# Alkaloid-Poor Plant Families, Poaceae and Cyperaceae, Are Over-Utilized for Medicine in Hawaiian Pharmacopoeia

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The theory of non-random medicinal plant selection predicts that the number of medicinal plant species in a given family is related to the total number of species in that family. As a consequence of such a strong relationship, some plant families are over-utilized for medicinal purposes while others are not. Medicinal plant families that are often over-utilized share evolutionary traits such as the presence of secondary plant compounds which are known to have medicinal values. Consistent with this model, several studies have shown that alkaloid-poor plant families such as Poaceae and Cyperaceae, two families known more for their physical defenses rather than their chemical defenses, are medicinally under-utilized across the world. In this study, we demonstrate that contrary to expectation, Poaceae and Cyperaceae are over-utilized in the Hawaiian ethnopharmacopoeia. One reason for this over-utilization is a result of the Hawaiian cultural practice of converting plants in the Poaceae and Cyperaceae families into ash for direct medicinal use or as a component in other medicinal preparations. The over-utilization of Poaceae and Cyperaceae is also potentially due to their versatility and greater availability in parts of the land divisions where most humans are allowed to visit. Knowledge of how to use ash is taught through mo'olelo, Hawaiian history, and represents a Native Hawaiian understanding of and relationship to chemical knowledge. Our study provides new evidence for the theory of non-random medicinal plant selection and shows, contrary to expectation, that unique patterns of plant family over-utilization could arise in unique cultural and geographical contexts.

**Key Words:** Non-random medicinal plant selection, phytochemicals, Hawaiian Islands, theoretical ethnobotany, ethnoecology, Lā'au Lapa'au, 'Ike Hawaii..

## Introduction

The theory of non-random medicinal plant selection was developed by Moerman (1979) in response to the popular academic belief that Native American medicine is a placebo medicine and based entirely within a symbolic system. The theory suggests that the number of medicinal plant species in a given family is positively linked to the number of species in that family. Plant families that have more species in general will be expected to have more medicinal species. From an applied ethnobotanical perspective, testing this theory can help identify medicinal plant families that may be targeted and which may provide cures for human diseases (Miller et al. 2005). The theory also predicts that some plant families will be over-utilized or under-utilized for medicinal purposes based on how many actual species of medicinal plant they contain compared to what should be expected. Defining this expected number of medicinal species has been discussed variously (Bennett and Husby 2008; Weckerle et al. 2012; Yessoufou et al. 2015), but the central ideas of using the linear regression residuals to identify plant families according to their level of uses for medicinal purposes remain intact.

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Daniel Moerman in a set of seminal papers demonstrates that some plant families such as the Euphorbiaceae, Asteraceae, Lamiaceae, Fabaceae, and Apiaceae are over-utilized, and other families such as the Poaceae and the Convolvulaceae are under-utilized within Native American pharmacopoeias (Moerman 1979, 1991; Moerman et al. 1999; Moerman and Estabrook 2003). Similar results have also been reported in other non-related geographies of people from around the globe (Amiguet et al. 2006; Bennett and Husby 2008; Leonti et al. 2003; Medeiros et al. 2013; Miller et al. 2005). In theory, over-utilized medicinal plant families are those that have developed phytochemical compounds in defense against diseases such as the growth of fungi, as well as protection from herbivory (Feeny 1976; Moerman 1991; Rhoades and Cates 1976). Humans have adapted over time to be able to utilize these phytochemicals for medicinal purposes. For example, Moerman (1991) refers to the bark beetle species adapting to the phytochemical defenses produced in pines and states that "the human use of bioactive botanical substances is analogous to these insect adaptations." Moerman et al. (1999) further demonstrates the correlation between phytochemical-rich plant families and their over-utilization by traditional people as medicine. Asteraceae and Lamiaceae are two over-utilized plant families in four of the five regions studied. These families are a rich source of a wide variety of phytochemicals such as aromatic volatile oils, as seen via superficial observation in plants such as *Achillea millefolium* L. (Asteraceae) and the common spice and medicinal plant *Rosmarinus officinalis* L. (Lamiaceae).

Unlike these plant families known for their chemical defenses, other families such as Poaceae and Cyperaceae are often dominated by alkaloid-poor species and thus are expected to be under-utilized in most ethnopharmacopoeias. This theoretical prediction has empirical support from several studies (Amiguet et al. 2006; Bennett and Husby 2008; Leonti et al. 2003; Medeiros et al. 2013). Moerman (1996) suggests that Poaceae in general represent the "food" plant families because they provide the main cereals that the world eats: corn, sorghum, rice. In general, Poaceae does not have strong chemical defenses against herbivory and tends to rely more on physical defenses (silica, leaf toughness) as a deterrent for herbivory (McNaughton and Tarrants 1983). As a result, it is not expected that Poaceae, except a few species, will have secondary chemistry that will confer medicinal values.

In this study, we show that contrary to expectation, Poaceae and Cyperaceae, which are typically the most under-utilized families for medicine in North America, are over-utilized in the Hawaiian ethnopharmacopoeia. We tested the theory of non-random medicinal plant selection using published data on medicinal plants and the existing flora of Hawaii. Specifically, we tested if the number of medicinal plant species per family is positively predicted by the total number of species in that family and investigated which plant families are under-utilized or over-utilized in the Hawaiian ethnopharmacopoeia. We compared these results to known tests of the theory of non-random medicinal plant selection across the world and discussed how the unique pattern of medicinal plant families used in this island context in Hawaii could have arisen due to a unique sociocultural and environmental contexts.

## Materials and Methods

### Study System

The Hawaiian Islands represent the most isolated land mass in the world. Surrounded by the Pacific Ocean, the vast island chain consists of eight main islands. The islands are formed by "emergent tops of volcanoes 5000–9000 m above the ocean floor" (Wagner et al. 1999). The Hawaiian chain itself continues into the Emperor Chain, which finally terminates off the Kamchatka Peninsula in Asia. The entirety of this vast archipelago contains over 100 major volcanoes, is 6000 km long, and involves an estimated 70 million years of volcanic activity from geologic hot spots (Wagner et al. 1999). The islands are governed generally by two seasons which fall between the months of April and May and September and October, with temperatures cooling and rainfall increasing during the latter. The Hawaiian Kingdom is a subcategory of the Polynesian Kingdom, which is an aspect of the larger Paleotropical Kingdom. Most plant communities in Hawaii are considered to be zonal (Good 1974; Wagner et al. 1999). Climate and elevation primarily dictate what species are found in each zone, and Hawaiian landscapes are known to change rapidly in very short distances because of factors such as rainfall (Wagner et al. 1999). The geographic domain for this study includes all seven major islands in the Hawaiian Island chain. This is the geographic area that is currently most accessible to the Native

Hawaiian community, and thus the area from which the majority of the plant medicines are obtained. Niʻihau is the only island that is off limits to all outsiders without special invitation.

Traditional Native Hawaiian plant medicine, or lāʻau lapaʻau, is a cultural practice of Native Hawaiian people that has roots throughout the Pacific and rises directly from their relationship with the land and sea (Gutmanis 2013; Whistler 2009). There are two major ecological and historical issues that complicate this study. One, since the arrival of voyaging Polynesian and European explorers to these islands, a large number of non-native plants and animals have been introduced by colonizing people (Howarth et al. 1988; Leopold and Hess 2017; Sakai et al. 2002). As a result of subsequent disruption of its native ecosystem by non-native herbivores and plants, Hawaii now has the highest rate of endemic species extinction in the world. A new IUCN report states that "of the 415 endemic Hawaiian plant species assessed so far for The IUCN Red List (out of ca. 1093 endemic plant species), 87% are threatened with extinction" (IUCN 2016). As a result, many native plants once utilized for medicine may no longer be available for observation and use. In addition, in the past, the Western practice of requiring medical professionals be licensed placed restrictions on how Native Hawaiians were allowed to practice their traditional forms of medicine (Judd 1998). There has, however, been a renaissance of Hawaiian cultural knowledge, and the practice of lāʻau lapaʻau continues to remain significant, evolve, and grow (Judd 1998).

### Constructing the Database

To test the theory of non-random medicinal plant selection, two main variables are necessary—the total number of species per family (predictor variable) and the number of medicinal plant species per family (response variable). We used The Manual of Flowering Plants of Hawaii with revisions from Wagner et al. (1999, 2012) to estimate the number of plant species per family. There are approximately 2089 species of flowering plants in Hawaii, organized into 152 families (Wagner et al. 1999, 2012). The four largest families in Hawaii are Asteraceae, Poaceae, Campanulaceae, and Fabaceae. To estimate the number of medicinal species utilized in Hawaii per family, we compiled a list of the species from four primary and comprehensive Hawaiian herbal texts. Two of these books were compiled by Native Hawaiian scholars: *The Outline of Hawaiian Physical Therapeutics* (Handy et al. 1934) and the "Ulu Mau Plant List" generated by the Edith Kanakaʻole Foundation's Maʻiola Indigenous Health (Edith Kanakaʻaole Foundation 2005). The two other books include "*The Secrets and Practice of Hawaiian Herbal Medicine*" (Gutmanis 2013) and the "*Plants in Hawaiian Medicine*" (Krauss 2001). These plant lists represented a combined total of 187 medicinal plant species from 75 families. These species include endemic, indigenous, naturalized plants, two Polynesian introductions that have not naturalized, and some cultivars. We standardized the binomial names to eliminate synonymous names and updated family names following the latest Angiosperm Phylogeny Group revision (Chase et al. 2016). For some medicinal species (e.g., *Peperomia* and *Bidens*), only the genus was listed. We counted these species once because they have a single local Hawaiian name.

### Data Analysis

We used a general linear model to test the relationship between the number of medicinal species per plant family and the total number of species per family. These variables were log $(x + 1)$-transformed prior to the analysis to ensure normal residuals and homogeneity of variance. To determine which families are over-utilized or under-utilized, we calculated the residuals for each family. Families with negative residuals were considered as under-utilized because this indicates that these families have less medicinal plant species than expected from the total number of species in such families. The expectation here is the fit line of the general linear model which represents the mean number of medicinal species that would be expected from that family given the total number of species. Families with positive residuals were considered as over-utilized because they have greater number of medicinal species than expected from the general linear model. All statistical analyses were conducted in R. The data used for this study and R script are available in Appendix S1 and S2.

## Results

Plant families with more species also had more medicinal species ($F = 151.5$, $p < 0.0001$, $R^2 = 0.53$). The number of medicinal species

found in each plant family in Hawaii was significantly and positively related to the total number of species in that family ($\beta$ = 0.423 ± 0.034, $p$ < 0.0001). Nearly 56% of the plant families were under-utilized with negative residuals indicating that they have less medicinal species than expected. Fabaceae (residuals = +0.93), Ericaceae (+0.87), Malvaceae (+0.87), Zingiberaceae (+0.85), and Apocynaceae (+0.84) were the five most over-utilized medicinal plant families in Hawaii (Fig. 1, Table 1, Appendix S1). Plant families such as the Poaceae (+0.54) and Cyperaceae (+0.16) were also over-utilized in the Hawaiian ethnopharmacopoeia (Fig. 1). Primulaceae (−1.31), Acanthaceae (−1.03), Loganiaceae (−1.00), Melastomataceae (−0.98), and Passifloraceae (−0.92), which had negative residuals with the highest absolute values, were the most under-utilized families (Fig. 1, Appendix S1). Lamiaceae (−0.55) was also included as an under-utilized medicinal plant family.

## Discussion

We analyzed data from well-known resources on Hawaiian herbal medicine to elucidate the plant families in the Hawaiian pharmacopoeia that are over-utilized and under-utilized for medicine. Fabaceae, Ericaceae, Malvaceae, Zingiberaceae, and Apocynaceae were the top 5 most utilized plant families in Hawaiian herbal medicine. Surprisingly, Poaceae and Cyperaceae were also over-utilized medicinal plant families, while Lamiaceae were under-utilized. If the expectation is that the most over-utilized plant families are those that produce alkaloids and other phytochemicals (Moerman et al. 1999; Moerman and Estabrook 2003), then it is exceptional that Poaceae and Cyperaceae are over-utilized plant families in Hawaii. Of the five geographic areas represented in Moerman et al. (1999), "there is substantial overlap of families in four regions. Asteraceae ranks first on the list of families in North America, Kashmir, and Chiapas; it ranks

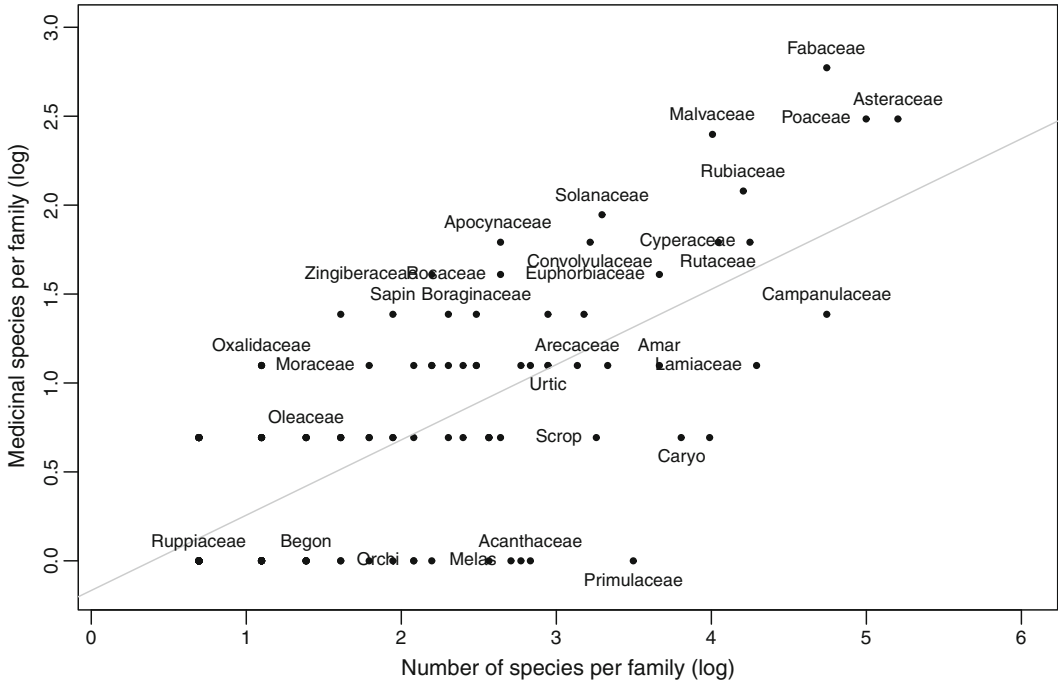


**Fig. 1.** Relationship between the number of plant species per family ($x$) and the number of medicinal plant species per family ($y$) in Hawaiian ethnopharmacopoeia (axes are log-log). Each *dot* represents a family; some family names are abbreviated to the first three letters only to make the figure readable (full list of families and their abbreviations are in the Appendix). The *line* is the linear fit of the log-log relationship and represents the line where the number of medicinal plant species in a given family is equal to the expected number of medicinal species as predicted by the general linear model $\log y = a + b\log x$.

second in Korea" (Table 1). In the three regions (North America, the Chiapas, and Kashmir), Poaceae was the least utilized family for medicine, and in Korea, it is ranked second to least. Finally, the study shows that "the top 5 families in Ecuador are very different from the other four regions." The top 5 over-utilized families in Ecuador are not found on the top 5 list of the other regions. Both Hawaii and Ecuador over-utilize Fabaceae and Malvaceae plant families, and yet, Bignoniaceae and Loganiaceae which are in the top 5 list in Ecuador, are not over-utilized as medicine at all in Hawaii (see Table 1 and Moerman et al. 1999). Fabaceae is known for it is multitude of phytochemicals and is over-utilized in both Hawaii and Ecuador, but Cyperaceae and Poaceae are uniquely over-utilized in the Hawaiian pharmacopoeia.

While considered to be alkaloid-poor families, both Poaceae and Cyperaceae are known to have physical defense systems such as silica in their leaves instead of relying on phytochemicals for defense like many other plants do. As observed from previous studies, most over-utilized medicinal plant families tend to be those with strong chemical antiherbivory defenses (e.g., Amiguet et al. 2006; Bennett and Husby 2008; Leonti et al. 2003; Medeiros et al. 2013; Moerman et al. 1999); thus, it is unique that Poaceae and Cyperaceae are over-utilized in Hawaii, while they are the least utilized families in other parts of the world. As suggested by Moerman et al. (1999), ethnographic data are important in the interpretation of trends discerned through patterns observed in exploring the non-random plant selection theory. In the following lines, we use an analysis of Hawaiian culture and traditional land division and management systems, as well as the biomedical context and biological traits of Poaceae and Cyperaceae, to explain why these two families are uniquely over-utilized in this insular context.

*The Availability Hypothesis*—. Poaceae and Cyperaceae are over-utilized because they are more available in the realms of humans, the coastal and lowland regions of the ahupuaʻa Hawaiian land division system (the *availability hypothesis*, see Gonçalves et al. 2016; Lucena et al. 2007). The practice of lāʻau lapaʻau is an inherent aspect of the overarching Hawaiian culture, which is practiced in accordance to specific protocol, cultural, behavioral expectations and norms. Hawaiians have and continue to demonstrate an ecological awareness of the land, and with cultural concepts such as aloha ʻāina and malama ʻāina, love and care for the land, forming foundational cultural paradigms, the biological practices inherent to Hawaiian culture may be among the culture's defining characteristic (Fung-Anderson and Maly 2002). This strong relationship of the Hawaiians with their land has a direct impact on how resources are gathered and utilized from the environment. The realm of the human and the realm of the gods are distinguished, inherent aspects of the land divisions Hawaiians utilize in their island-based ecological management systems. These land divisions, known as ahupuaʻa, range from the top of the mountain to the sea, corresponding well with the western system of dividing the land according to elevation bands. Yet, in Hawaiian cosmology, these divisions are also associated with a deep and animated spiritual ecology (Abbott 1992; Wagner et al. 1999). While kahuna lāʻau lapaʻau do venture into these realms [the upper elevations] when forest plants are needed, "these trips were conducted in keeping with clear protocol" (Abbott 1992). In a society that practices herbal medicine as its primary form of healthcare, one might hypothesize that the realm of the gods in the upper mountainous regions of the islands, by which precise ceremonial protocol is required to enter, would not be as accessible to the total of the populace, but instead reserved for one who is trained and prepared to travel there. The natural habitats of both Poaceae and Cyperaceae plant species are typically located in the coastal and lowland regions, allowing them to be accessed more easily and more frequently, without having to travel into the higher elevations where the gods dwell. It is interesting to note that both Poaceae and Cyperaceae are known as mauʻu, meaning both grass and sedge in the Hawaiian

Table 1. Top 5 over-utilized medicinal plant families in Hawaii and other regions studied in Moerman (1999).

| Rank | Hawaii | Ecuador | North America | The Chiapas Highlands | Kashmir | Korea |
|---|---|---|---|---|---|---|
| 1 | Fabaceae | Araceae | Asteraceae | Asteraceae | Asteraceae | Liliaceae |
| 2 | Ericaceae | Fabaceae | Apiaceae | Lamiaceae | Euphorbiaceae | Asteraceae |
| 3 | Malvaceae | Bignoniaceae | Ericaceae | Solanaceae | Ranunculaceae | Lamiaceae |
| 4 | Zingiberaceae | Loganiaceae | Rosaceae | Rosaceae | Lamiaceae | Ranunculaceae |
| 5 | Apocynaceae | Malvaceae | Ranunculaceae | Apiaceae | Liliaceae | Apiaceae |

language, and are often present in the areas that people frequent and their habitations dwell. In other words, their natural habitat is the ao kanaka, or human realm, which is located in the lower elevated grass, marsh, and coastal lands (Wagner et al. 1999). As Abbott states, "most of these regularly utilized medicinal plants grew near habitations" sometimes represent Polynesian introductions and cultivars and have multiple uses in addition to being utilized for medicine. This is consistent with the availability hypothesis (Albuquerque 2006; Lucena et al. 2007) proposed to explain why most medicinal plant species are those that are available to local people. This hypothesis has support given that two of the most over-utilized families, Poaceae and Fabaceae, are also the largest plant families in Hawaii (Wagner et al. 1999).

*The Versatility Hypothesis*—. Plants in the Poaceae and Cyperaceae families are also major commodities in traditional Hawaiian culture. The multitude of ways in which species from these families were used to construct useful materials is too extensive to fully capture in this discussion alone. Such versatility partially explain why these families are over-utilized (the *versatility hypothesis*, see Alencar et al. 2010; Bennett and Prance 2000). Consider, for example, one species of the Poaceae family commonly used as medicine. *Heteropogon contortus* (L.) P.Beauv. ex Roem. & Schult., known as pili in Hawaiian, was selected in "drier places" as thatching material for houses and was "generally favored for its pleasant odor" (Abbott 1992). In the thatching of hale, or Hawaiian homes and buildings, the leaf of another Poaceae, Kō, *Saccharum officinarum* L., is used as a lining of the inner roof in order to make it more appealing (Abbott 1992). The juice of kō is also used to mix with herbal concoctions in order to sweeten the taste, and for this reason, it is "the most commonly used plant in preparing medicine" (Gutmanis 2013). ʻOhe *Schizostachyum glaucifolium* (Rupr.) Munro (Poaceae) is yet another grass utilized as a building material, and fibers of ʻahuʻawa, *Mariscus* sp. (Cyperaceae), are used to make a strainer for kava and arrowroot preparations (Abbott 1992). Given the multitude uses of many plants in Poaceae and Cyperaceae, the "versatility hypothesis" (Alencar et al. 2010; Bennett and Prance 2000), which proposes that cultures are more likely to utilize plants for medicine when these plant species are already serving many other utilitarian functions, provides a framework for understanding further why alkaloid-poor families are over-utilized in the Hawaiian ethnopharmacopoeia. However, the most important explanation can only come from the Hawaiians themselves.

*Physical Defense Indirectly Confers Medicinal Value*—. Listening to the stories of Hawaiians reveals a personal world view and mode of transmitting healing, chemical, and biological knowledge that is encoded in moʻolelo—Hawaiian history and storytelling. Moʻolelo suggests that the methods of medicine preparation are as important as the plant itself, and in the case of the Poaceae and Cyperaceae, the plants are often converted into ash before use. The ash is used either directly mixed with water as a single ingredient or combined with other plant-based concoctions (Abbott 1992; Edith Kanakaʻaole Foundation 2005; Gutmanis 2013; Kumu Keoki Baclayon, pers. comm.). In one such moʻolelo, Kumu Keoki Baclayon, a professor of Lāʻau Lapaʻau at the University of Hawaii Mānoa School of Hawaiʻinuiākea, says

> "*Kupuna kahiko* [Hawaiian ancestors] learned that there was life in the ashes through *moolelo*—recorded history—but most specifically through the *moolelo* of *Pele* and *Hiiaka.* One of the most noted *moolelo* that we haven t talked about in detail or to any degree of thoroughness are the *moolelo* related to and associated with *lehu [ash].* The most prominent story that comes to mind is that of *Hiiaka* restoring *Lohiau* back to life. The *moolelo* of *Pele* and *Hiiaka* were so truly well known throughout the islands and *Moananuiahiwa* [the ocean expanse] that my great-grandfather William Kualu was chanting about their exploits in his old age—and he was born on *Niihau* and raised on *Kaua i* never having traveled to *Mokuokeawe* [Hawaiʻi Island]. So, I know for a fact that Hawaiians knew their stories from *mauka* to *makai,* and from island to island.
>
> The other point from witnessing the *mana* of *Pele's* destructive power is the life that she brings to the *aina* as a result of destroying it. Ash and charcoal being left behind, once living organic material is now non-living organic material. Still yet, containing properties of that once living *lā au.* "How" *kupuna ma ka wa kahiko* knew to utilize it isn't as important to me as to "why" they used it. Because once, they learned of the medical application of *lehu* it evolved into a practice that they applied using a multiple host of *mau u* [grasses and sedges]. So, back to *Hiiaka,* an interesting fact, the prayers that she uses is

> called *mele kunikuni* or a prayer/song of burning. She isn't actually putting him on fire, but, she is taking what's left of his body (symbolically the *lehu)* and restores the "fire" within it or his spirit until it animates the ashes again."

As can be seen, moʻolelo is encoded with healing knowledge related to the virtuous properties of ash, representing a specific kind of knowledge perpetuated by Polynesian and Hawaiian people and their experience of the land, specifically fire from volcanoes. The Hawaiian use of various plant ashes for medicine can be viewed in many significant ways. Such a chemical knowledge of ancient cultures is a subject under-represented in ethnobiology, yet for all the times that humankind has had fire, humans have also had ash and its chemical properties are not unknown. The production and use of potash date from the ancient times in several countries of the world and were first used in a crude way as a domestic cleansing agent (Babayemi et al. 2011). The cleansing property of ash and water is perhaps most exemplified through its use in the production of lye, an often caustic substance, which forms a foundational ingredient in soaps (Babayemi et al. 2011; Dunn 2003). It is particularly noteworthy that the ash of Poaceae and Cyperaceae plants is used to treat boils, cuts, sores, and thrush in the Hawaiian ethnopharmacopoeia (Edith Kanakaʻaole Foundation 2005; Gutmanis 2013). In the moʻolelo, Kumu Keoki Baclayon mentioned a wide variety of ashes which are utilized, and the utilization of ash extends beyond these two plant families. However, because plant species in the Poaceae and Cyperaceae families contain more fibers and less water, they dry easily, quickly, and burn faster than other plant families. As a result, Poaceae and Cyperaceae are a better and quicker source for ash, and this may explain why they are over-utilized in this particular cultural context. Poaceae and Cyperaceae are mostly under-utilized in other parts of the world because they lack chemical defense. However, in our study region, the traits (fiber, dryness) that are central to physical defense in grasses make these species a good and quick source of ash, and this determines their medicinal value.

*Limited but Existing Phytochemistry in Grasses*—. There are pathways by which plants in Poaceae and Cyperaceae may also be selected due to the potential presence of phytochemicals. The potential that some species within the typically alkaloid-poor families Poaceae and Cyperaceae may contain phytochemicals should not be disregarded. For example, *Cymbopogon citratus* (DC.) Stapf (Poaceae) is famous for its culinary uses, as a tea, a seasoning, and a medicinal infusion (Ekpenyong et al. 2015; Wagner et al. 1999). Commonly known as lemon grass, and lūkini in Hawaii, its aromatic and therapeutic properties are due to the presence of volatile oils. *C. citratus* also contains flavonoids, tannins, alkaloids, and other phytochemicals, as well as nutrients such as vitamins A and C and minerals including sodium, potassium, zinc, and magnesium (Ekpenyong et al. 2015). *C. citratus* is popular in the Philippines in the treatment of gastrointestinal diseases, to relieve stress, and is used in herbal medicine worldwide for a wide range of applications, including antibacterial, antifungal, antiprotozoal, anticarcinogenic, antiinflammatory, antioxidant, cardioprotective, antitussive, antiseptic, and antirheumatic activities (Ekpenyong et al. 2015). This wide range of phytochemicals and medicinal uses is uncommon in a plant family typically dominated by starchy grains, yet its presence within the herbal medicinal practices of many cultures globally also makes it insignificant in this study.

It is surprising that Lamiaceae, which are often listed as over-utilized in other regions (see Table 1; Moerman et al. 1999), are under-utilized in the Hawaiian ethnopharmacopoeia. Lamiaceae are globally known and used for their medicinal values (Rahmatullah et al. 2010; Venkateshappa and Sreenath 2013; Zgórka and Glowniak 2001) because they have strong chemical defense mechanisms, such as volatile oils that make them so popular as aromatics. However, several plants that have evolved on oceanic islands such as Hawaii have lost their defense mechanisms against mammalian herbivores (Bowen and Van Vuren 1997; but see Barton 2014; Hoan et al. 2014). As a result, the Hawaiian endemic mint is "mintless" (Carlquist 1970; Leopold and Hess 2017). Such limitations in the production of secondary compounds in some Lamiaceae may explain the under-utilization of this family for medicinal purposes in Hawaii contrary to reports elsewhere.

*Within Plant Organ Selection for Medicinal Purpose*—. Another potential pathway in which species in the Poaceae family may be utilized due to the production of phytochemicals that have medicinal, physiological effects is through the utilization of specific plant parts at specific stages of plant growth and yearly cycles. The Ulu Mau report documents that four pounded leaf buds of *S. officinarum*, Poaceae, and Kō in Hawaii, mixed with koali, *Ipomoea indica* (Burm.) Merr., Convolvulaceae, is a treatment for bone fractures (Edith Kanakaʻaole Foundation 2005). While koali, *I. indica*, may be considered the dominant plant in this formula, harvesting a leaf bud for

medicine may be an opportune time to maximize the plants' phytochemical potentials, as plant defense theory proposes that seedlings sometimes have higher phytochemical defenses for protective purposes (Barton and Hanley 2013). The roots of *Schoenoplectus lacustris*, Cyperaceae, also known as nānakū, and the roots of ʻahuʻawa, *Mariscus* sp., Cyperaceae, are also used in Hawaiian remedies, also indicating the potential for physiologically important phytochemicals present in these organs. Thus, it is important to consider the significance of a working body of knowledge of when to harvest a plant and what part to use and how this can radically alter and influence the type of constituents available for medical applications.

## Conclusion

The theory of non-random plant selection predicts that not all medicinal plant families are utilized equally and, generally, that over-utilized plant families are high in phytochemicals that have a physiological effect in humans. We performed a regression analysis with Hawaiian medicinal plants, obtaining residuals by comparing the number of medicinal plants in a given family to the number of species on the islands in that family. This has resulted in data that projects a unique pattern of Hawaiian herbal practice when compared to other studies from other geographical areas (Moerman et al. 1999). Our study suggests, surprisingly, that alkaloid-poor families such as the Poaceae and Cyperaceae are over-utilized in Hawaii. Such over-utilization of alkaloid-poor plant families in the Hawaiian ethnopharmacopoeia is facilitated by the cultural practice of burning the plant and utilizing the ashes, as well as the relative availability and versatility of these families in the coastal and lowland of the Hawaiian land division system, the ahupuaʻa. Our study contributes to testing the theory of non-random medicinal plant selection and provides a unique pattern that nuances existing results from other regions of the world that Poaceae and Cyperaceae are the least utilized medicinal families in the plant kingdom.

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