodlands in Firmihin with weakened old trees are, therefore, more sensitive to the effects of strong winds (compare Figures 6, 7 and 9).

The problem of Dragon Tree regeneration lies also in its very slow growth, with the annual height increment reaching, maximally, 2.0–3.0 cm per year [17]. Therefore, long-term protection against goat grazing and browsing is necessary for a pastoral landscape with a free grazing system [30] and requires close coordination with and between local communities and long-term conservation support [1]. For long-lived tree species with sporadic (and slow) regeneration, such as the Socotran Dragon's Blood Tree, dynamic management programs are needed to preserve such an iconic species [31].

4.3. Evaluation of Dead Trees and the Link to Global Warming

Strongly influencing the decline of Dragon Trees on Socotra is the occurrence of cyclones, which strike the island with increasing intensity. In recent years, three extremely severe cyclonic storms caused damage on Socotra Island. Cyclone Chapala passed the island on the 1 November 2015, and cyclone Megh followed one week later, on the 7 November 2015; finally, cyclone Mekunu passed the island three years later on the 25 May 2018. The effects of these cyclones on terrestrial habitats containing endangered species in

Socotra have been described in other studies, for example, the decline of a large population of the endangered frankincense tree *Boswellia elongata* Balf. f. in Homhil Nature Sanctuary on the eastern limestone plateau [26].

Chapala and Megh reached the island in 2015 along a similar trajectory, following the northern shore of Socotra; Mekunu moved near the eastern shore of the island with a south–north trajectory (Figure 13). Due to the counter-clockwise rotation of cyclones in the Northern hemisphere, Chapala and Megh struck Firmihin, together with the rest of the island, with hurricane-force winds in a western–eastern direction. This direction corresponds with that of the fallen dead tree bodies we analyzed in the Firmihin forest. It indicates to us that the majority of these fallen trees most likely died as a consequence of the violent cyclone events in 2015 by Chapala and Megh; winds of the Mekunu cyclone of 2018 struck the island in predominantly a north–south direction. Firmihin is protected from the northern side by the Skand mountains; therefore, Mekunu did not cause significant damage to the plateau's *Dracaena* population.

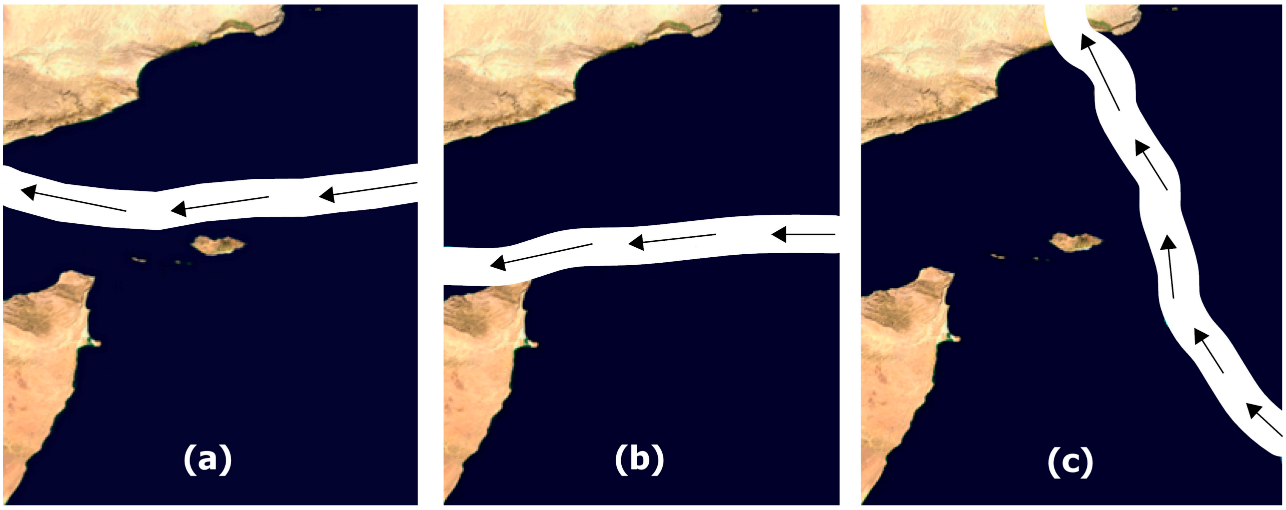

Figure 13. From left: Chapala (**a**) and Megh (**b**), both hitting Socotra Island in 2015, and the Mekunu (**c**) cyclone, which passed in 2018. Redrawn after [32].

In total, we counted 2123 dead trees, totaling 5.6% of the entire *Dracaena* population. We can expect that some of the dead trees were entirely decayed and therefore not visible on our orthophoto seven years after the major cyclone event that affected Firmihin. Therefore, the direct effect of the cyclones in November 2015 could exceed 5.6% of the population, but also some trees may have been uprooted later. In addition, many of the remaining (standing) trees are damaged (parts of the crown missing) and dying, yet they were counted here still as living. Such a relatively high number of trees killed by a single disturbance event could substantially decrease the survival time in *Dracaena cinnabari* extinction models [11,33,34].

Especially, the relatively less dense and overmature parts of the Firmihin population are highly sensitive to the disturbance effect of the strong winds and could go locally extinct relatively rapidly due to extreme weather events. The overmature and less dense tree stands are mainly in the western half of the plateau (Figures 6 and 7). More abundant populations can obtain the "first strike" or "press pulse" [35], which reduces the size and heterogeneity of the population, followed by a "second strike" where the population can be reduced to a number below some minimum threshold, inevitably leading to extinction [36]. In general, wind speeds due to cyclones can strongly modify forest structure [37], and we believe that this is currently the case for the endemic Dragon Tree forest in Firmihin.

On Socotra Island, which has a high ratio of endemic species [38], every tree counts because entire trophic chains depend on the Dragon's Blood Trees as primary producers, including other endemic organisms [39–42]. With every dead tree, we risk losing not only the endangered tree species itself but also all its ecosystem services (e.g., tourism, local medicinal uses, capturing horizontal precipitation, etc.), among which is their provision of a crucial link to the cultural identity of the Socotri and the importance of the tree as a vital habitat for sympatric endemic biodiversity.

Seasonal winds on Socotra can be quite intense and have a predominantly NE to SW direction (winter monsoon, normally in late October to early February) or the reverse, a SW to NE direction (summer monsoon, normally in April to June) [22]. Even though local effects may change general wind directions at a smaller scale, the presence of the Haggeher mountains just north of Firmihin largely shelters the area from the effects of the winter monsoon (as for cyclone Mekunu). It is likely that, therefore, mainly the summer monsoon has an additional, annual wind effect on the forest. However, considering the general direction of the summer monsoon winds, one would then expect the trees to fall in a predominantly northeastern direction, which is not the case, as our analysis shows the dead trees are mainly directed towards the eastern, and sometimes even southeastern, direction (Figure 11). In addition, the intensity of the 2015 cyclones was much higher than any regular winds recorded on Socotra before, made tragically clear by the damage to houses, human lives, and biodiversity [25]. Even so, we cannot exclude the likeliness that the annual summer monsoon has an additional effect on the unrooting of trees, especially on the oldest trees and those which have been already damaged/weakened by the recent and strongly dominant cyclone events.

4.4. Significance of Dracaena Conservation

Our current study is significant for the conservation of *Dracaena*, not only in Socotra Island. The method can be applied to other areas where Dragon Trees occur, to produce relatively low-cost, high-resolution, accurate inventories to understand the population structure of other species, many of which are endangered, and which are more scattered in distribution (within a population). The additional value of these UAV-generated high-resolution remote sensing data for Dragon Trees is that crown measurements can be used for age structure (taking into account that different species have different growth rates). Such data can be further used to assess population health, density, and resilience against current and potential threats (such as extreme weather events), leading to better-informed conservation management plans.

In the case of the Socotran endemic *Dracaena cinnabari*, extreme weather events in combination with at least two centuries of overgrazing have strongly affected the current population structure. Areas in Firmihin with sparsely distributed older trees are more vulnerable than the denser areas with relatively younger individuals. For future conservation management planning and reforestation/natural regeneration efforts, this heterogeneity in age and sensitivity to storms should be considered. Despite the very slow growth of these trees, the Firmihin plateau, harboring a significant proportion of the global population of this species, deserves strong protection and immediate conservation (natural regeneration) efforts.

5. Conclusions

Using UAVs, we provide a cost-effective method to generate a high-resolution georeferenced dataset to study the largest population of a culturally relevant and vulnerable endemic tree of Socotra Island, *Dracaena cinnabari*. Our analysis of the drone inventory, the first ever published for Dragon Tree population studies, allows new insights into the population structure and highlights once again the importance, as well as the vulnerability, of this area for the conservation of this relict species. Using crown age estimations, our study confirms that overmaturity is a typical feature of this forest, which is, on average, ca. 300 years old, and that the effects of overgrazing must have intensified in the last 2 centuries. We suggest a wind-tree correlation between the direction of the 2015 cyclones that affected Socotra and the dominant direction of a significant proportion of fallen (dead) trees, constituting 5.6% of the Firmihin population. We identified areas that are relatively more vulnerable to wind forces and local extinction, such as mainly the western half of the plateau, which contains the older trees. The remaining living population of 33,419 standing trees of Firmihin constitutes up to 40% of the total number of all *Dracaena cinnabari* trees estimated for the island. This high proportion illustrates the urgent need for the establishment of a well-managed (i.e., in collaboration with local communities) nature reserve for Firmihin and urgent conservation action to protect the last Dragon Tree forest on our planet.

Author Contributions: P.V.: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision. K.V.D. and P.M.: Conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review, and editing, visualization, supervision, project administration, funding acquisition. R.N., H.H., J.T., K.L., L.Z. and E.A.: Investigation, data curation, writing—original draft preparation, writing—review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the fieldwork in Socotra were funded by the Franklinia Foundation (2020–2023) "Conservation of the endangered endemic Boswellia trees on Socotra Island (Yemen)" Phase I, grant number 2020-03, and Phase II, grant number 2023-03.

Data Availability Statement: Data contained within the article are available on request from the corresponding author.

Acknowledgments: We are grateful to the local team on Socotra for facilitating the practical work of the "drone team" during the UAV surveys (Keybani, S.; Hamdiah, S.; Amar, M. and Shanayeghen, M.). We wish to thank, in particular, the local authorities in Socotra Island (in particular the Governor of the Socotra Archipelago) for providing the official approval to use UAV for conservation purposes of the endangered tree species on the Firmihin Plateau, and EPA (Socotra Branch) for permission and a keen interest in our scientific fieldwork. Preliminary results of this work were presented by the leading author during the Friends of Soqotra and Dragon Tree Conference (24–27 September 2021) held at Ghent University Botanical Garden (Ghent University, Belgium), to which we extend our thanks.

Conflicts of Interest: The authors declare no conflict of interest.

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