Drone Use in Forestry 2021

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December 8, 2021

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Executive Summary

In the last few years, the utilization of Unoccupied Aerial Vehicles (drones) for research has become extremely popular. The advancement of microelectronics and battery technology has led to a rapid increase in the development of low-cost drones (Johnston, 2019). There are various advantages to using drones including on-demand remote sensing, flexibility in time and space, high precision, reduced cost/labor, and reduced human risk (Johnston, 2019; Banu *et al.*, 2016). For all of these reasons, drones are now being employed in the field of forestry where they are being used to gather a diverse set of data that can aid in a multitude of management activities (Banu *et al.*, 2016)

As this technology progresses, it is paramount to gain insight into the status and limitations of drone-use in forest management. This will enable the forest managers to better understand constraints and opportunities in order to make informed decisions going forward. To do this a nationwide survey targeting those in forest management was developed, distributed, and analyzed. The design of the research question as well as the design of the survey were created through personal experience, communication with experts, and guidance from my client, The Forestland Group.

This survey examined many job sectors, job types, terrains and species compositions in order to get a better understanding of the use of drones in the forest management today. The results of this survey demonstrate that more than half of the sample population are not currently using drones. The majority of those who do not use drones would like to, however, many cite a lack of knowledge and training to do so. The remaining respondents are already utilizing drones in a variety of ways including monitoring active logging jobs, inspecting post-timber harvest and

using them as communication tool. The ways in which respondents use drones was compared among various factors, including species compositions. In this instance, it was found that drones are used more significantly in pine plantations for a number of operational jobs in forest management, such as monitoring active logging, inspecting post-timber harvest and in for non-harvest activities. Respondents reported on the benefits they experienced from using drones in management, which include increased efficiency, quick access to high resolution imagery and improved safety.

However, there are limitations to drone use in forest management. These were highlighted when comparing reported limitations to various factors including species compositions and terrain. For instance, those who reported terrain as a significant limitation were working predominantly in mixed broadleaf and pine dominated forests in mountainous areas. The limitations that respondents highlighted most frequently were FAA regulations, the affordability of drones and sensors, as well as the availability of educational resources.

Going forward it will be vital to educate those in forest management on how to use drones to gather data whether it be imagery or from sensors. It will be important to inform people about software as well as the methods in processing and interpreting data gathered using a drone. Additionally, forest managers should monitor the evolution of FAA regulations as they have the power to influence the ways in which drones can be utilized. Taking these steps will enable forest managers to use this powerful tool to its full potential, across varying terrains and species compositions, as technologies become more affordable.

Introduction

In the last few years, the utilization of Unoccupied Aerial Vehicles (drones) for research has become extremely popular. The advancement of microelectronics and battery technology has led to a rapid increase in the development of low-cost drones (Johnston, 2019). There are various advantages to using drones including on-demand remote sensing, flexibility in time and space, high precision, reduced cost/labor, and reduced human risk (Johnston, 2019; Banu *et al.*, 2016). Additionally, new processing technology has also allowed for more information to be gathered from the imagery captured using drone technology. For instance, photogrammetry enables 2D imagery captured by a drone to be used to render 3D models of the earth. This can be used to measure heights of trees, delineate tree crowns, as well as gather other vital information regarding forests (Panagiotidis, 2016). One downside to this technology is that it requires imagery of the ground in order to produce height measurements, which is difficult in areas with variable terrain and dense canopies (SkyLab, personal communication, June 16, 2021).

In order to enhance the data gathered using drones, various sensors are now being utilized including light detection and ranging (LiDAR), multispectral, and hyperspectral sensors. LiDAR is an active sensor (sends out and measures signal) that uses laser pulses to measure ranges from the earth. These data are used to produce highly accurate 3D models (Wich & Piel, 2021). It is a powerful alternative to photogrammetry, with the primary advantage being the ability to penetrate dense vegetation, allowing for height measurements regardless of the density of canopy cover (Neuville *et al.*, 2021). Both multispectral and hyperspectral cameras are passive sensors (detects input from the physical environment, i.e. sunlight being reflected off the earth) that can detect more of the electromagnetic spectrum than a traditional camera which only "sees" red, green, and blue (RGB) (Wich & Piel, 2021). This enables users to understand more fine scale information from imagery that wouldn't otherwise be possible (Ballanti, 2016).

Drones are now being employed in the field of forestry where they are being used to gather a diverse set of data that can aid in a multitude of management activities (Banu *et al*., 2016). For instance, drones can be used to aid in a better understanding of wildfire and wildfire recovery. Drones offer a higher spatial resolution than satellite and airborne collections allowing for the burned area to be classified more accurately and in a timelier fashion, along with the potential to assess forest recovery through time (Aicardi *et al*., 2016, Samiappan *et al*., 2019). Multispectral sensors are being used to detect flame height, fire intensity, and spread rate (Samiappan *et al*., 2019). Additionally, drones have kept firefighters safe. According to the US Forest Service nearly a quarter of wildland firefighter fatalities are related to aviation, most of which can be avoided through the utilization of drones (Smithsonian Magazine, 2021).

Wildfire is not the only use of drones relating to fire management in forests. Drones have recently been used to assist in prescribed fires. In fact, US Forest Service and various professionals have started using an IGNIS system, developed by Drone Amplified in partnership with the Department of Interior, which drops fire ignition from a drone in order to start the prescribed burn (Smithsonian Magazine, 2021). Aside from starting the fire, drones have been utilized for monitoring prescribed fire using videography and thermal imaging, as well as evaluating the forest post-fire (Commonwealth of Massachusetts, 2021).

Drones are also being used to assess plant health, wildlife damage, and damages after natural disasters. Drones mounted with a multispectral camera are useful in detecting and monitoring plant health, specifically disease outbreaks, through the detection of discoloration in foliage (Dash *et al*., 2017). Although, in some cases outbreaks can even be detected using RGB cameras (Abdalla *et al*., 2020). For forest disturbance monitoring, drones are being used by Puttock *et al*. (2015) to look at and monitor the impacts of beavers. They found that drones are a useful tool because they allow for rapid and regular monitoring in an ecosystem flooding and tree removal that changes often due to dam and canal building by the beavers. This rapid and regular monitoring is also why the use of drones is useful in the event of a natural disaster (Zwegliński, 2020).

Aside from drones' utility in fire management and assessing plant health, wildlife and natural disaster damage, they have also been utilized in a number of traditional forest management roles, such as active logging, post-timber harvest inspection, non-harvest activities (including site prep and planting), as well as inspecting and mapping property. West Virginia's Division of Forestry is using drones to inspect active logging jobs as well as inspecting jobs post-harvest, ensuring that best management practices are being adhered to. The director of the program, Rodger Ozburn, even states that an inspection that once took several hours to complete could now be done in under an hour with a drone (West Virginia Division of Forestry, 2021). Rayonier had very similar reactions to drone-use regarding their increased efficiency (Rayonier, 2020). Additionally, they have also been utilizing drones in order to attach cables in tower logging; this process would normally take days but with drones it now takes about 10 minutes (Rayonier, 2020).

In addition, drones are beginning to be used to conduct timber inventory in areas that are mostly pine-dominated or pine plantations. Alonzo *et al. (*2018) explored the potential use of drones and structure-from-motion software to create tree density, basal area, and above ground biomass estimates in a pine-dominated area with hilly/rolling topography. The predominant species were black spruce (*Picea mariana*) and white spruce (*Picea glauca*) on four plots that were each 0.17 acres. Panagiotidis *et al*. (2016) focused on determining crown diameter and tree height using high resolution drone imagery on a flat 0.154-acre plot in the Czech Republic with a Norway spruce (*Picea abies*) dominated forest. However, the use of drones has not yet been adopted by those working on steep terrains with complex species compositions, such as those in mixed broadleaf forests that contain more than 3 to 4 species. Using drones, without LiDAR, in steep terrain combined with dense canopies make the acquisition of tree height nearly impossible. In addition, the crown overlap in broadleaf forests makes it difficult, if not impossible, to identify and count individual crowns. Finally, in forests with complex species compositions it is hard to speciate the canopy even when using a multispectral camera (SkyLab, personal communication, June 16, 2021).

While there are many advantages to the use of drones in forestry and forest management, it should be noted that there are also many limitations when applying methods across varying terrain, species compositions, and economic scales (SkyLab, personal communication, June 16, 2021). Additionally, the Federal Aviation Administration (FAA), has a number of regulations on the use of drones, including maximum altitudes, the inability for pilots to fly beyond visual line of sight, and restrictive airspace (FAA, 2021). While the regulations are in place as safety measures, they are restrictive to those working on large acreages as well as those in areas with variable terrain. Further, while many see the potential of drones, they are still waiting for technological advances, such as longer flight times, affordable sensors and software, more accurate GPS systems within the drone, etc.

Nevertheless, more people in forest management are beginning to explore the use of drones in forest management today. Currently, there is not a resource that lays out all of the ways in which drones are being used in forest management and the limitations that collectively affect further utilization. In order to provide this resource, a nationwide survey targeting those in forest management was developed, distributed, and analyzed. The design of the research question as well as the design of the survey were created through personal experience, communication with experts, and guidance from my client, The Forestland Group. Overall, this survey is intended to summarize the practical uses of drones in forestry today, limitations, and potential avenues for the future.

Methods

Section 2.1. Survey Description

The Forestland Group is a timber investment management operation (TIMO) that manages 2.3 million acres of natural forestland. When managing that much land, innovation and new technology that offer the promise of increased efficiency are appealing. At the outset of this study, I was hoping to explore the possibility of using drones to conduct timber inventory in the mountainous, mixed broadleaf forests of West Virginia in partnership with The Forestland Group. However, after much research, correspondence with various professionals in the field and failed field trials, it was determined that conducting timber inventory in mountainous mixed broadleaf forests was not feasible operationally using consumer-grade drones. The scope of the study then shifted to gaining a sense of the opportunities and constraints in regard to drone-use in forestry. In order to do this, a nationwide survey targeting those in forest management was created and distributed.

To create this survey, I used my own experience in trying to conduct timber inventory using drones and field experience using drones to do post-timber harvest inspections as well as a multitude of other activities. I spent time with foresters discussing possibilities for drone-use, where they saw a need as well as where they saw limitations. Additionally, I spoke with various professionals in the field to better understand how they were utilizing drones. I also used the expertise and experience of those at The Forestland Group to guide my questions.

The survey first asked people to identify their gender, race, job sector, and job type. This was followed by a multiple-choice question regarding whether they used drones or not. Those who did not use drones were asked a multiple-choice question regarding their interest level in using drones in their line of work. This was followed by another multiple-choice question regarding their reasoning for not using drones. For those who did use drones I used a series of multiple-choice questions that inquired about how often they use drones, how many people at their place of employment use drones, the terrain they flew in, the species composition where they flew, etc.

I also asked two questions using the Likert scale. A Likert scale question provides respondents with a set of, in this case, verbal options that range from one extreme to another. For the Likert scale question regarding work done using drone I gave numeric values to each response, in which “Does not describe me” = 1, “Describes me slightly well” = 2, “Describes me moderately well” = 3, “Describes me very well” = 4, and “Describes me extremely well” = 5.

Similarly, I assigned numeric values to the Likert scale question regarding limitations of drone use, in which “None at all” = 1, “A little” = 2, “A moderate amount” = 3, “A lot” = 4, and “A great deal” = 5.

Additionally, I had three open-ended questions that addressed the benefits of drone-use, what people hoped to use drones for that they couldn’t currently, as well as any additional comments they had (see Appendix B).

Section 2.2 Survey Distribution

This survey was intended to survey as many people in forest management as possible. It was focused on the entirety of the United States, aiming to capture a breadth of experience, terrain, species composition, etc. On September 21, September 28, and October 5, 2021 the survey was distributed using the online survey platform Qualtrics. The majority of the recipients were people listed as certified foresters through the Society of American Foresters (SAF), foresters or forestry-related professionals found on Division of Forestry, or its equivalent, websites for all 50 states, and people listed as working for the National Forest Service. In total, the survey was sent to 10,296 people in a forestry related profession. Every survey had an accompanying email prompting the recipient to fill out the survey. Both the email and the final survey can be found in Appendix B. On October 25, 2021 the survey was closed, and no more responses were collected after this time.

Section 2.3 Survey Limitations

It is important to remember there are several possible sources of error in this survey, including: self-selection, non-random sampling, limitation of choices, coverage error, as well as item non-response.

Self-Selection

Self-selection bias is a problem that results from allowing survey respondents to decide on their own whether or not they want to participate in the survey and will likely not be representative of the entire target population (Lavrakas, 2008). This means that the respondents of this survey are likely to be people who have a strong opinion one way or the other regarding drone use, rather than capturing those who have a more neutral stance. For instance, people in forest management who are using drones regularly or in an innovative way are going to be highly motivated to respond. In contrast to these respondents, people in forest management who feel very strongly that drones should not be used in the field of forestry are likely to respond as well. Generally, the issue with this sampling is that only the most extreme viewpoints are captured.

Non-Random Sampling

Non-random sampling, or non-probability purposive sampling, is another source of error in my survey. I gathered emails for this survey with a specific purpose in mind and I had a predefined group that I was interested in surveying (Trochim, 2021). More specifically, I was interested in forestry-related professionals and their experience or lack thereof with drones. The issue with this type of sampling is that I am likely to get opinions of my target group, however I am likely to overweight subgroups within my population, especially if contact information was more readily accessible (Trochim, 2021).

Limitation of Choice

The respondents of the survey were given a list of choices in 18 of the 26 questions of the survey. I tried to be as inclusive as possible and included a text box in nearly all of these questions. I did this so that if someone did not feel represented, they could share their answer. Although this effort was made, respondents may have omitted or skipped questions if they did not feel represented in the answer choices. People are more inclined to choose an option rather than type one.

Coverage Error

The survey was not evenly distributed throughout the United States. Some states had a plethora of contact information on their website while others did not. Therefore, some parts of the country are more well-represented than others.

Item Non-Response

Not all participants of this survey responded to every question that they were prompted to answer, which leads to an item non-response bias. There are many reasons for this bias including but not limited to: the participant doesn't know the answer, they have reasons for not responding which aren't understood, the survey was interrupted and not completed which is especially likely in an online survey such as this (NCES, 2012).

Section 2.4 Survey Analysis

In order to quantify the text entries for "What benefits have come from using drones in your line of work?" and "What would you like to do with drones that you can't currently?" I determined trends in the words used in answers and created categories based on those. I then created a binary system in which 1 indicated that the person belonged to the given category, and

0 indicated that the person did not belong to that category. The categories created for the question “What benefits have come from using drones in your line of work?” include: ‘Increased Efficiency’, ‘New Perspective’, ‘Save money’, ‘High resolution’, ‘Communication’, ‘Safety’, ‘Reconnaissance’, and ‘Temporal’. The categories created for the question “What would you like to do with drones that you can’t currently?” include: ‘Timber Inventory’, ‘Planting/Survival’, ‘Ease Regulations’, ‘Burn’, ‘Easier Mapping’, ‘Carrying capacity’, ‘Drone swarms’, ‘Increased Flight time’, ‘Utilize sensors’, ‘Education’, ‘Affordable software’, and ‘Terrain’. The definitions of these categories can be found in the Appendix A.

The median of the Likert scale questions (ranked 1-5) were recorded in order to better understand where drones were being used most and which limitations were the most limiting. Further, these questions were then analyzed across the varying demographics using a Kruskal-Wallis test, which tests for any significant difference in the means of Likert scale responses across the given demographics. If significance was found, a post-hoc Dunn Test was run in order to understand the degree that one group was ranked higher than another group (Mangiafico, 2016). The Kruskal-Wallis and Dunn Tests were run in R version 4.0.3 (R Core Team, 2020) using the packages *FSA* (Ogle *et al*., 2021) and *rcompanion* (Mangiafico *et al*., 2021). Data were visualized using Excel for pie charts, and the R package *tidyverse* (Wickham *et al*., 2019) for bar plots and box plots.

Results

Section 3.1 Respondent Demographics

This survey was sent to 10,296 people. Of those people, 1,330 people started the survey and 1,131 responded, meaning there was a 79% completion rate. In total there was a 11% response rate. The data was cleaned by removing those who did not understand the scope of the project, specifically retired people and people who worked/studied at universities and tried to respond for the university as a whole. Additionally, those who completed less than 50% of the survey were removed. After cleaning the data there were a total of 808 responses to analyze. The survey received at least one response from all 50 states in the United States, with high concentrations in the East Coast, Midwest, and Pacific Northwest (Figure 1). The vast majority of the respondents were male, most of the remaining respondents were female, with one respondent identifying as non-binary. The rest preferred not to share or did not respond, as shown in Table 1. The majority of these respondents identified as white, the remaining identified as Asian, Hispanic or Latino, Black or African American, American Indian, Alaska Native, Native Hawaiian or other Pacific Islander, or they preferred not to share/did not respond, as shown in Table 2.

Distribution of Survey Respondents in the US

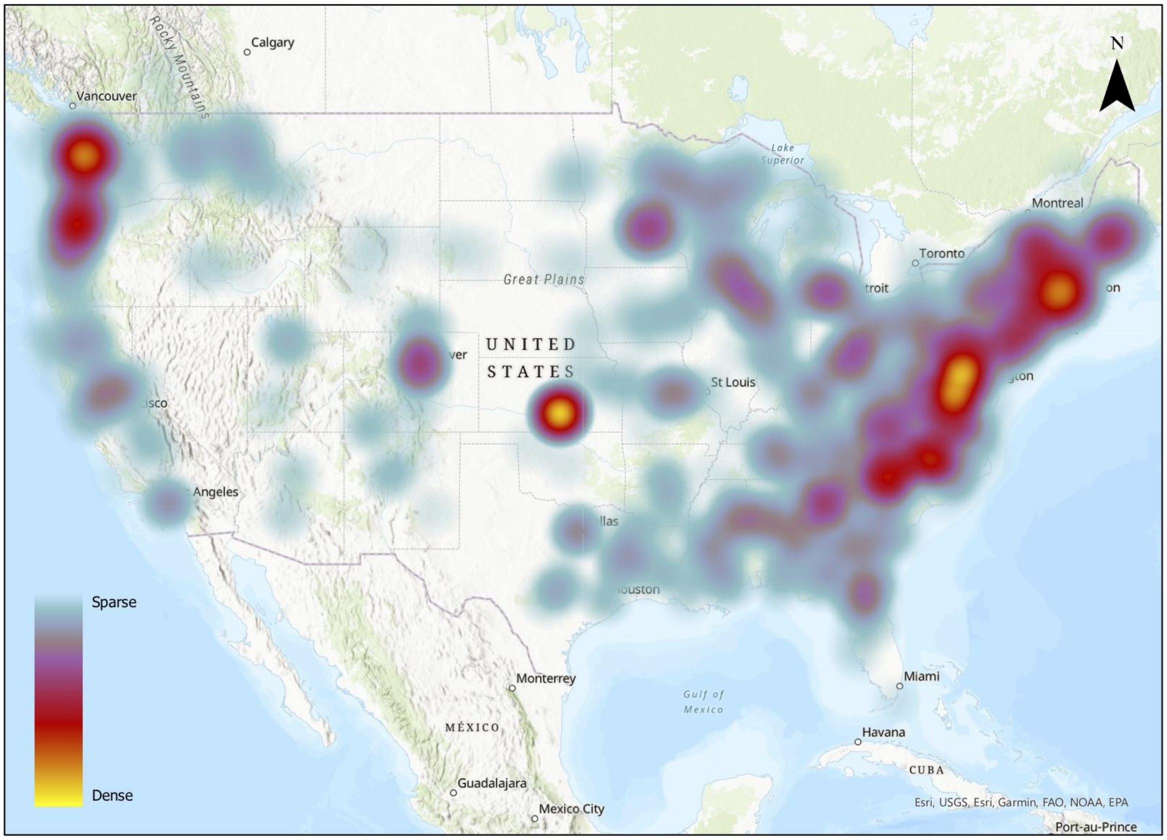

Figure 1. Geographic density of respondents and their distribution throughout the United States. At least one person was surveyed in each state. Not shown are the sparse number of people who responded in Hawaii and Alaska.

Table 1. This is a table of all of the genders represented in this survey.

Gender	Percent (%)	Count
Male	81.3	657
Female	15.4	124
Non-binary	0.1	1
Prefer not to share	2.8	23
No response	0.3	3
Total	100	808

Table 2. Races represented in this survey.

Race	Percent (%)	Count
White	89.6	724
Asian	1.7	14
Hispanic or Latino	0.4	3
Black or African American	0.4	3
American Indian or Alaska Native	0.3	2
Native Hawaiian or other Pacific Islander	0.1	1
Prefer not to share	7	57
No response	0.5	4
Total	100	808

The largest response sector work for private (for profit) companies (44.3%). About a quarter work for a state government. This is followed by those who work for an educational institution. Others work for the federal government or a private not-for-profit (environmental NGO). A few respondents work for a local or tribal government. The remaining either did not respond or identified as "Other", which is people working as consultants to all of the above, people dealing with utilities, as well as financial institutions (Figure 2).

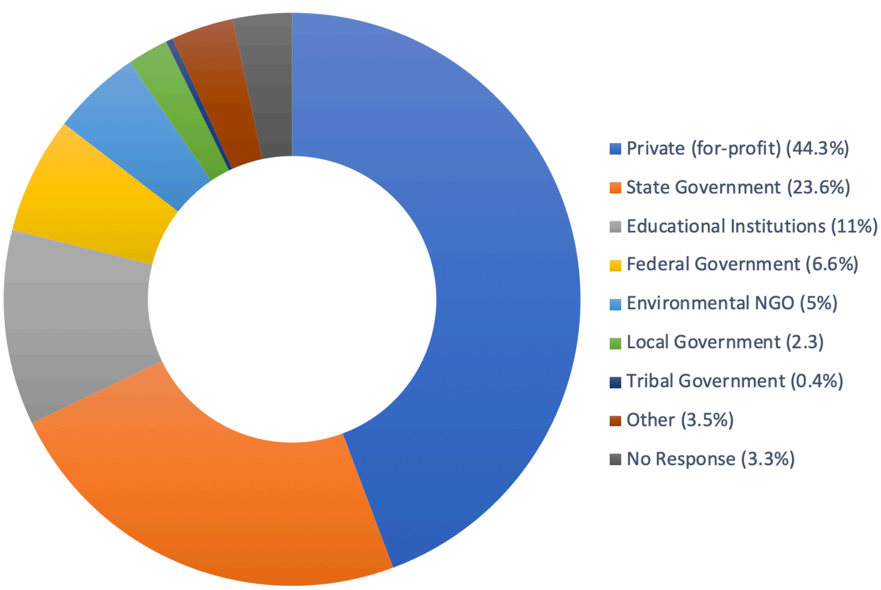

Figure 2. Proportions of job sectors represented by respondents of this survey.

Within these categories 38.6% of respondents identified themselves as field foresters, and a quarter of them identified as administrative/planning foresters. A substantial number identified themselves as researchers/educators. A few more identified as mapping/GIS professionals or field ecologists. The remaining either did not respond or identified as “Other”, which comprised of people in a multitude of different positions including those who identified as “all of the above”, CEOs, urban foresters, procurement foresters, logging professionals, forest biometricians, arborists, fire specialists, a historian, and a REDD+ advisor (Figure 3).

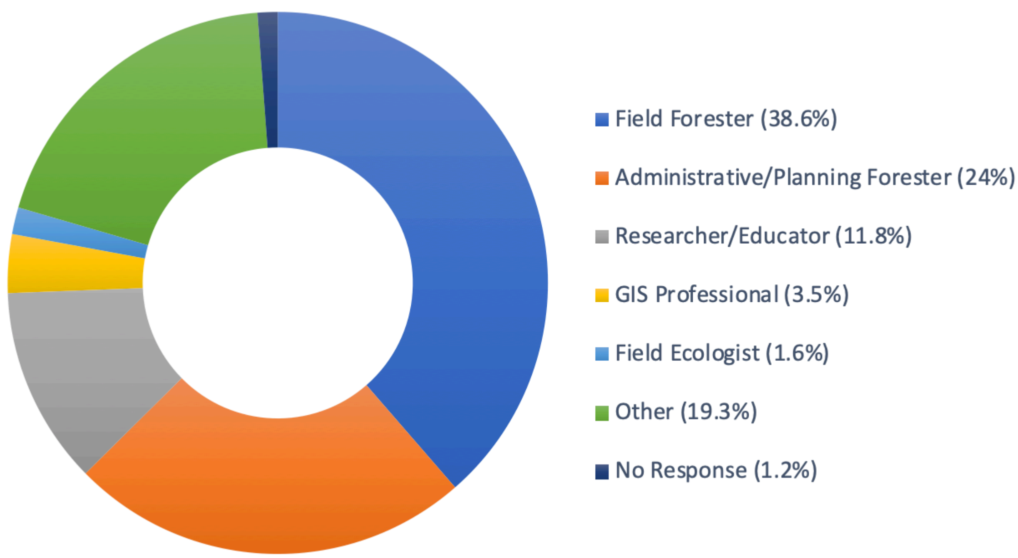

Figure 3. Proportions of job types represented by respondents of this survey.

The majority (65%) of these respondents have been in forest management for longer than 15 years, the remaining have been in forest management for under 1 year to 15 years. Of these people, 37% have been in their current role for more than 15 years, about a quarter have been in their current role for 1-5 years, a substantial amount have been in their current role for 5-15 years, and a few have been in their current role for under 1 year. The remaining 0.4% did not respond to this question.

Section 3.2 Demographics on the Absence of Drone-use Among Respondents

Of the 808 respondents, 430 reported that their place of employment had never used drones, of those nearly half work for private [for-profit] entities.

Among the 430, 21.4% (92 people) reported having no interest in drone use. Within this group of respondents, 39% said that they didn't see a need or the utility of a drone in their line of work. A substantial number of people said that it was due to a lack of knowledge/training, restrictive regulations, too expensive, or an ability to utilize a third party to gather data. A few others said that they were waiting for further advancements in technology. The remaining either did not respond, stated that all of the reasons stated above contributed to them not using drones, or they were not sure (Figure 4).

The majority of respondents (53.3%) within the group who have never used drones at their place of employment said that they were somewhat interested in using them. Most of these respondents (38%) said this was due to a lack of knowledge and training. This is followed by those who said they were waiting for further advancements in technology, it was too expensive, they could utilize a third party, or for "other" reasons. A few other respondents stated that it was due to restrictive regulations, no use for drones at this time, or they had a lack of time to learn how to utilize drones. The remaining claimed they were not using drones for "all of the above" reasons, the limited battery life of drones, lack of access to a drone, the negative perception surrounding drones, waiting for proven utility, or that they preferred "traditional" methods (Figure 4).

On the other hand, about a quarter of respondents (24.7%) who had never used drones at their place of employment said that they were definitely interested in using drones. 33% of those respondents stated that the reason they had not begun using drones was due to a lack of knowledge and training. A substantial number of respondents said that it is too expensive, they are waiting for further advancements in technology, restrictive regulations, or their ability to utilize a third party. A few others stated that it was due to a lack of time and resources to focus on implementing a new technology, their place of employment doesn't have an interest in new technology, or they haven't found the right application yet. The remaining people either did not give an answer or stated that it was for "all of the above" reasons (Figure 4).

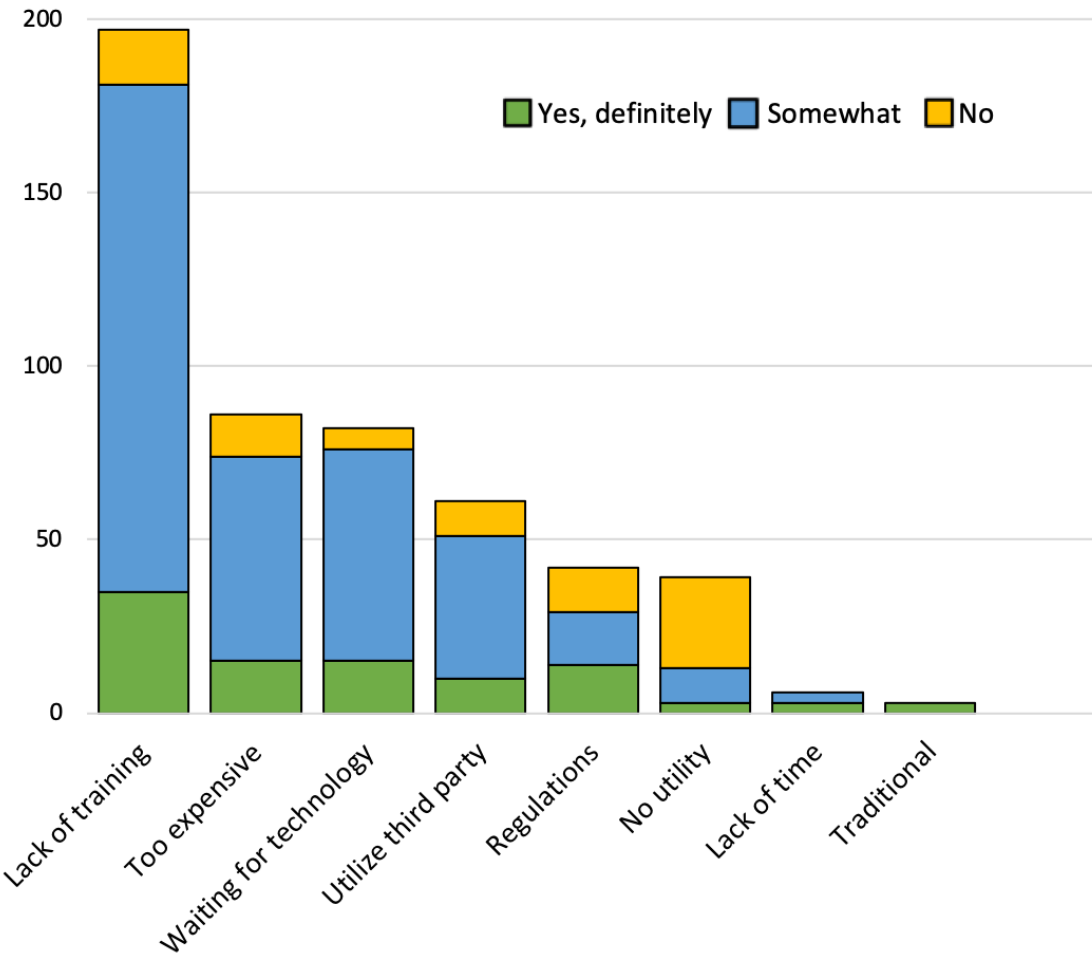

Figure 4. Respondents who were not currently using drones (n = 430). Interest in using drones (green = definitely, blue = somewhat, yellow = not interested) and the reasons why people are not using drones (X axis, count of respondents).

Section 3.3 Demographics on Drone Use among Respondents

Of the 808 respondents, 378 reported flying drones with some frequency. The greatest percentage (38%) of those who fly drones with some frequency reported using drones monthly. A substantial number reported using drones weekly or yearly. A small percentage of respondents reported using drones daily. Some respondents indicated they used drones with varying frequency, which includes use quarterly, infrequently, or a few times per year (Appendix C: Figure 1).

Length of Drone-use & Number of Pilots

In terms of how long the respondents' places of employment flew drones, I found that 60% had been flying drones for more than 24 months (2 years), a substantial number had been flying them for 12-24 months, and a small percentage for 0-12 months. The remaining 1% did not respond to this question (Appendix C: Figure 2). Of these respondents, the majority had 4 or more pilots, while over a quarter of respondents only had 1 pilot. A smaller portion only had 2 or 3 pilots. The remaining 8.3% did not respond to this question (Appendix C: Figure 3).

Species Composition

Among those that reported flying drones, 357 reported on the species composition where they fly most frequently. 32% of respondents fly most often in pine dominated forest, a little over a quarter of respondents fly most often in areas with mixed broadleaf species, and about a fifth of respondents fly most often in pine plantations. The remaining respondents fly most often in non-forest, coastal wetlands, and "other" (8.8%) which is comprised of responses such as: "all of the above", tundra, northern hardwood/mixed wood, prairie, mixed conifer, oak woodland, and agroforest (Appendix C: Figure 4).

Terrain

Among those who reported flying drones, 358 reported on the terrain where they flew most frequently. 56% of people flew in either hilly/rolling terrain or mountainous terrain (i.e. Appalachian Mountains, Rocky Mountains, etc.). Nearly a fifth of respondents reported flying most often in flat areas (plains), a few reported flying most often in coastal terrains, and a very small portion flew most often in marsh/swampland, canyons, and "other" which included responses such as: "all of the above", urban, and atolls (Appendix C: Figure 5).

Acreage

Nearly half (46%) of the respondents manage greater than 100,000 acres. About one fifth of the respondents manage 10,001-100,000. A substantial number either manage 1,001-10,000 acres or “none”. A few others manage 1-100 acres or 101-1,000 acres (Appendix C: Figure 6).

Hardware and Software

Of the respondents using drones, 236 reported their top performing drones, some people reported having more than one top performing drone. The vast majority (91%) are using DJI products. The most common top performing drone is DJI’s Mavic 2 Pro, followed by DJI’s Phantom series. This is followed by the DJI Matrice series (100, 210, 300 RTK and 600). A small number reported using DJI’s Mavic Mini or Mavic Air. A few reported using Evo II Pro drones, custom drones, DJI Sparks and DJI Inspire drones. One to two people reported using one of the following: Sensefly eBees, Yuneec H520, Birdseye’s FireFLY6, Parrot Bebob Thermal, Hubsan X4 FPV, Deerc DE22, 3DR Solo, SwitchBlade Elite, EXO drone, and IGNIS. The remaining respondents specified using DJI drones but did not include the model (Figure 5).

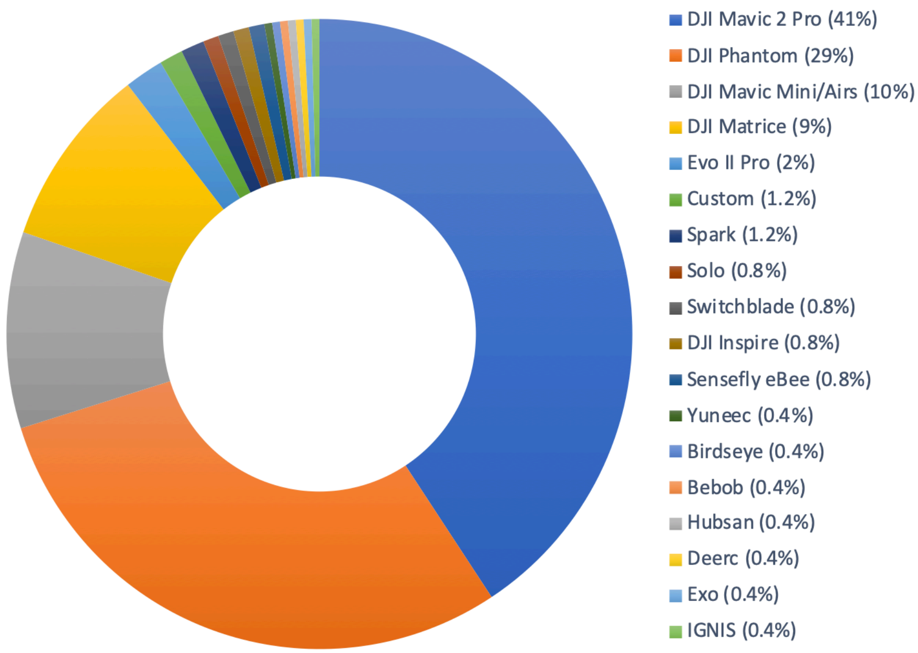

Figure 5. This pie chart highlights the proportions of hardware used by respondents of this survey.

As for the software, 321 respondents shared information on the software packages that they use most often when flying/processing imagery. Whether the software is used for flight or image processing cannot be discerned from the information gathered. Respondents were not limited to one choice; they could select as many choices that applied. I found that 38% reported using DJI software products. The second software most often used are ESRI Products. This is followed by DroneDeploy and Pix4D. The next software packages reported to be used most often are Maps Made Easy and AgiSoft Metashape. A few respondents report using OpenDroneMapper, Measure Ground Control, and SimActive. Others mention using Adobe Studio, B4UFLY, BotLink, Carlson PhotoCapture, DroneAmplified IGNIS, DroneSense, ENVI, Flightdeck, Global Mapper, Google Earth, Litchi, QGIS, Tower, Mission Planner, and Virtual Surveyor (Figure 6).

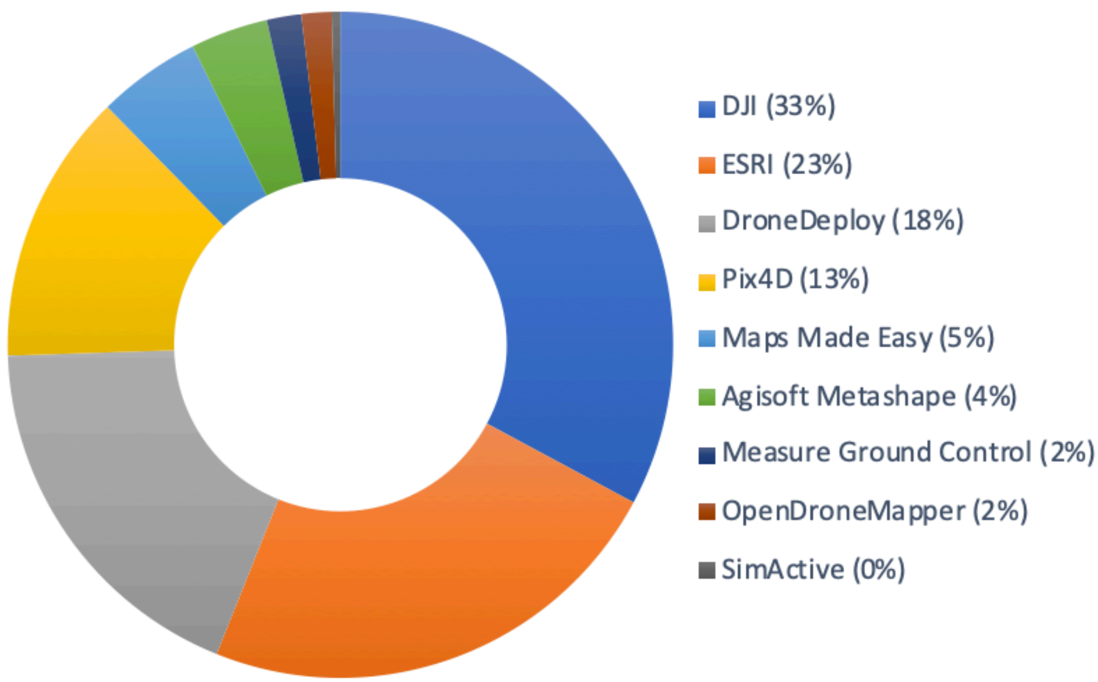

Figure 6. Proportions of software used by respondents of this survey.

Work Done Using Drone

Of the Likert scale questions, ranging from 1-5, the median responses were recorded. The work done using drones that describes people the best include use for communication purposes (median 3), mapping property (median 3), monitoring plant health (median 3), and post-timber harvest (median 3). This is followed by active logging (median 2) and non-harvest activities (median 2). The work done using drones that describes people the least (all with a median of 1) are conducting/monitoring prescribed fire, real estate, conducting timber inventory, urban planning, monitoring wildlife, and monitoring wildfire (Figure 7).

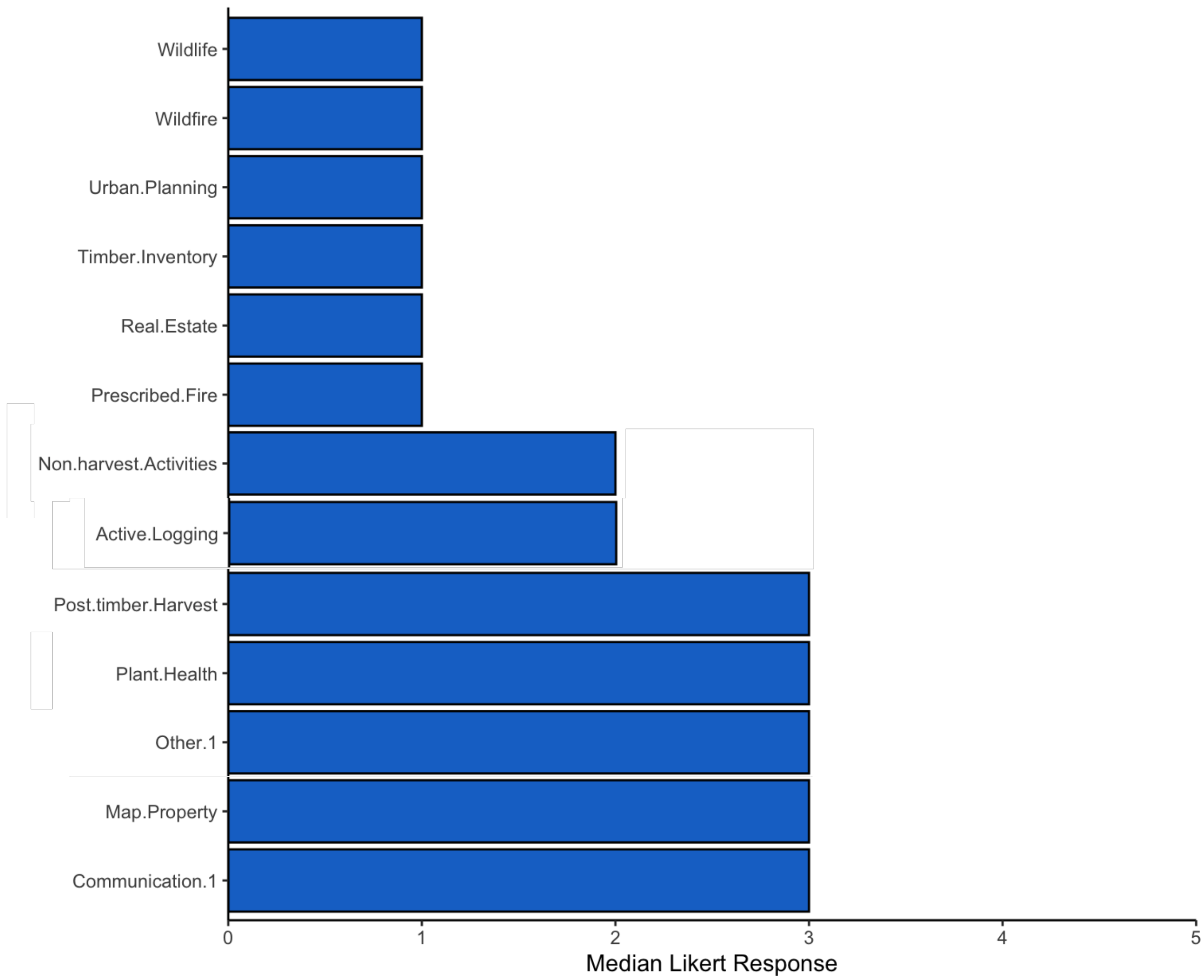

Figure 7. Median Likert response of work done using drones where 1 = "Does not describe me", 2 = "Describes me slightly well", 3 = "Describes me moderately well", 4 = "Describes me very well" and 5 = "Describes me extremely well".

Limitations of Drone-use

The greatest limitation affecting people using drones from accomplishing a task at hand is the inability to fly their drone beyond visual line of sight (median 3). Battery life (median 3), large acreage (median 3) and weather (median 3) were three other factors that impacted people's ability to accomplish the task at hand. Following these limitations, we have a lack of access to affordable sensors (median 2), terrain (median 2), lack of access to affordable software (median

2), computation power/storage (median 2), and species composition (median 2). “Other” had a median of 1, the text responses for this included complicated airspace, administrative hurdles, availability/cost of drones, canopy closure during the leaf-on season, wildlife interactions, federal regulations on China-made drones, drone payload, and ample data with not enough time to process all of it (Figure 8).

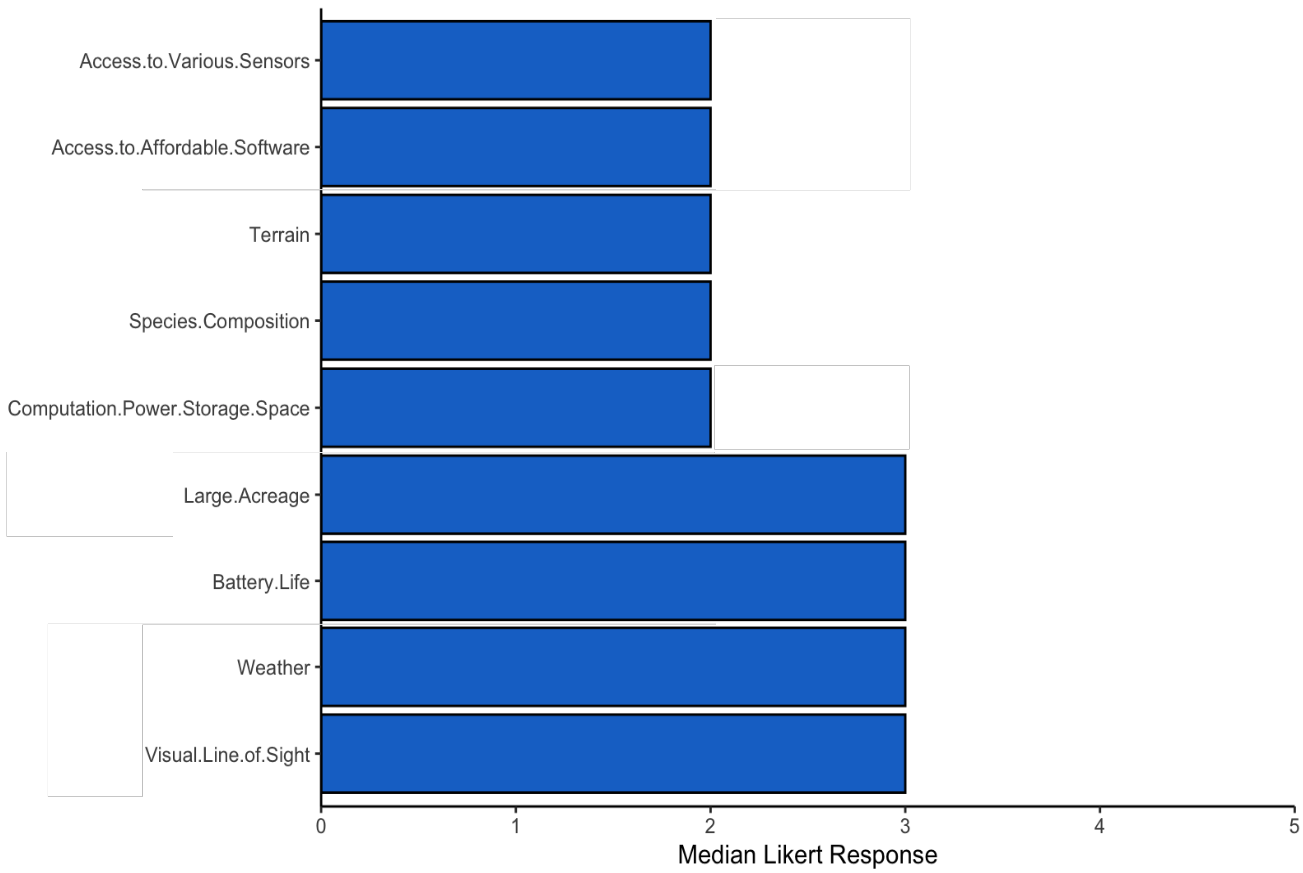

Figure 8. Median Likert response of limitations while using drones where 1 = “None at all”, 2 = “A little”, 3 = “A moderate amount”, 4 = “A lot” and 5 = “A great deal”.

Benefits of Drone-use

Of the respondents who use drones, 314 of them reported on the benefits that have come from using drones in their line of work; they were not limited to the number of benefits that they could report. More than half of these respondents reported increased efficiency as a benefit of using drones. Nearly 20% of respondents discussed the benefits of drones as a reconnaissance tool. A few other highly reported benefits include quick access to high resolution imagery, increased safety for workers, gaining a new perspective, and usefulness as a communication tool. Following these were the benefits of saving money and the ability to collect before and after imagery (Figure 9).

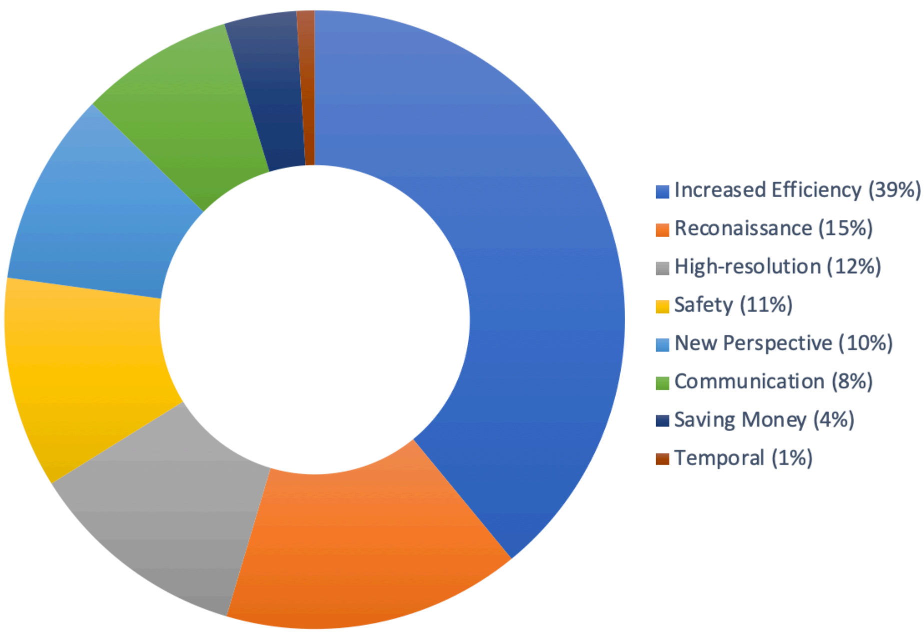

Figure 9. Proportions of benefits that respondents reported.

Hopes for Future Uses of Drones

Of the respondents who use drones, 258 of them reported on what they hope to be able to do with drones in the future; they were not limited in how many items they could report. Nearly 60% of these respondents hoped to conduct timber inventory/cruise timber, utilize more sensors on their drones, or fly with less regulations. 3 reported wanting to conduct stem counts and assessing TPA. A substantial number of respondents reported wanting increased flight time in order to get more extensive coverage as well as wanting the ability to more easily map things such as SMZs, tree crowns, property lines and regeneration. Others reported wanting to use drones for a multitude of activities regarding planting/survival, burning (prescribed fire, wildfire, ignition) as well as for delivering supplies to fire lines and aerial herbicide spraying (this would be done by increasing the carrying capacity of the drone). A few others reported wanting access to affordable software, to be able to use a swarm of drones, more education including workshops and training, or an easier way to deal with variable terrain. Additionally, one or two people hope for the ability to monitor wildlife, collect samples, measure log decks, gather more accurate above ground level (AGL) measurements, and zoom (Figure 10).

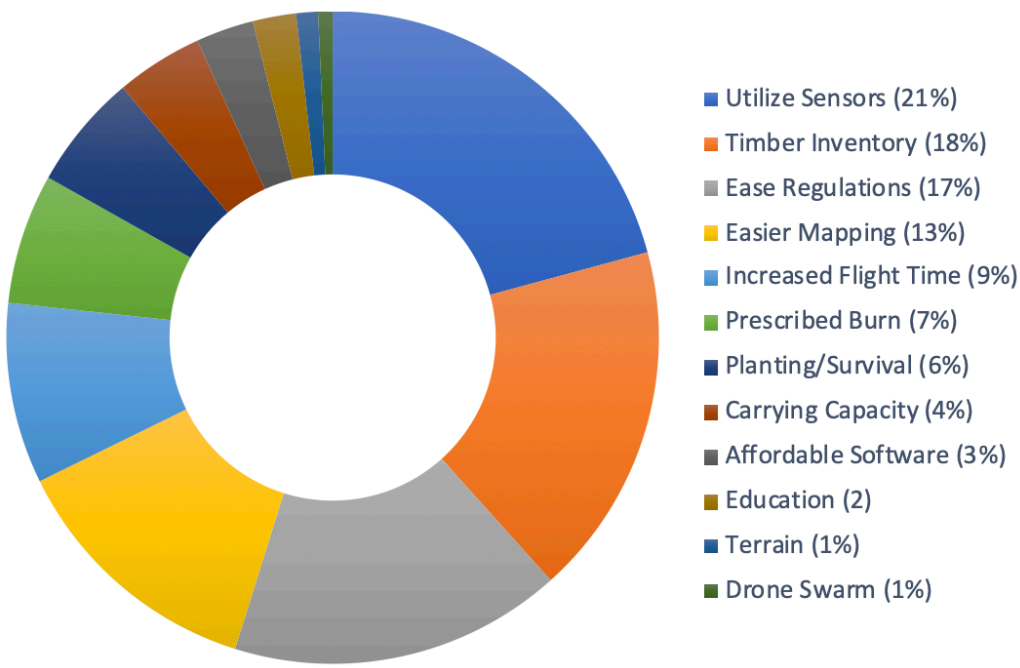

Figure 10. Proportions that respondents reported on what they hope to be able to do with drones in the future that they can't currently.

Section 3.4 Data Analysis on Drone-use

For this analysis two Likert scale questions were used: 1) "which of these describe the work that you do using drones?" and 2) "how much do each of these limitations affect you while using drones?” (Appendix B). The work that people do using drones included: wildfire, prescribed fire, active logging, post-timber harvest, non-harvest activities, timber inventory, urban planning, real estate, plant health, mapping property and communication. The limitations included: access to affordable sensors and software, terrain, species compositions, computation power/storage, large acreage, battery life, weather, and visual line of sight. I compared responses across various demographics including job sector, job type, terrain, species compositions and amount of acreage managed. I performed a Kruskal-Wallis test to determine whether there was any significant difference between the means and reported the p-value. Only comparisons that were found to be significant were reported. These results only represent the sample population, not the population as a whole.

Comparisons with Work Done Using Drones

Job Sector Comparison

Wildfire

When comparing work done using drones for wildfires across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 75.311, df = 6, $p<0.001$). The results of the post-hoc Dunn Test, suggest that the federal government uses drones for wildfires significantly more than educational institutions ($p<0.001$) as well as private (for-profit) ($p=0.01$). The state government uses them significantly more than educational institutions ($p<0.001$) and private (for-profit) ($p<0.001$). There is a trend where the state government is higher than self-employed ($p=0.08$). There is no significance in the rank of state and federal government (Figure 11).

Prescribed Fire

When comparing work done using drones for prescribed fire across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 63.857, df = 6, p<0.001). The results of the post-hoc Dunn Test, suggest that the state government uses drones for prescribed fires significantly more than educational institutions (p<0.001), as well as private (for-profit) (p<0.001). There were no other significant differences (Figure 11).

Active Logging

When comparing work done using drones for active logging across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 44.962, df = 6, p<0.001). The results of the Dunn Test suggest that there is a trend where "other" use of drones is higher than the federal government (p=0.02) or educational institutions (p=0.08). Private (for-profit) drone use for active logging is significantly higher than educational institutions (p<0.001), the federal government (p<0.001), or the state government (p=.003). Private (for-profit) is trending higher than private (not-for-profit) (p=0.06). The state government is trending higher than educational institutions (p=0.09). The state government uses drones for active logging significantly more than the federal government (p = 0.02) (Figure 11).

Post-timber Harvest

When comparing work done using drones for post-timber harvest across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 47.354, df = 6, p<0.001). The results of the post-hoc Dunn Test, suggest that private (for-profit) uses drones for post-timber harvest significantly more than educational institutions, state government and federal government (p<0.001). Private (for-profit) use drones for post-timber harvest significantly more than people who are self-employed ($p=0.04$). The state government is trending higher than the federal government ($p=0.05$) (Figure 11).

Non-harvest activity

When comparing work done using drones for non-harvest activities across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 21.265, df = 6, $p=0.0016$). The results of the post-hoc Dunn Test, suggest that private (for-profit) uses drones for non-harvest activities significantly more than the federal government ($p = 0.01$) and the state government ($p = 0.02$) (Figure 11).

Mapping Property

When comparing work done using drones for mapping property across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 23.519, df = 6, $p< 0.001$). The results of the post-hoc Dunn Test suggest that “Other” is trending higher than both the federal government ($p = 0.07$) and educational institutions ($p = 0.06$). Private (for-profit) uses them significantly more than the federal government ($p = 0.004$) and the state government ($p = 0.03$) (Figure 11).

Real Estate

When comparing work done using drones for real estate across various sectors, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 43.483, df = 6, $p<0.001$). The results of the post-hoc Dunn Test suggest that private (for-profit) uses drones for real-estate purposes significantly more than the federal government ($p=0.001$) and educational institutions ($p=0.002$). The state government uses them significantly more than the federal government ($p<0.001$) (Figure 11).

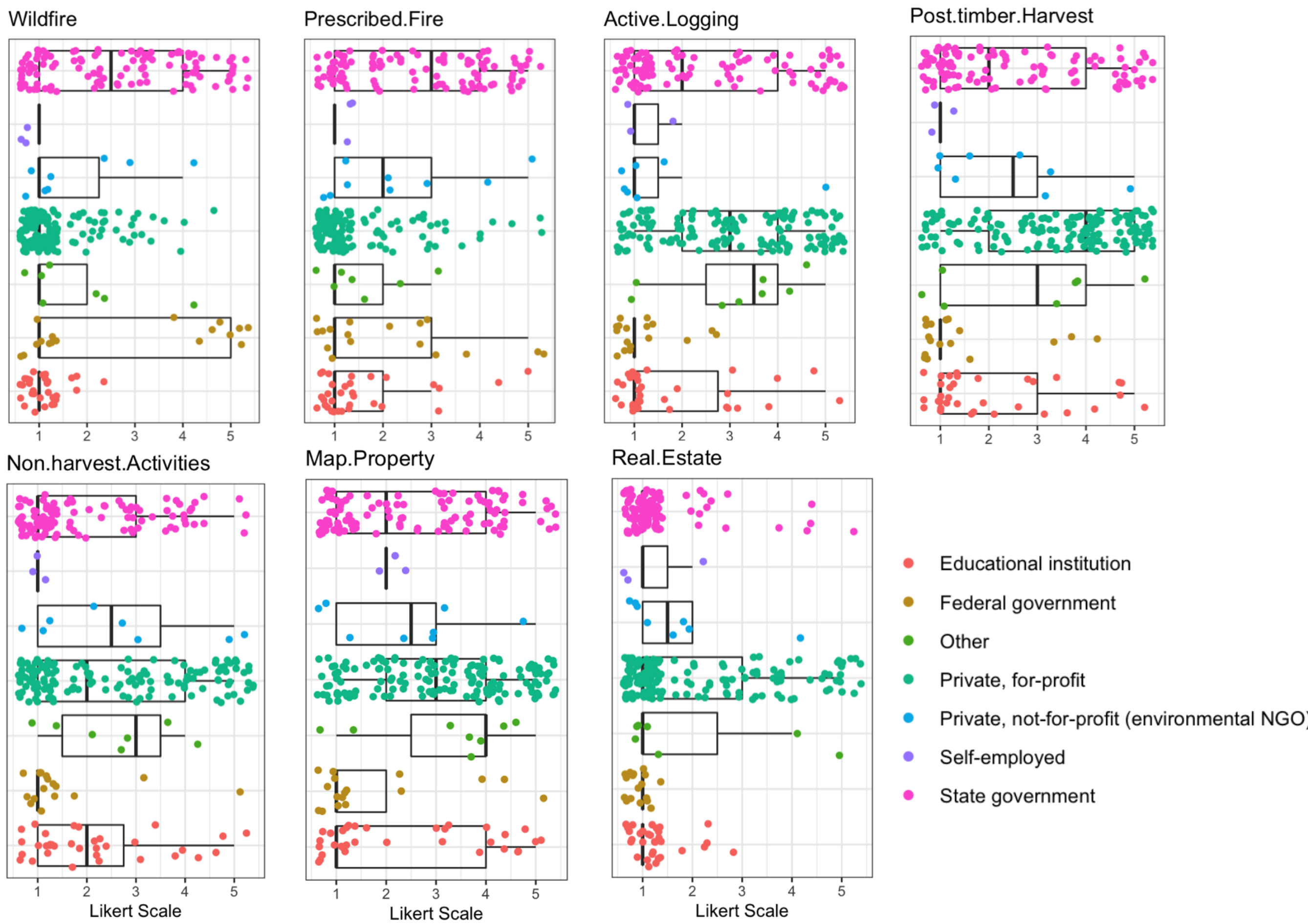

Figure 11. Likert scores for the work that respondents are doing using drones compared among job sectors. Significant differences were found among job sectors in all applications shown above. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Job Type Comparison

Wildfire

When comparing work done using drones for wildfire across various job types, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 16.103, df = 4, p=0.003). The results of the post-hoc Dunn Test, suggest that the administrative/planning foresters use drones for wildfires significantly more than researchers/educators (p=0.02).

Additionally, field foresters (p=0.002) and “other” (p=0.003) use drones for wildfires significantly more than researchers/educators (Figure 12).

Active Logging

When comparing work done using drones for active logging across various job types, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 17.564, df = 4, p=0.002). The results of the post-hoc Dunn Test, suggest that administrative/planning foresters use drones for active logging significantly more than researchers/educators (p=0.004). Field foresters use drones for active logging significantly more than researchers/educators (p =0.002). Additionally, those who identify as “other” also use drones significantly more for active logging than researchers/educators (p=0.04) (Figure 12).

Post-timber Harvest

When comparing work done using drones for post-timber harvest across various job types, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 17.108, df = 4, p=0.002). The results of the post-hoc Dunn Test, suggest that administrative/planning foresters (p=0.02) and field foresters (p=0.004) use drones for post-timber harvest significantly more than researchers/educators. Additionally, field foresters' use of drones for post-timber harvest is trending higher than field ecologists (p=0.08) (Figure 12).

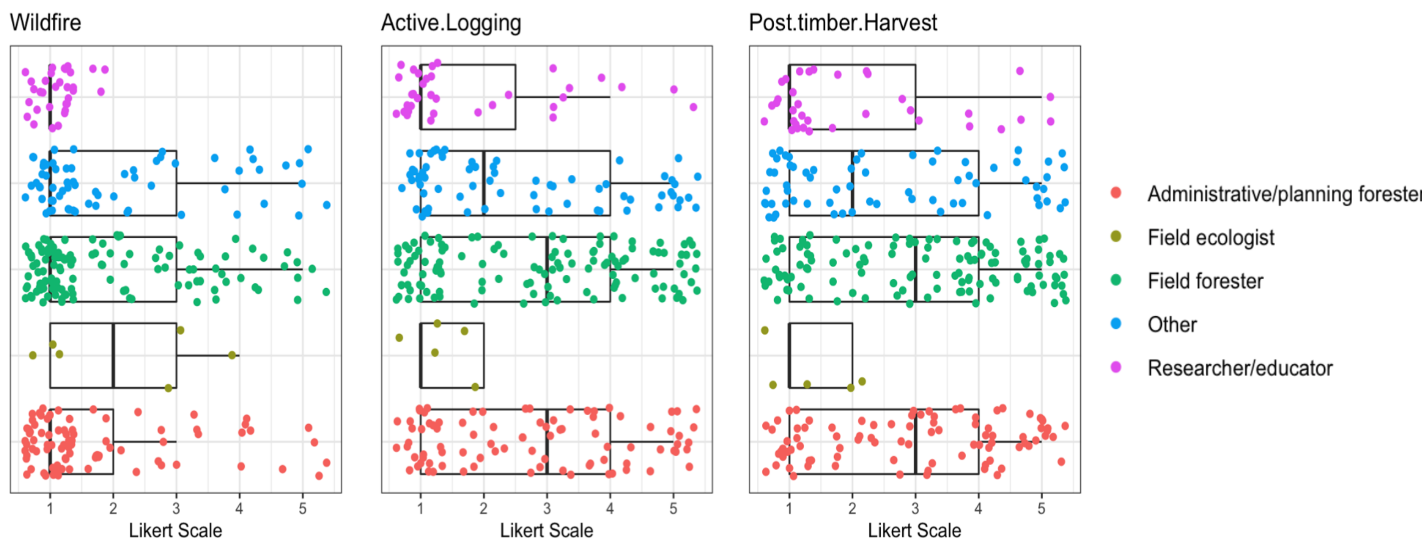

Figure 12. Likert scores for the work that respondents are doing using drones compared among job types. Significant differences were found among job types in all applications shown above. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Terrain Comparison

Wildfire

When comparing work done using drones for wildfires across various terrains, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 20.94, df = 6, p=0.002). The results of the post-hoc Dunn Test, suggest that drones are used in wildfires significantly more in mountainous terrain than in hilly/rolling terrain (p=0.008) or plains (flat) (p=0.03) (Figure 13).

Non-harvest Activities

When comparing work done using drones for non-harvest activities across various terrains, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 26.755, df = 6, p<0.001). The results of the post-hoc Dunn Test, suggest that drones are used in non-harvest activities significantly more in plains (flat) terrain than in coastal terrain (p=0.04), hilly/rolling (p<0.001) or mountainous terrain (p<0.001) (Figure 13).

Urban Planning

When comparing work done using drones for urban planning across various terrains, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared = 12.341, df = 6, p=0.05). However, a post-hoc Dunn Test found no significant pairwise differences between terrains (Figure 13).

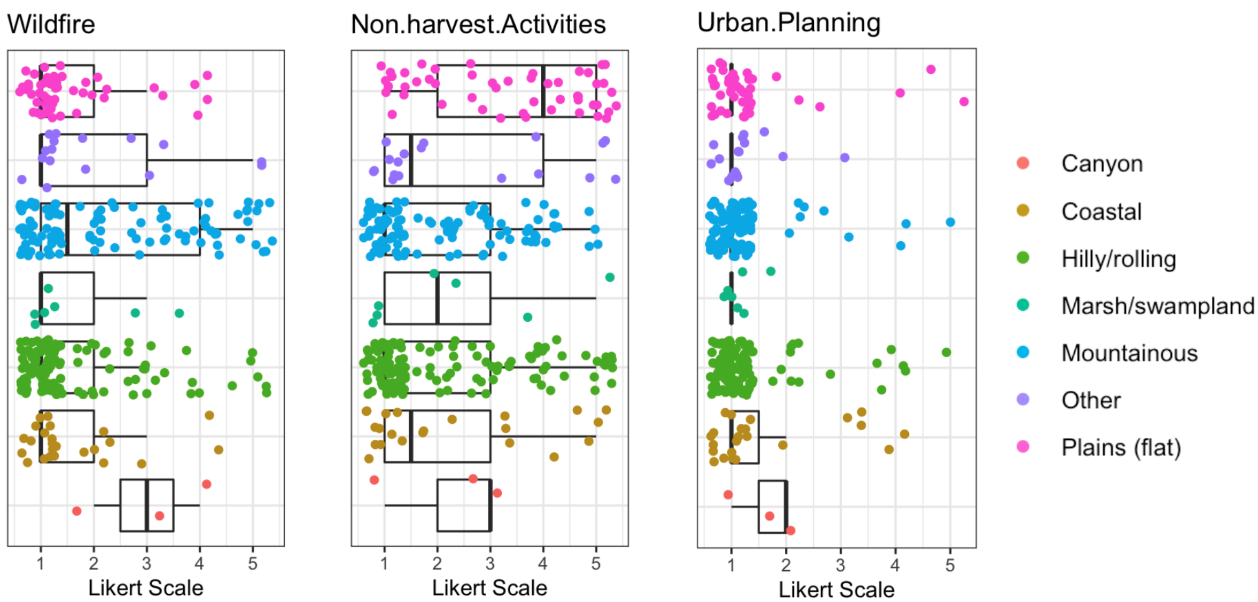

Figure 13. Likert scores for the work that respondents are doing using drones compared among terrains. Significant differences were found among Wildfire and Non-harvest Activities. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Species Composition Comparison

Wildfire

When comparing work done using drones for wildfire across various species compositions, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared=9.3808, df=4, p=0.05). However, a post-hoc Dunn Test found no significant pairwise differences between species comparisons (Figure 14).

Active Logging

When comparing work done using drones for active logging across various species compositions, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 14.827, df = 4, p=0.005). The results of the post-hoc Dunn Test, suggest that those using drones in mixed broadleaf forests are trending higher than those in "other" (p=0.07). Pine dominated (p=0.06) and "other" (p=0.08) are trending higher than non-forest. Pine plantation is trending higher than mixed broadleaf (p=0.06). Additionally, the use of drones for active logging in pine plantations is significantly greater than in non-forest (p=0.01) and pine dominated forests (p=0.04) (Figure 14).

Post-timber Harvest

When comparing work done using drones for post-timber harvest across various species compositions, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 22.525, df = 4, p<0.001). The results of the post-hoc Dunn Test, suggest that the use of drones in mixed broadleaf forests is significantly more than in non-forests (p=0.01). "Other" is trending higher than non-forest (p=0.05). The use of drones for post-timber harvest in pine dominated forests is significantly higher than in non-forests (p=0.007). Additionally, the use of drones in pine plantations is significantly greater than in mixed broadleaf forests (p=0.01), non-forest (p=0.005), and "other" (p=0.009). Drones used for post-timber harvest in pine plantations are trending higher than in dine dominated forests (p=0.05) (Figure 14).

Non-harvest Activity

When comparing work done using drones for non-harvest activities across various species compositions, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 29.764, df = 4, p<0.001). The results of the post-hoc Dunn Test, suggest that drones are used for non-harvest activities in pine dominated forests significantly more than mixed broadleaf forests ($p=0.04$). It also suggests that drones are used in non-harvest activities significantly more in pine plantations than in mixed broadleaf forests ($p<0.001$) or pine dominated forests ($p=0.006$). Additionally, the use of drones is trending higher in pine plantations than non-forest ($p=0.03$) and "other" ($p=0.04$) (Figure 14).

Map Property

When comparing work done using drones for mapping property across various species compositions, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 10.087, df = 4, $p=0.04$). The results of the post-hoc Dunn Test suggest that the use of drones in mapping is trending higher in pine plantations than in mixed broadleaf forests ($p=0.08$) (Figure 14).

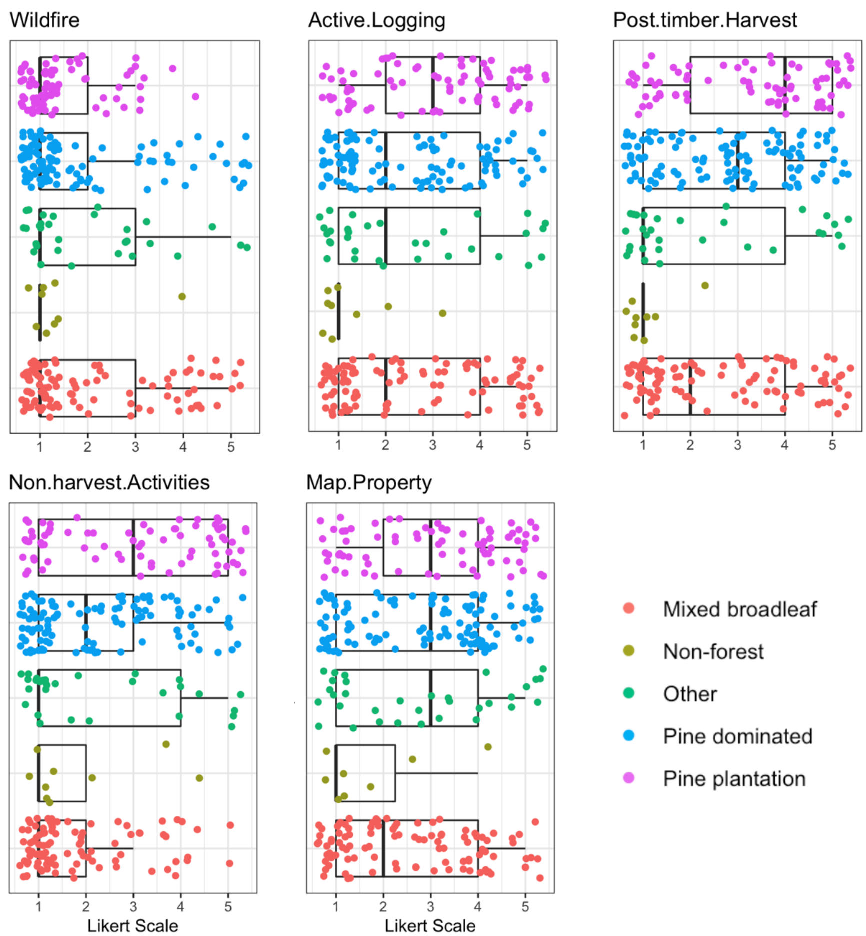

Figure 14. Likert scores for the work that respondents are doing using drones compared among species compositions. Significant differences were found among species compositions in all applications shown above except for Wildfire. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Limitations When Using Drones

Job Sector Comparison

Terrain

When comparing the limitation of terrain on drone use across various sectors, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared = 13.723, df = 6, p=0.03). However, a post-hoc Dunn Test found no significant pairwise differences between job sectors.

Large Acreage

When comparing the limitation of large acreage on drone use across various sectors, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared = 15.079, df = 5, p=0.02). However, a post-hoc Dunn Test found no significant pairwise differences between job sectors.

Terrain Comparison

Terrain

When comparing the limitation of terrain on drone use across various terrain, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 62.633, df = 6, p<0.001). The results of the post-hoc Dunn Test, suggest that the limitation of terrain is more significant in mountainous areas compared to coastal (p<0.001), hilly/rolling (p<0.001), plains (flat) (p<0.001), and “other” (p=0.002). The limitation of terrain is significantly more in areas that are hilly/rolling (p=0.001) and canyons (p=0.02) compared to plains (flat) (Figure 15).

Species Composition

When comparing the limitation of species compositions on drone use across various terrain, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared = 12.67, df = 6, p=0.05). However, a post-hoc Dunn Test found no significant pairwise differences between terrains (Figure 15).

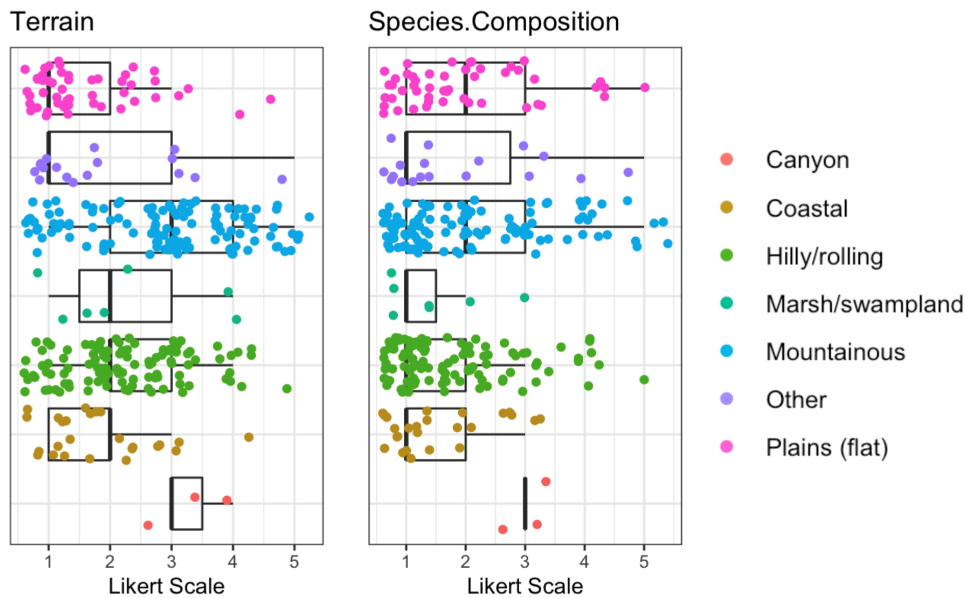

Figure 15. Likert scores for limitations respondents experience while using drones compared among terrains. Significant differences were only found among Terrain. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Species Composition Comparison

Terrain

When comparing the limitation of terrain on drone use across various species, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 43.599, df = 4, p<0.001). The results of the post-hoc Dunn Test, suggest terrain is a limitation more significantly in areas with mixed broadleaf forests (p<0.001), pine dominated forests (p<0.001) compared to pine plantations (Figure 16).

Terrain

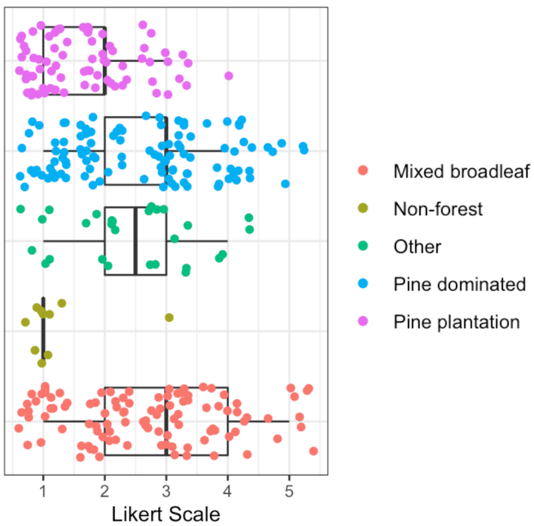

Figure 16. Likert scores for limitations respondents experience using drones compared among terrains. Significant differences were found among terrains with only the limitation Terrain. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Acreage Comparison

Visual Line of Sight

When comparing the limitation of visual line of sight on drone use across various amounts of acreage, a significant difference in the means was determined among all groups (Kruskal-Wallis chi-squared = 10.135, df = 5, p=0.07). However, a post-hoc Dunn Test found no significant pairwise differences between acreages (Figure 17).

Terrain

When comparing the limitation of terrain on drone use across various amounts of acreage, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 28.557, df = 5, p<0.001). The results of the post-hoc Dunn Test, suggest that the limitation of terrain is significantly more for those working in areas that are greater than 100,001 acres (p=0.06) than those working on 1,001-10,000 acres (p<0.001) and those managing "none" (p=0.003). 10,001-100,000 is trending higher compared to those working on 100,001+ acres (Figure 17).

Computation and Storage Space

When comparing the limitation of computation power/storage on drone use across various amounts of acreage, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 13.055, df = 5, p=0.02). The results of the post-hoc Dunn Test, suggest that the limitation of computational power/storage is trending higher for those working in areas that are greater than 100,001 acres (p=0.06) than those managing 10,001-100,000 acres. Computational power/storage as a limitation is trending higher for those managing 10,001-100,000 acres than those managing 1,001-10,000 acres (p=0.07). However, "None" is trending higher than 1,001-10,000 acres (p=0.07) (Figure 17).

Large Acreage

When comparing the limitation of large acreage on drone use across various amounts of acreage, a significant difference in the means was determined (Kruskal-Wallis chi-squared = 35.455, df = 5, p<0.001). The results of the post-hoc Dunn Test, suggest that the limitation of large acreage is significantly more for those managing 100,000+ acres than those managing "none" (p<0.001), 101-1,000 acres (p=0.003), 1,001-10,000 acres (p<0.001), and those managing 10,001-100,000 acres (p=0.03) (Figure 17).

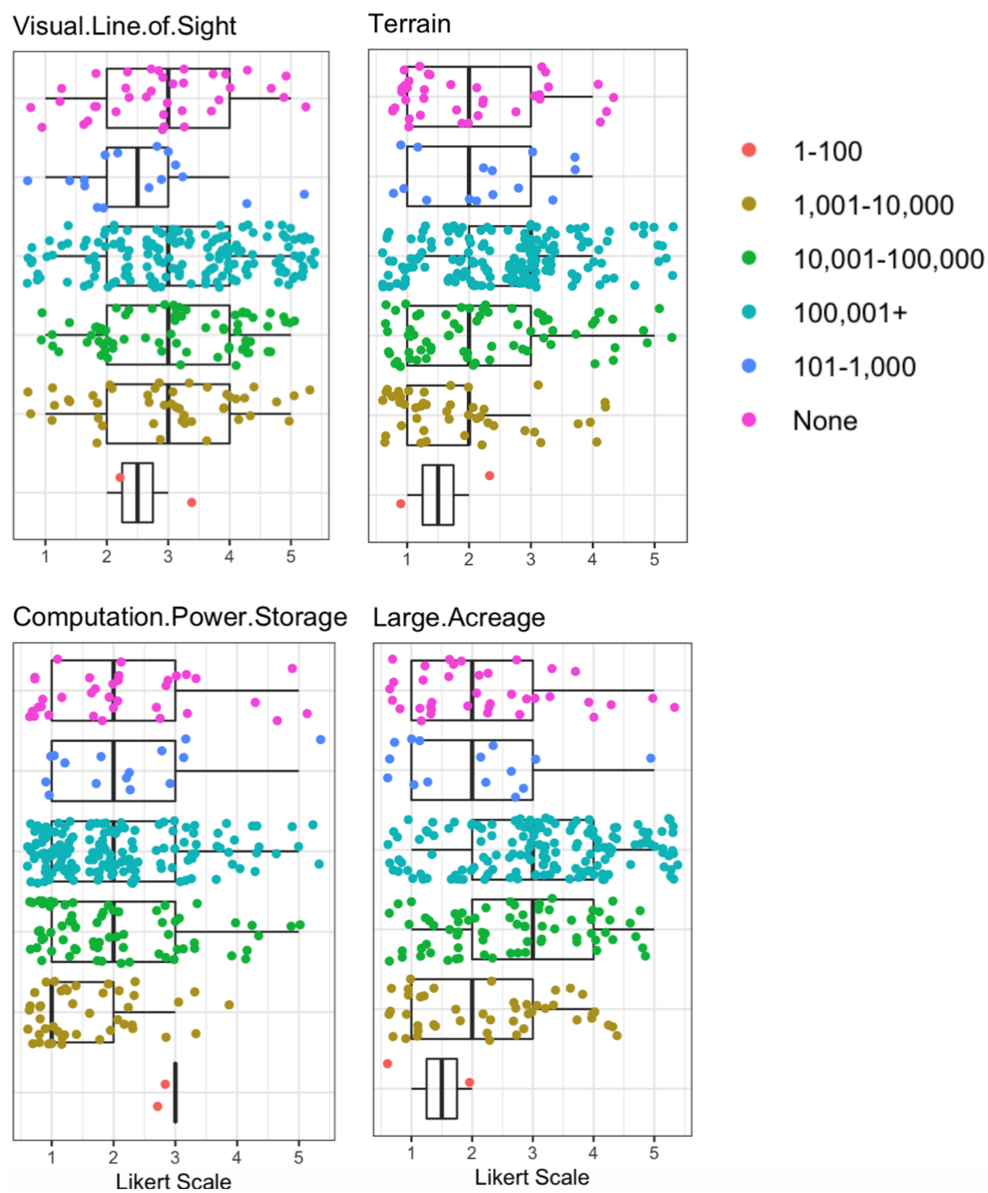

Figure 17. Likert scores for limitations respondents experience using drones compared among acreages. Significant differences were found among Terrain, Computation Power/Storage and Large Acreage. Points represent individual Likert scores. For visualization purposes points were jittered from actual, discrete Likert scores.

Discussion

This survey examined many job sectors, job types, terrains and species compositions in order to get a better understanding of the use of drones in forest management today. The results of this nationwide survey targeting those in forest management demonstrate that more than half of the sample population are not currently using drones. The majority of them would like to use drones, however, many cite a lack of knowledge and training to do so. The remaining respondents are already utilizing drones in a variety of ways. Within this sample population drones are used most often for capturing video and photography for communication purposes, mapping property, or as a reconnaissance tool for various logging activities.

The work done using drones was then compared across various job sectors, job types, terrains and species compositions in order to better understand whether there were any significant differences among them. From this it was found that among the sample population the state and federal government use drones significantly more for monitoring wildfire than other groups. State governments use drones significantly more for monitoring prescribed fire than other groups. Private (for-profit) companies use drones significantly more for monitoring active logging and non-harvest activities. As for the job type, it was found that administrative and field foresters are using drones significantly more than other job types for wildfire, active logging and post-timber harvest activities. As for terrain, it was found that drones are used significantly more in the mountains for monitoring wildfires. Additionally, drones are used significantly more for non-harvest activities in plains than other terrains. In terms of species composition, it was found that drones are used significantly more in pine plantations than other species compositions. Drones are also used in pine plantations followed by pine dominated forests for monitoring active logging, inspecting post-timber harvest and non-harvest activities.

Similarly, the limitations respondents encountered were then compared across various job sectors, terrains, species compositions, and amount of acreage in order to better understand whether there was any significant difference between them. From this it was found that the majority of respondents who reported terrain as a limitation worked in a mountainous region with mixed broadleaf or pine dominated forests. Additionally, the largest amount of acreage that could be reported was 100,000+ acres and this was reported as being the most limiting amount of acreage. With an increase in the number of acres managed, it was found that terrain and computational power/storage were reported more as limitations.

An overwhelming majority of the sample population are using DJI drones. The most popular products being used are the DJI Mavic 2 Pro and DJI Phantom series. Currently both of these products cost $1,600 (DJI, 2021). However, there were a wide variety of products reported, ranging from inexpensive (< $300) to thousands of dollars. Similarly, the software used for processing was overwhelmingly DJI products, although many also used ESRI products and DroneDeploy. The software reported also ranged in price from a $57 one-time fee (OpenDroneMap, 2021) to $299/month (DroneDeploy, 2021). These prices are associated with a single-use business license and are not representative of all options given by the companies.

Of the sample population there were several benefits that were reported by an overwhelming number of people, this included: increased efficiency, use as a reconnaissance tool, and quick access to high resolution imagery. One respondent reported, "I can more effectively inspect timber harvests for water quality concerns. Having a drone also allows us to quickly scout fire-line in rough terrain in the mountains." Another reported, "sav[ing] time, locating where loggers are working, [ability to] get a quick overview of a property from above, locat[ing] storm damage quickly and [using drones] to look for 'missing' persons, hunting dogs & horses". Although some see drones as beneficial, there are also factors that are holding them back. An example of this is demonstrated in this survey response: "Drones have been helpful, but our foresters are still slow to adapt them into their daily workflows. Factors for this include the Part 107 test, cost of drones and software, and lack of technical expertise." It should be noted that while many see this as technology as beneficial, they still appreciate boots-on-the-ground work. One respondent reported that "it's hard to beat walking a piece of forest land and seeing the details and making assessments on the ground."

In terms of what people hope for future drone-use, the majority of people are hoping for an ease in regulations, the ability to utilize sensors, and the ability to conduct timber inventory. The regulation that was highlighted the most was the ability to fly beyond visual line of sight, which is currently a regulation enforced by the FAA. One respondent said that the ability to fly beyond visual line of sight on large tracts of land "would greatly increase [their] productivity." We are beginning to see the FAA making changes that may help to enable flying beyond visual line of sight safely. Based on a report done by Levitate Capital, "a venture firm focused on advanced air and space technology", the ability to fly beyond visual line of sight without a waiver could be possible as soon as 2025 (Levitate Capital, n.d). Evidence that the FAA is moving in this direction is the implementation of a Remote ID, which will be required on all drones by 2023. The Remote ID will allow authorities to identify the pilot and drone in the air, which will hold pilots accountable. Additionally, drone manufacturers are aiming to put sensors in drones that will detect and give right of way to manned aircrafts, a safety measure that will be vital to flying beyond visual line of sight (Hidden Levels, 2019).

Looking to the future many people are interested in seeing a variety of sensors available for consumer-grade drones. LiDAR was mentioned more by respondents than any other sensor. Currently you can purchase LiDAR sensors for as cheap as $8,000. DJI LiDAR sensor costs $13,000

(DJI, 2021). However, a robust LiDAR sensor costs nearly $23,000, which does not include the cost of the drone used to carry the sensor which is an additional $10,000-$16,000 (Roe, 2021). DroneDeploy reported that the LiDAR industry, which was worth $1.1 billion in 2019, is estimated to be $3.2 billion by 2027 (DroneDeploy, 2021). This is a 34% increase in 8 years. The cause of this increase is correlated with the growing interest in self-driving cars which require LiDAR sensors (Lee, 2018). With increased production of LiDAR sensors, it is likely that the cost will go down and these sensors will become available to the average consumer (Heliguy, 2021).

It is important to consider any economic advantage that may come from investing in drone-mounted LiDAR when compared to traditional ground sampling of timber inventory. However, there have not been any recent studies doing a cost-benefit analysis comparing the two. What is evident is the costs of LiDAR sensors have gone down and the utilization of drones has lowered the costs of acquiring data, making this a more viable option in recent years. In fact, drone-mounted LiDAR is about ten times less costly than traditional LiDAR collected using a manned aircraft (Kellner *et al*., 2019). There are still issues with using drone-mounted LiDAR sensors when dealing with large acreages due to battery life limitations and visual line of sight regulations in place by the FAA. In addition to these limitations, capturing and processing LiDAR data requires a large amount of computational power/storage space as well as knowledge and experience in order to get accurate measurements. Therefore, it is vital to seek education on the topic and gain the necessary skills and tools to process the data.

People also mentioned interest in utilizing multispectral and hyperspectral sensors. Multispectral and hyperspectral sensors can be used in a variety of ways, namely for monitoring plant health but they can also be used in the classification of trees. Multispectral imagery is used in land cover classification and forest type identification, specifically to the level of conifer or broadleaf. Hyperspectral imagery on the other hand allows for more fine scale distinctions, even identifying forests to the species level (Ballanti *et al*., 2016). Between the two, multispectral and hyperspectral, hyperspectral had a much higher rate of success when speciating trees than did multispectral (Clark *et al*., 2005). When data from multispectral or hyperspectral cameras are combined with LiDAR, we can gain valuable information regarding forests at the plot, stand, and tree levels (Tusa *et al*., 2020). Generally, when using a drone, LiDAR data and multispectral/hyperspectral imagery would be collected separately, and the data fused during processing. However, we are now seeing the emergence of sensors that simultaneously collect both imagery and LiDAR data, which increases efficiency (Headwall, 2018).

All three of these innovations, ease of regulation, access to LiDAR, and access to multispectral and hyperspectral sensors - along with extended battery life and accessibility of drones with highly accurate GPS units (namely RTK) - will lead to a more widespread ability to conduct timber inventory. This is of interest to many forestry professionals due to its ability to increase efficiency and provide highly accurate data on demand. These innovations will be particularly beneficial to those working in mountainous areas with a wide variety of species compositions.

While it will be vitally important to stay up to date on development of regulations and various sensors, it will also be important to educate people in forest management of the utility of these tools and how to deal with the data that they can produce. This will ensure that drones can be used to their full potential going forward. One respondent reported that they “think there could be useful applications for using drones, but [they’ve] just been too busy with regular job demands to have time to investigate." Another said that they "don't understand the potential uses [of drones and] would like to learn more through Continuing Forestry Education (CFE) opportunities."

The addition of CFE courses pertaining to drones and drone-related technology would be highly beneficial since they are required by all certified foresters and could potentially provide the time that foresters may not otherwise have in their day-to-day. In addition to CFE courses, there is already an effort to start adding classes on the use of drones for the management of natural resources in many universities across the United States. This will help increase the use of this technology across the profession at a faster rate. In addition, exposing students to this technology will provide the future of the profession with opportunities to apply this technology in new and innovative ways; which aligns with the Society of American Foresters' goal of "producing more society-ready practicing professionals in forestry" (Unger *et al*., 2019).

Conclusion

This study began as research to determine whether drones could be used operationally to conduct timber inventory in a mountainous area dominated by mixed broadleaf species. After gaining a more calibrated sense of what was possible, the objective became to understand the operational use of drones in the forest management in 2021 through a nationwide survey targeting those in forest management. Based on the survey conducted, it was found that drones are already being utilized in forest management in a multitude of ways by various sectors. There are many benefits being reported about their positive impact on management. However, there are still limitations to use including FAA regulations, the affordability of drones and sensors, as well as the availability of educational resources.

Going forward it will be vital to educate those in forest management on how to use drones to gather data whether it be imagery or from sensors. It will be important to inform people about software as well as the methods in processing and interpreting data gathered using a drone. Additionally, people in forest management should watch for the evolution of FAA regulations as they have the power to influence the ways in which drones can be utilized. Taking these steps will enable forest managers to use this powerful tool to its full potential as technologies become more affordable.

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Appendix A: Definitions to Make Text Entry Questions into Binary

'Increased Efficiency' is defined by words such as: less work, better planning, better management, increased efficiency, time savings, job easier, quick, quickly, faster, less walking, more productive, immediate, and real-time.

'New Perspective' is defined by words such as: different angles, big picture, sky vs ground, perspective, see more, different visuals, and birds eye view.

'Save Money', is defined by words such as: inexpensive, cost savings, and money saved.

'High Resolution' imagery is defined by words such as: higher accuracy, better resolution, ability to see individual trees, high definition, detailed, high quality, lovely imagery, and the ability to take accurate measurements.

'Communication' is defined by words such as: sales, photography, content, teaching, presentations, progress reports, educational, promotional, marketing, advertising, instructional, social media and communication.

'Safety' is defined by words such as: risk, exposure, danger, situational awareness, safe and safety. 'Reconnaissance' is defined by words such as: surveillance, access remote areas, monitor, reconnaissance, gain access, inaccessible, detection, and inspection.

'Temporal' is defined by words such as: before and after and temporal.

'Timber inventory' is defined by words such as: delineate crown, volume, cruise, inventory, tree heights and diameters.

'Planting/Survival' is defined by words such as: seedling, survival, and plant.

'Ease Regulations' are defined by words such as: nighttime flying, beyond visual line of sight, licensed pilots, and federal restrictions.

‘Burn’ is defined by words such as: burn, prescribed burn, wildfire, fire, fuel loading, PSD, and ignition.

‘Easier Mapping’ is defined by words such as: real time, faster processing, and easier to map, 3D mapping and mapping in the context of regeneration, revegetation and property lines.

‘Carrying capacity’ is defined by words such as: payload, deliver supplies, heavy lift, herbicide spraying, and ability to carry more.

‘Drone swarm’ is defined by words such as: drone swarm and drone swarms.

‘Increased flight time’ is defined with words such as: longer flight time, longer battery life, more extensive coverage, longer range, more distance, and more coverage.

‘Utilize sensors’ are defined by words such as: ability to detect insects and disease, LiDAR, multispectral, hyperspectral, species identification, infra-red, FLIR, and thermal.

‘Education’ is defined by words such as: workshop, training, get better with, and lack of qualified staff.

‘Affordable software’ is defined by words such as: affordable software, access to apps, and lack of software.

‘Terrain’ is defined by words such as: follow the terrain, terrain is limiting, and variable terrain.

Appendix B: Survey

Email to respondents:

Dear Forestry and Natural Resource Professionals,

My name is Elisabeth McElwee. I am a Master of Forestry Candidate at Duke University and the 2021 Charles Collins Intern with The Forestland Group. As part of my Master's Project, I am conducting a survey to better understand the use of drones in forest management. **Please take 5-10 minutes to complete this quick survey** and help me to reach my goal of capturing the experiences of as many forestry/natural resource professionals as possible.

Your identity will remain anonymous in the reported results. I truly appreciate your help.

Thank you,
Elisabeth McElwee

Drones in Forestry Survey

Start of Block: Intro

Q1 This survey is being put forth by Elisabeth McElwee, a Master of Forestry candidate at Duke University and the 2021 Charles Collins Intern with The Forestland Group. The purpose of this survey is to better understand the use of drones in forest management today. Your identity will remain anonymous in the reported results. Thank you for taking the time to participate.

Q2 Vote for your preferred lunch item.

____

Q3 Job title/position

____

Q4 Employer

____

Q5 Which job category best describes you?

- ○ Field forester (1)
- ○ Administrative/planning forester (2)
- ○ Mapping/GIS (3)
- ○ Field ecologist (4)
- ○ Researcher/educator (5)
- ○ Other (6) ____

Q6 Do you work for one of the following?

- ○ Federal government (1)
- ○ State government (2)
- ○ Private, for-profit (3)
- ○ Private, not-for-profit (environmental NGO) (4)
- ○ Educational institution (6)
- ○ Other (5) ____

Q7 How long have you been employed at your current job?

- ◯ Under 1 year (1)
- ◯ 1-5 years (2)
- ◯ 5-10 years (5)
- ◯ 10-15 years (3)
- ◯ 15+ years (4)

Q8 How long have you worked in a forestry-related profession?

- ◯ Under 1 year (1)
- ◯ 1-5 years (2)
- ◯ 5-10 years (3)
- ◯ 10-15 years (4)
- ◯ 15+years (5)

Q9 Gender

- ◯ Male (1)
- ◯ Female (2)
- ◯ Non-binary (3)
- ◯ Prefer not to share (5)

Q10 Race

- White (1)
- Asian (2)
- Black or African American (3)
- Hispanic or Latino (4)
- Native Hawaiian or other Pacific Islander (5)
- American Indian or Alaska Native (8)
- Prefer not to share (9)

Page Break

Q11 Approximately how often does your place of employment use drones for work? This does not include hiring other companies to collect drone imagery/data for you.

- ◯ Daily (1)
- ◯ Weekly (2)
- ◯ Monthly (3)
- ◯ Yearly (4)
- ◯ Never (6)
- ◯ Other (5) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q12 How long has your place of employment been using drones?

- ◯ 0 - 6 months (1)
- ◯ 6 - 12 months (2)
- ◯ 12 - 24 months (3)
- ◯ 24+ months (4)

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... = Never

Q13 Does your place of employment have any interest in using drones?

- ◯ Yes, definitely (1)
- ◯ Somewhat (4)
- ◯ No (2)

Display This Question:

If Does your place of employment have any interest in using drones? = No

Or Does your place of employment have any interest in using drones? = Somewhat

Q14 What are potential barriers to using drones?

- ◯ Ability to hire other companies to gather drone imagery/data for you (1)
- ◯ Lack of knowledge/training (4)
- ◯ Too expensive (2)
- ◯ Waiting for further advancements in technology (5)
- ◯ Other (3) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... = Never

And Does your place of employment have any interest in using drones? = Yes, definitely

Q15 What are potential barriers to using drones?

◯ Ability to hire other companies to gather drone imagery/data for you (1)

◯ Lack of knowledge/training (5)

◯ Too expensive (2)

◯ Waiting for further advancements in technology (3)

◯ Other: (4) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q16 How many people at your place of employment fly drones?

◯ 1 (1)

◯ 2 (2)

◯ 3 (3)

◯ 4+ (4)

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q17 What is the model of your current top performing drone? (DJI Mavic 2 Pro, SenseFly eBee X, DJI Matice 300 RTK, etc.)

____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q18 Rank the lunch options according to your order of preference.

	Does not describe me (24)	Describes me slightly well (25)	Describes me moderately well (26)	Describes me very well (27)	Describes me extremely well (28)
Monitor wildfires (1)	○	○	○	○	○
Conduct/monitor prescribed fire (43)	○	○	○	○	○
Monitor plant health (insect/fungal damage, etc.) (2)	○	○	○	○	○
Inspect active logging jobs (45)	○	○	○	○	○
Inspect post-timber harvest (3)	○	○	○	○	○
Conduct timber inventory (41)	○	○	○	○	○
Conduct non-harvest activites (planting, site prep, etc.) (48)	○	○	○	○	○
Inspect/map property (boundaries, etc.) (4)	○	○	○	○	○
Communication (photography/videography) (6)	○	○	○	○	○
Monitor wildlife/wildlife damage (42)	○	○	○	○	○
Urban planning (46)	○	○	○	○	○
Real estate (due diligence, etc.) (51)	○	○	○	○	○
Other (39)	○	○	○	○	○

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q19 When using drones, do any of these factors hold you back from accomplishing the task at hand?

	None at all (21)	A little (22)	A moderate amount (23)	A lot (24)	A great deal (25)
Limited visual line of sight (1)	o	o	o	o	o
Limited battery life (2)	o	o	o	o	o
Lack of access to affordable software (3)	o	o	o	o	o
Lack of access to various sensors (multispectral/hyperspectral/LiDAR) (11)	o	o	o	o	o
Lack of computation power/storage space (13)	o	o	o	o	o
Terrain (4)	o	o	o	o	o
Weather (5)	o	o	o	o	o
Wide variation in species composition and/or age classes (7)	o	o	o	o	o
Large acreage (12)	o	o	o	o	o
Other (9)	o	o	o	o	o

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q20 How many acres does your place of employment manage?

- ◯ 1-100 (2)
- ◯ 101-1,000 (3)
- ◯ 1,001-10,000 (4)
- ◯ 10,001-100,000 (5)
- ◯ 100,001+ (7)
- ◯ None (1)

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q21 What best describes the terrain where you fly most often?

- ◯ Mountainous (i.e. Appalachain mountains, Rocky Mountains, etc.) (1)
- ◯ Hilly/rolling (5)
- ◯ Plains (flat) (7)
- ◯ Marsh/swampland (8)
- ◯ Coastal (3)
- ◯ Canyon (9)
- ◯ Other (4) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q22 What best describes the vegetation where you fly most often?

◯ Mixed broadleaf (i.e. oak/hickory, aspen/birch, etc.) (1)

◯ Pine dominated (i.e. boreal forest, douglas fir, etc.) (3)

◯ Pine plantation (5)

◯ Coastal wetlands (2)

◯ Non-forest (7)

◯ Other (4) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q23 Which software packages do you use most when flying/processing imagery? Select all that apply.

- ▢ DJI Products (1)
- ▢ Pix4D (2)
- ▢ DroneDeploy (3)
- ▢ Maps Made Easy (4)
- ▢ Open Drone Mapper (5)
- ▢ AgiSoft Metashape (6)
- ▢ Esri products (8)
- ▢ SimActive (7)
- ▢ Other (9) ____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q24 What benefits have come from using drones in your line of work?

____

Display This Question:

If Approximately how often does your place of employment use drones for work? This does not include... != Never

Q25 What would you like to do with drones that you can't currently?

____

Q26 Is there anything else you would like to share about drones?

____

End of Block: Intro

Appendix C: Supplementary Tables and Figures

Table 1. This table shows the role the respondents fill within their given job sector.

Job Sector	Educational Inst.	Federal Gov't	Local Gov't	Other	Private, for-profit	Private, not-for-profit	Self-employed	State Gov't	Tribal Gov't	(blank)	Grand Total
Administrative/planning forester	5	17	5	7	89	14	3	52	2		194
Field ecologist	3	1			1	1		7			13
Field forester	5	11	8	6	181	8	11	82	1		313
Mapping/GIS	1	7			12			8			28
Other	4	9	6	13	70	14	6	33			155
Researcher/educator	72	7			6	3	1	8			97
(blank)	2	1		2	1			2			8
Grand Total	92	53	19	28	360	40	21	192	3		808

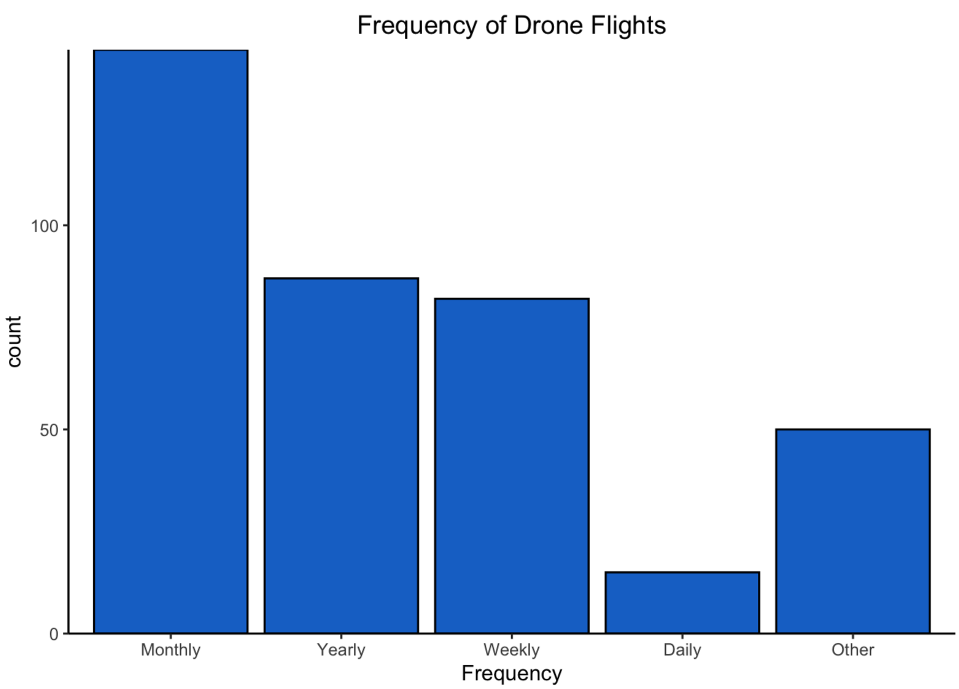

Figure 1. This bar chart shows the proportion of respondents' frequency of drone usage at their respective places of employment.

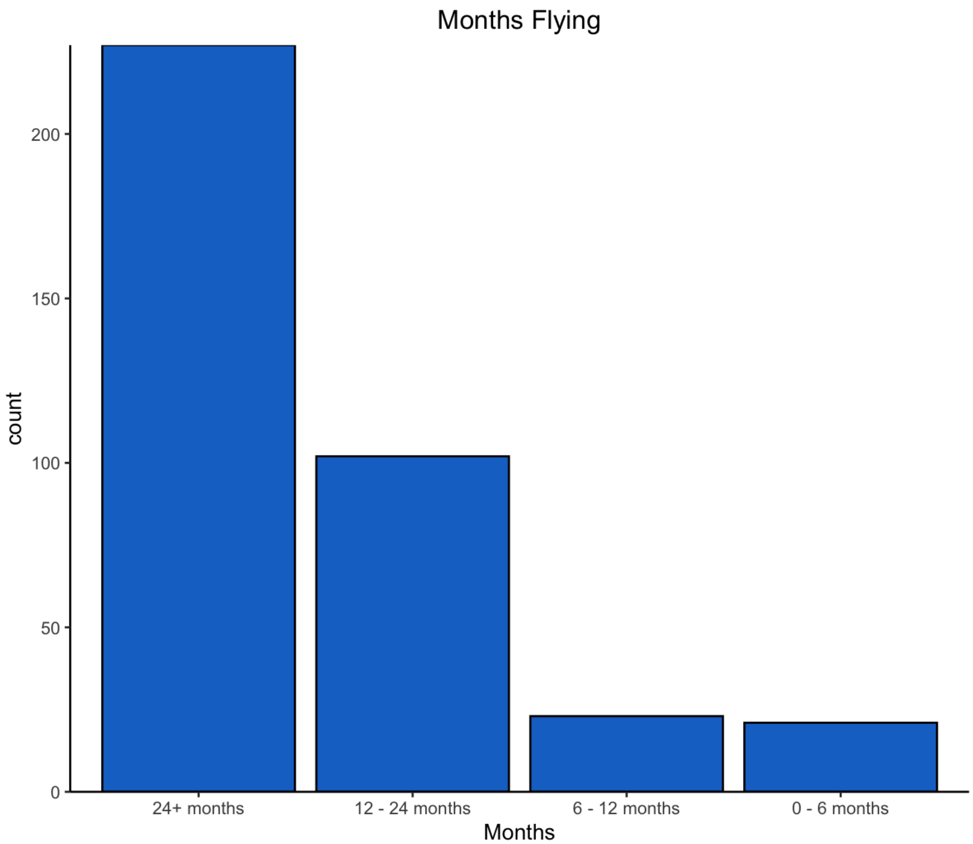

Figure 2. This bar chart shows the number of months that respondents have been using drones at their place of employment.

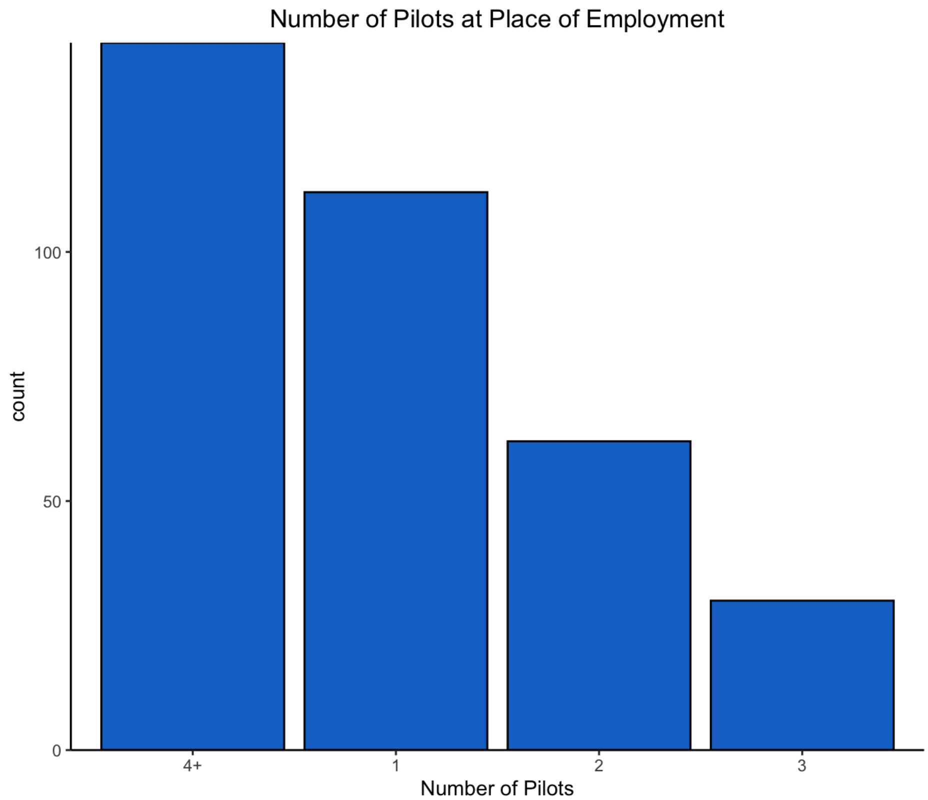

Figure 3. This bar chart shows the number of pilots at the respondents' place of employment.

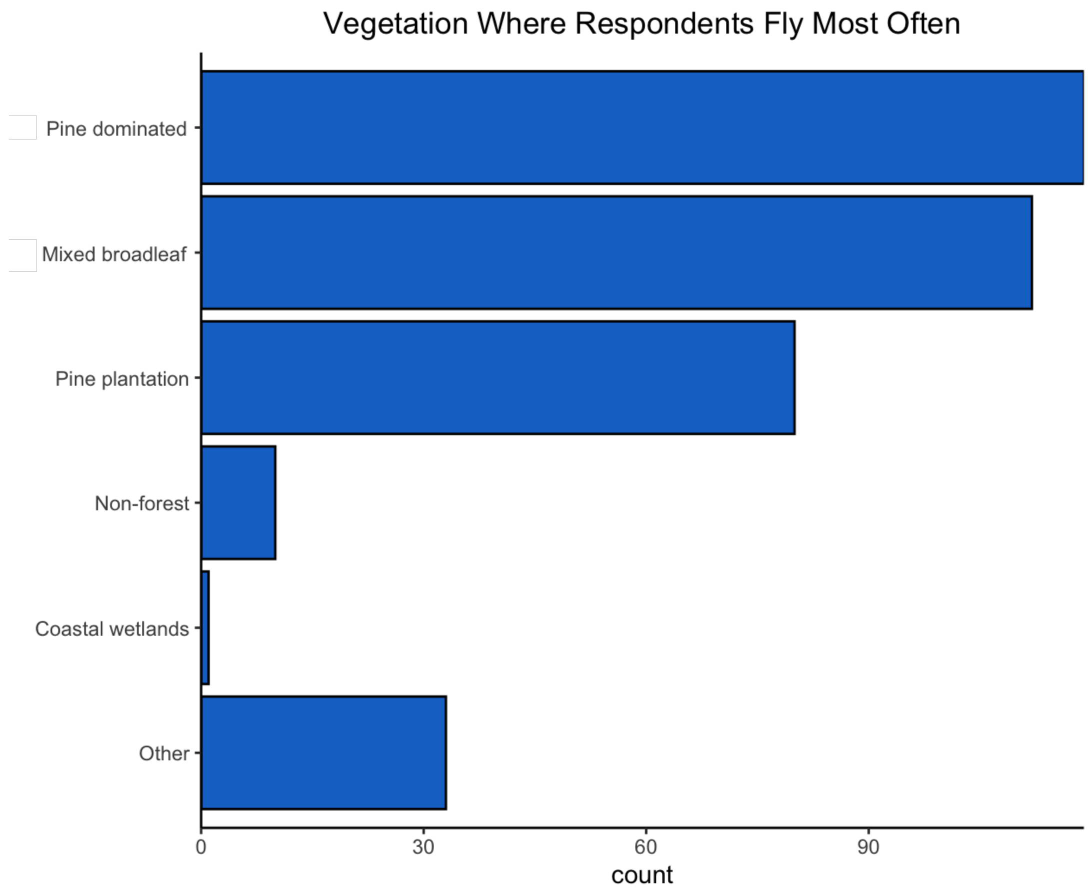

Figure 4. This bar chart shows the species compositions where respondents fly most often.

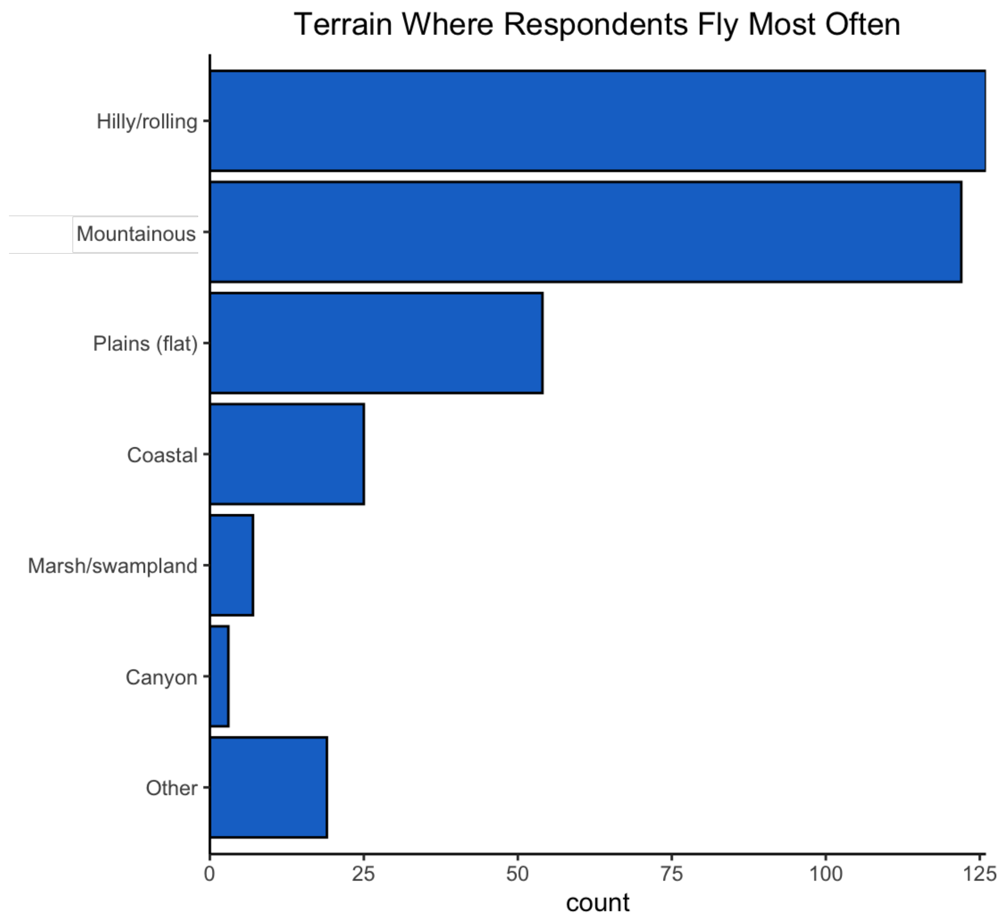

Figure 5. This bar chart shows the terrains where respondents fly most often.

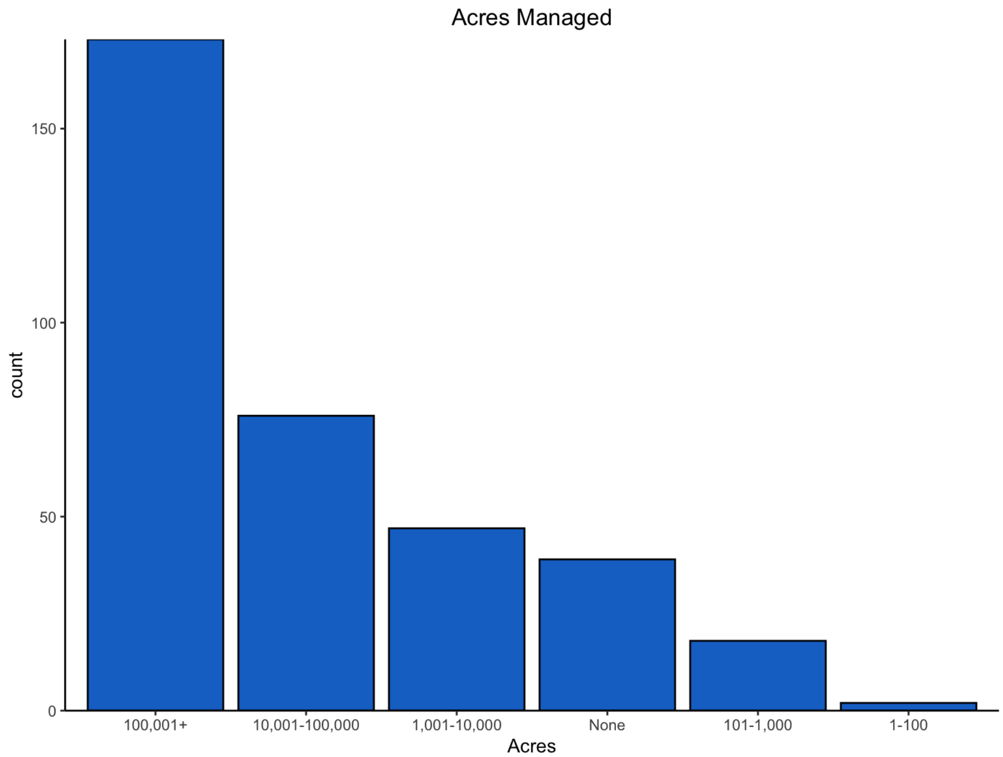

Figure 6. This bar chart shows the number of acres managed by respondents.