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Type of the Paper: Article

The test of the availability hypothesis across a protected area reveals the needs for *ex-situ* conservation to open window for ethnobotanical knowledge development

Kowiyou Yessoufou*, Isidore Muleba, Isaac Rampedi

Department of Geography, Environmental Management and Energy Studies, University of Johannesburg, APK Campus, Johannesburg, South Africa; kowiyouy@uj.ac.za; isidore_muleba@yahoo.com.au

* Correspondence: kowiyouy@uj.ac.za

Abstract: In ethnobotany, the availability hypothesis predicts that plants that are abundant and easily accessible to people are more likely to be medicinal than not. By protecting species diversity away from people, protected areas (PAs) may act as a limiting factor to a sustainable development of traditional knowledge concerning medicinal uses, and in so doing, PAs provide opportunity to prioritize *ex-situ* conservation for species that are PAs restricted. In this scenario, ex-situ conservation becomes the only chance for people to develop traditional knowledge on plants which otherwise wouldn't be documented as traditionally useful to people. To test these expectations, we used data collected for almost 20 years of fieldworks on plant medicinal uses and their abundance inside and outside the Kruger National Park (KNP), South Africa. We fitted four different scenarios of structural equation models (SEMs) to the data collected. We found that total plant abundance (abundance outside + inside KNP) is a significant positive predictor of medicinal status, and so is abundance outside KNP, thus supporting the availability hypothesis. However, not only abundance inside KNP is not a direct significant correlate of medicinal status, but also the relationship between both is negative. The lack of predictive power of inside-abundance is most likely because some species are exclusively found inside KNP, and local communities do not have access to them. It also shows that the positive and direct correlation of total abundance with medicinal status is driven by outside-abundance. In addition, the negative relationships between inside abundance and medicinal status implies that abundant plants inside KNP tend to be not-medicinal, further providing evidence that PAs hinder the development of medicinal knowledge. Furthermore, when inside and outside abundance were included simultaneously in a model as two distinct variables, inside abundance was never a direct significant predictor of medicinal status, but it was so, via an indirect path mediated by outside abundance. This suggests that outside abundance is the key variable driving the development of medicinal plant knowledge. Cumulatively, our findings suggest that anything that promotes the growth of PA-restricted plants beyond the natural realized niches of these plants (ex-situ conservation) such as in botanical gardens, private gardens, in agroforestry systems, etc., is to be promoted so that people-plant interactions may continue for the benefits of ethnobotanical knowledge development.

Keywords: Availability hypothesis; Ethnobotany; Ex-situ Conservation; Kruger National Park; Sustainable Development of Traditional Knowledge; Traditional medicine

1. Introduction

Documenting people's knowledge of medicinal plants is the first critical step in the search for drugs that improve human health [1]. The ongoing worldwide efforts to document medicinal plants show that we might have between 10,000 to 53,000 plant species used in traditional medicine [2]. How have traditional knowledge of medicinal plants been developed? This is a question of research interest for all ethnobotanists simply because understanding the mechanism driving the development of traditional knowledge would inform how to manage this knowledge, how to protect them in a sustainable manner and, more importantly, how to promote their continuous development for the benefit of future generations.

One of the hypotheses formulated in response to the question - known as availability hypothesis - predicts that plants that are abundant and easily accessible to people are more likely to be medicinal than those that are rare and inaccessible due to restricted distribution [3,4]. In their recent study, ref. [5] showed that people's floristic environment is a key factor shaping medicinal plant knowledge. This finding suggests that plants that are available to people dictate the development of traditional medicinal knowledge, another support for the availability hypothesis but a recent study showed that this development of medicinal knowledge is time dependent (resident time hypothesis; [6]). However, evidence of less-abundant plants being preferentially used medicinally has also been reported (e.g., [4,7,8]), and this calls for a comprehensive assessment of factors that may impede the development of traditional knowledge for plants readily available. We hypothesized that protected areas (PAs) are potentially one of those factors that may limit or prevent a comprehensive or sustainable development of medicinal plant knowledge by local people.

Protected areas (PAs) are key ecological systems delimited to protect species-rich geographic regions for a continued or sustainable provision of ecosystem goods and services [9-11] , and as such PAs are irreplaceable particularly in the face of the ongoing worldwide biodiversity crisis [12]. In particular, national parks are geographically specified areas where restrictive measures are put in place to prevent uncontrolled access and consequently preserve effectively their ecological, geomorphological and aesthetic features [13]. By protecting species-rich habitats away from the frequent use of local communities, we expect PAs to prevent or at least limit the development, by these communities, of a comprehensive medicinal knowledge of plants distributed within their borders, an implication of the availability hypothesis [3,4].

In the present study, we investigated this expectation using the Kruger National Park (KNP) in South Africa as a model PA. The flora of the KNP, with its 20,000 km^2 across two provinces of South Africa (Mpumalanga and Limpopo), is one of the largest national parks in Africa. Its entire flora is estimated to exceed 1900 plant species, including 458 tree and shrubby plants (henceforth referred to as woody flora). In the present study, 806 woody plants, both inside and outside the KNP across the two provinces of Mpumalanga and Limpopo were documented over 10 years of intensive data collection by experienced botanists (e.g., [14]). These documented species were updated following further fieldworks over an additional eight years in 2005-2007 [15] and 2008-2012 [16]. In addition, the following information were also documented for each of the 806 plant species: point locations, medicinal status (medicinal vs non-medicinal), the number of recipes and the total number of plant organs used for medicinal treatment (see details in Materials and Method). The main objective of the study was to use this dataset not only to test the availability hypothesis but, more importantly, to show that -ex-situ conservations are beneficial for both biodiversity and medicinal knowledge development.

2. Materials and Methods

2.1. **Study area**

The Mpumalanga province is one of the nine South African provinces within the Greater Maputaland-Pondoland Albany Region, harbouring the southern half of the Kruger National Park (KNP) and other centres of endemism [16]. The KNP is located in the north-eastern part of South Africa between 22°25′ and 25°32′S and 30°50′ and 32°E. The KNP covers an area of 20,000 km^2 and is one of the largest national parks in the world. The province's entire flora is ~ 1900 plant species, including 458 tree and shrubby plants [14]. Various ethnic groups are found in it and around the KNP with a huge and well documented medicinal traditions and knowledge in comparison to the rest of South Africa. The dominant cultures and ethnic groups in Mpumalanga province include *Swati* culture (30%), *Zulu* culture (26%), and *Ndebele* culture (10.3%), *Northern Sotho* culture (21.2%) and *Tsonga* culture (11.6%).

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2.2. **Definition of variables used in this study**

The following variables are defined for data analysis. The variable '*inside abundance'* is the number of sites where each plant is found inside the Kruger National Park. '*Outside abundance'* is the number of sites where each plant is recorded outside the Kruger National Park. '*Total abundance'* is the sum of *inside* and *outside abundances*. Data on abundance were collected from fieldworks complemented by various sources indicated above. Plant medicinal knowledge is defined using three metrics, *medicinal status, number of recipes and number of organs used medicinally.*

2.2. Data collection

Data used in the present study were collected over a long period of extensive effort and were documented in multiple forms (books, papers and online database). First, ref. [14] conducted over 10 years of botanical survey across the Mpumalanga province, including the KNP, published a reference book "*Trees and shrubs of Mpumalanga and Kruger National Park*". This book provides photographic illustrations, different uses (including medicinal), broader distributions including site locations of all woody species in the province and in KNP. The number of site locations for a species is used as a metric for *inside* or *outside abundance* for the species.

Second, in the Department of Botany of the University of Johannesburg, multiple botanical expeditions were also conducted. For example, ref. [15] and ref. [140 collected, through intensive seven-year fieldworks in the study area (from 2005 to 2007, and 2008-2012, respectively), plant information and plant materials that are preserved in various herbariums and Labs in South Africa, including the herbarium of the University of Johannesburg. These field collections and the book of ref. [14] are the main sources of species distributions used in the present study for 806 woody plants, both found inside and outside the KNP across the province of Mpumalanga.

Lastly, in addition to the book of ref. [14], data on medicinal status of each plant (medicinal vs. non-medicinal), the total number of recipes involving each plant and the number of plant organs (roots, leaves, barks) used in those recipes were collected through an intensive literature search of the different uses of recorded plant species. First, we used the Web of Science (WoS) to retrieve existing scientific ethnobotanical studies in the region. Second, we performed search for each species by using combinations of keywords such as "scientific name of species", "South Africa", "uses", "usages", "Utilisation" and "benefit". We also made use of Google and Google Scholar for scientific and grey literature using similar keywords to retrieve online resources such as country-specific journals, proceedings, technical reports, herbarium, and commercial websites informing on the uses of woody plants in our dataset. In addition, we consulted key books on the regional flora such as *Trees of Southern Africa*, and *Field Guide to Trees of Southern Africa* [18-20]. Additionally, the *Prelude Database for Medicinal Plants in Africa* (http://www.africamuseum.be/collections/external/prelude; accessed on 10 February 2017) was also consulted [21], a database of all ethnobotanical studies that ever took place in Africa, country by country, since 1847. We additionally explored other sources such as SANBI PlantZafrica (SANBI PlantZafrica; http://pza.sanbi.org/ accessed 2018) and (ethno)-botanical books that focused on the southern Africa's woody flora [18,22-24].

2.3. **Data analysis**

All analyses were done in R 3.5 [25] in the library *piecewiseSEM* [26], and the R scripts used are provided as supplemental information. We first tested whether 'total abundance' predicts plant medicinal knowledge, which was measured either as medicinal status, number of recipes or number of organs used. To this end, we fitted the structural equation model (SEM) to the dataset as implemented in the R library *piecewiseSEM* [26]. This SEM analysis was done on our first meta-model built based on the following assumptions. We assumed that 'total abundance' would predict medicinal status, and this assumption is grounded on the availability hypothesis. As an implication of the

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availability hypothesis, we also expect 'total abundance' to predict the number of recipes involving a given species and the number of organs used medicinally. The rationale for these assumptions is that more abundant species are more likely to be medicinal (availability hypothesis), and plants that have more organs used medicinally are more likely to be involved in more recipes than not. Finally, plants involved in a medicinal recipe are obviously medicinal. We translated all these expectations into our first meta-model (Figure 1), and then tested the fitness of this meta-model to our data using the function *glm* with specifically a binomial error structure for medicinal status (as this is a binary variable, medicinal vs non-medicinal).

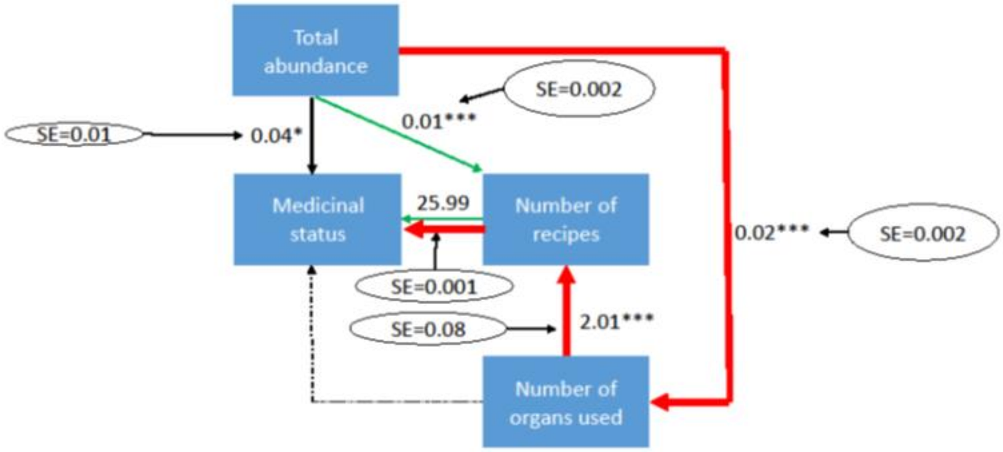

Figure 1. Meta-model illustrating the prediction of availability hypothesis. Different paths (arrows) of the relationships of total abundance with medicinal status are color-coded; black= direct path, green= shortest indirect path, and red = longest and most strong indirect path. The width of arrow is indicative of the strength of the relationships between two variables. Values on the arrows are path coefficients; SE, standard error

To test potential influence of PAs on the development of medicinal plant knowledge, we built three additional alternative meta-models. These meta-models are too based on similar expectations explained above and upon which the first meta-model is grounded with the following differences. In the meta-model in Figure 2a, 'total abundance' is replaced with 'abundance outside' the KNP; in Figure 2b, 'total abundance' is replaced with 'abundance inside' the KNP, and in the last meta-model (Figure 3), total abundance is replaced by both 'abundance outside' and 'abundance inside' the KNP.

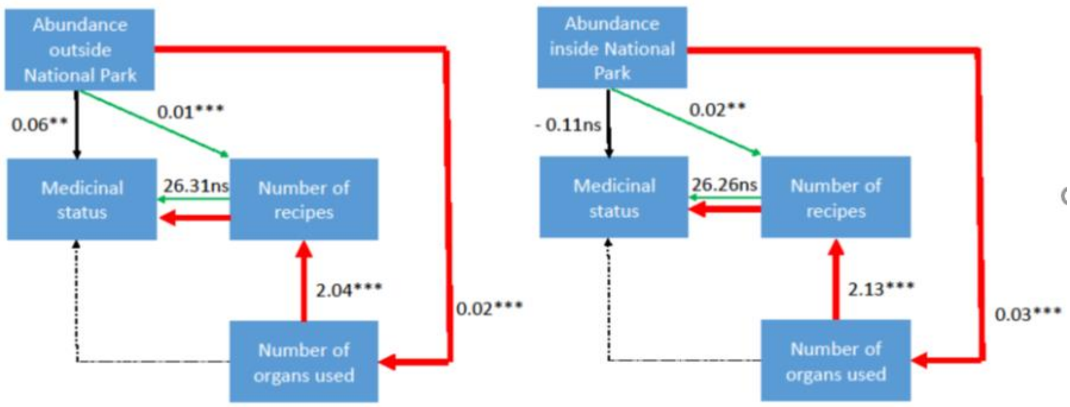

Figure 2. Meta-model illustrating the potential influence of plant abundance outside (a) versus inside (b) the Kruger National Park. Different paths (arrows) of the relationships of total abundance with medicinal status are color-coded; black, direct path, green,

shortest indirect path, and red, longest and most strong indirect path. The width of arrow is indicative of the strength of the relationships between two variables. Values on the arrows are path coefficients.

Our rationale is that plants that are inside PAs are less likely to be medicinal, even if they are abundant inside the park, because they are less often in contact with local communities (unless they are abundant outside the KNP). In contrast, plants that are outside the park would more likely be medicinal because they are in contact everyday with local communities, particularly plants that are abundant (availability hypothesis). We tested these expectations by fitting SEM to all meta-models as presented in detail in the R scripts (Supplemental Information).

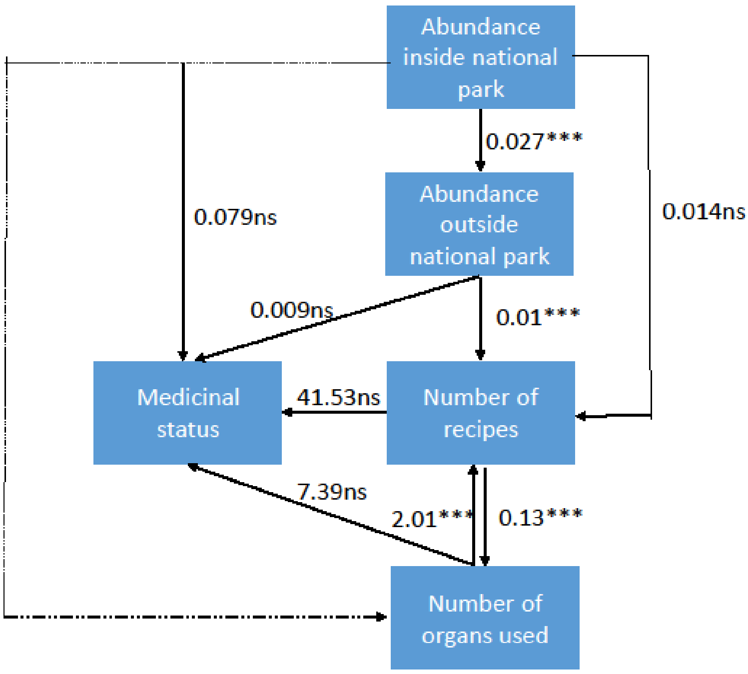

Figure 3. The most complex meta-model illustrating simultaneous influence of outside and inside plant abundance on medicinal knowledge. Different paths (arrows) of the relationships of total abundance with medicinal status are color-coded; black, direct path, green, shortest indirect path, and red, longest and most strong indirect path. The width of arrow is indicative of the strength of the relationships between two variables. Values on the arrows are path coefficients; SE, standard error.

3. Results and Discussion

We first tested the availability hypothesis, employing the structural equation modelling (SEM) approach. The meta-model built includes total plant abundance (plant abundance inside + outside of KNP), number of recipes for each plant and number of organs used medicinally (see Figure 2 for full meta-model). Our SEM analysis revealed a perfect fit of this meta-model to the data collected (Fisher C = 0, df = 2, P = 1.00). This model shows that only total plant abundance is a significant positive predictor of medicinal status; that is, more abundant plants tend to be medicinal than not, a support for the availability hypothesis [3,4]. The model further reveals three paths through which total plant abundance predicts their medicinal status. There is a direct path (black arrow on Figure 2) with a path coefficient β = 0.04. Then, there are two indirect paths, one through 'number of recipes' (green path on Figure 2, β = 0.25), and the other one through both 'number of organs used' and 'number of recipes' (the red path on Figure 2) with the highest path coefficient (β = 1.03).

Second, we explored the main question: does the establishment of such a large national park, the Kruger National Park (20,000 km^2), protecting ~ 500 woody plants [14,27], influence the development of medicinal plant knowledge in the region? Our theoretical expectation is that plants that are inside PAs would less likely be medicinal, even if they are abundant within KNP. Alternatively, plants that are outside the KNP would more likely be medicinal because they are easily accessible to local communities, particularly plants that are abundant (availability hypothesis).

To explore these two alternative expectations, we built two meta-models (Figures 3a,b) in which only plant abundance outside and inside KNP was included, respectively (Figure 3), as opposed to only 'total abundance' in Figure 2. The first meta-model (Figure 3a) that contains only plant abundance outside the KNP (henceforth referred to as "outside abundance") has an overall perfect fit to our data (C = 0, df = 2, P = 1.00) and is similar, from all aspects, to the meta-model in Figure 2. Specifically, outside abundance predicts better medicinal status through exactly the same three paths identified in the meta-model containing total abundance (Figure 2), with the red path in Figure 3a being the strongest (black path, β = 0.06; green path, β = 0.26 and red path, β = 1.07). This is an additional support for the availability hypothesis: more abundant plants outside KNP tend to be medicinal than not.

However, the second meta-model (Figure 3b), which also shows a perfect fit to the data (C = 0, df = 2, P = 1.00), reveals one important difference from the previous models (Figures 2&3a): not only the direct path between abundance inside KNP and medicinal status is no longer significant, but the coefficient of this direct path is negative. If abundance inside KNP is not a significant predictor of medicinal status, this is evidence that, by strictly protecting biodiversity, PAs break or block the natural processes or mechanisms driving the development of medicinal knowledge by local communities. This lack of predictive power of inside abundance is most likely due to the fact that, although both inside and outside KNP share some common species and outside abundance predicts inside abundance (see Figure S1), other species are exclusively found inside KNP (Table S1) that local communities may not know of, or do not have access to. It also shows that the positive and direct effect of total abundance on plant medicinal status, reported in Figure 2, is actually driven by outside abundance (Figure 3a). In addition, our finding of negative relationships between inside abundance and medicinal status implies that abundant plants inside KNP tend to be not-medicinal, further providing evidence that protected areas hinder the development of medicinal knowledge. Interestingly, while the direct path between inside abundance and medicinal status becomes non-significant, the indirect path mediated by both 'number of organs used' and 'number of recipes' become the strongest among all models (β = 1.66).

Finally, to further clarify this negative effect of PAs on the development of medicinal plant knowledge, we constructed our last meta-model, in which inside and outside abundances are simultaneously included as two distinct variables (Figure 4). If PAs truly have this negative effect, we might expect the positive effect of outside abundance (Figure 3a) to be cancelled or at least weakened by the negative effect of inside abundance (Figure 3b) such that none of these two variables (outside and inside abundances) would be significant predictors of medicinal status. Our SEM analysis of this last meta-model (Figure 4) identified the path "organ used ~ inside abundance" as a missing path, but a non-significant one with P = 0.73, meaning that plant abundance inside KNP is not a significant predictor of number of organs used in traditional medicine, confirming that KNP may be limiting knowledge of plant usages. As suggested above, this is most likely due to the fact that KNP has plants that are exclusively found within its borders and for which no medicinal usages could be developed because they are not accessible to people. However, when this missing path was included in the meta-model, all endogenous variables become conditionally dependent, and the test of directed separation becomes impossible. We therefore left that missing path out of the SEM analysis. This did not affect the strength of the meta-model as the model shows a good overall fit (C = 0.6, df = 2 and P=0.739; Figure 4). This model further confirms that the abundance of plants inside the PA is not a significant predictor of the number of recipes, adding to the support of negative effect of PAs on medicinal plant knowledge development. Surprisingly, abundance outside the park (β =0.009 ± 0.029, P = 1.00) is no longer a significant predictor of medicinal status, as opposed to the results of the meta-model in Figure 3a where inside abundance was excluded. This is a confirmation that the inclusion of inside abundance cancels or weakens the predictive power of outside abundance on medicinal plants, thus providing, once more, a support for the negative effects of PAs on medicinal plant knowledge development. Furthermore, in this last meta-model (Figure 4), inside abundance was never a direct significant predictor of number of recipes or number of organs used medicinally, but was so, via an indirect path mediated by outside abundance. This suggests that outside abundance is the key variable driving the development of medicinal plant knowledge (i.e., here medicinal recipes and number of organs used), thus clarifying the drivers of the availability hypothesis – accessibility to plants triggers or mediates the development of medicinal knowledge (number of recipes and number of organs used medicinally).

Ethnobotany, the discipline of plant-human interactions, lacks, for long, unifying theories or hypotheses that explain how or why some plants are selected in traditional medicine [28-33]. The availability hypothesis, along with other recently proposed hypotheses (see review of ref. [33]), has been formulated, indicating that more available and accessible plants are more likely to be medicinal. Reports on the availability hypothesis are mixed: while some studies confirm its validity, other studies found rather that less-abundant species are used medicinally when abundant species are not [4,7,8]. Given these mixed findings, ref. [33] called for the definition of a multi-dimensional index of availability that could perhaps be used universally in different contexts. We suggest that the finding of the opposite scenario to the prediction of the availability hypothesis is not counter-intuitive as range-restricted plants may be preferred for some medicinal treatments when these plants are more effective than the abundant ones. We therefore suggest that PAs offer a more appropriate opportunity to test the availability hypothesis in any contexts. The present study used Kruger National Park to provide the first evidence of how PAs may be hampering the development of medicinal knowledge. This eventuality has been raised in a recent study by ref. [34] who, unfortunately, did not test it. Overall, we suggest that specimens of plant species that are found exclusively in PAs be grown outside the PAs, in botanical gardens, in home gardens (*ex situ* conservation) and in natural ecosystems accessible to local communities so that the latter may develop some knowledge around the uses of these plants (given that the environment shapes medicinal knowledge [6]. This requires that we study the biology (e.g., germination; horticulture) and ecology of these species to facilitate their propagation outside their PAs for the benefits of local communities. Our study therefore shows how ethnobotanical knowledge can be used to advocate for *ex situ* conservation of some plant species restricted within the border of a protected area. We call for further studies to test the metamodels tested in the present study with different data across different geographical regions.

4. Way forward: *ex-situ* conservation

Protected Areas (PAs) are traditionally designed to protect the environment and its resources for the benefits of the environment itself and humans. One important benefit that the environment provides to human is medicinal plants. However, medicinal plant knowledge is developed only on plants that are readily available for local people. Because some PAs, e.g., National Parks, prevent easy and frequent access of local people to plants within their borders, it is likely that medicinal knowledge of plants inside PAs would be limited. We tested for the first time this hypothesis and provide strong evidence that PAs may prevent the development of medicinal knowledge on plants inside their borders.

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We consequently suggest that *ex-situ* conservation programs should be developed specially for PAs-restricted plant species such that local people can have easy and frequent access to these plants, allowing these plants to be subject of traditional medicinal usages. According to the Convention on Biological Diversity, ex-situ conservation is ''the conservation of components of biological diversity outside their natural habitats'' [35], i.e., outside their realized ecological niches. Outside these niches may imply in botanical gardens, privately own gardens, in germplasm collections of wild and domesticated taxa, in various forms such as seeds, genes, or whole plants [36]. It is therefore not a practice that happens overnight since the survival of the plants or seeds outside its natural range depends on several factors, e.g., physiology, seed germination ability, and autecology of the species at hand, that need to be studied and understood to inform ex-situ conservation decisions.

In conclusion, in the context of limited ethnobotanical knowledge for plants restricted to PAs, ex-situ conservation is the only option we find possible to remedy to this limitation, and as such, while ex-situ conservation is meant to preserve biodiversity, our study suggests that it can also be used to give a chance for the development of ethnobotanical knowledge.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: Correlation between woody plant species abundance inside and outside the park; **Table S1:** Table S1. Data generated and analyzed in the present study. The definition of variables is as follows. Status (medicinal or not); status_number (1=medicinal, 0=non-medicinal); outside (plant abundance outside Kruger National Park, KNP); inside (plant abundance inside Kruger National Park); occurrence (is the plant occurring inside or outside KNP only or in both); abundance total (abundance inside + outside); recipes (number of recipes recorded); root, bark and leaf (1=used for medicine; 0 = not used for medicine); **- R script** used for statistical analysis

Author Contributions: Conceptualization, K.Y.; methodology, K.Y.; formal analysis, K.Y.; investigation, I.M.; and K.Y.; resources, I.M.; data curation, I.M.; writing—original draft preparation, K.Y.; writing—review and editing, K.Y.; I.M.; project administration, K.Y.; funding acquisition, K.Y.

Funding: This research received no external funding.

Institutional Review Board Statement: The study did not require ethical approval.

Data Availability Statement: All data analyzed are in Supplementary Information files.

Acknowledgments: We acknowledge the University of Johannesburg

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

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