PUBLIC PARTICIPATION TO ESTIMATE FOREST FUELS LOADING: THE DEVELOPMENT AND TESTING OF AN APPLICATION FOR REMOTE SENSING

by

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Abstract

Advances in mobile computing provide an increasing number of possibilities for public participation in scientific research (PPSR). For example, a growing number of people have access to mobile computing devices, such as smartphones, equipped with sensors including a camera, global positioning system, the ability to record observations, and the ability transfer them over a network for collection and analysis. Literature has shown that PPSR-based approaches can have positive outcomes for volunteers (*e.g.*, opportunities to pursue interests, develop skills, and influence decisions), for resource management (by providing data to inform management strategies), and for science. The objective of this dissertation is to explore how volunteers can use smartphones to collect data to inform forest management in a remote sensing project. The management of wildfires in communities near forested areas was chosen as a case study, and a smartphone application was developed and tested for collecting observations of the amount and arrangement of forest fuels by participants with a range of forestry experience living in fire-affected communities. First, to establish context, other projects using smartphones to collect Earth observation data were reviewed including related terms, concepts, challenges, and opportunities to identify methods of data collection and data processing. Second, questionnaires were given to the volunteers before and after using the application to collect data and were analyzed to understand the social and management considerations including the volunteers' motivations, attitudes, and behaviours, and the potential of using a PPSR approach for wildfire management. Third, the locations where volunteers submitted data were re-measured and the quality of the data were assessed to provide guidelines for ensuring attribute accuracy and logical consistency. Fourth, the smartphone data was combined with multispectral remote sensing data and topography data to make estimates over broader areas. Finally, a framework was presented

to direct future efforts using volunteered remote sensing data. This dissertation demonstrates an approach with potential to apply technology to help inform forest management in communities, with potentially positive outcomes for volunteers, communities, and forest managers.

Preface

In this dissertation I established the research objectives and questions, conducted the analysis, and wrote the manuscripts and chapters. The co-authors of the manuscripts used in chapters provided direction, advice, and editorial comments.

The fieldwork component of the research in this thesis, analyzed in chapters 2, 3, and 4 was approved by the UBC Behavioural Research Ethics Board application H12–00257, titled "Mobile Remote Sensing of Forest Fuels in Central British Columbia".

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List of Abbreviations

App - Application

css - cascading style sheets

csv - comma separated values

HTML - Hyper text markup language

K-MSN - K (variable) most similar neighbours

LiDAR - Light detection and ranging

GIS - Geographic information systems

GPS - Global positioning system

ODK - Open data kit

PPSR - Public participation in scientific research

VGI - Volunteered geographic information

WUI - Wildland-urban interface

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Chapter 1: Introduction

Recent advances in mobile computing devices, such as smartphones and tablets, have resulted in large amounts of the population having access to mobile devices with advanced computing and network capabilities (ITU 2010). Mobile devices have tools that make it possible to collect information about environments, including: a touchscreen to present graphical user interfaces; sensors such as a camera, microphone, global positioning system, compass, accelerometer, and gyrometer; the ability to quickly install applications using application stores; and the ability to store data and transfer them over a network. As a result, there is potential to engage broad audiences in public participation in scientific research (PPSR). In PPSR, also known as citizen science, members of the public engage in "intentional collaborations in which members of the public engage in the process of research to generate new science-based knowledge" in projects that "aim explicitly to contribute to scientific research and/or monitoring" (Shirk *et al.,* 2012, p. 2). Although the monitoring of natural resources to inform management decisions is not typically focused on purely scientific research related activities, such as formulating and testing new theories, the approaches are informed by science and the data that are collected may be used to generate new scientific knowledge. In addition, approaches developed in PPSR can readily be applied to the task of monitoring resources (*e.g.,* members of the public can monitor of the health and status of ecosystems).

PPSR approaches can encourage conservation in ecosystems near residential lands, where citizens help study and manage ecosystem integrity, promote positive social outcomes (such as changes in attitudes that contribute to ecosystem conservation), and feedback is provided that can be used to iteratively refine conservation goals (Cooper *et al.,* 2007). Shirk *et al.,* (2012) identified several potential outcomes of PPSR approaches for individuals, resource management, and for science. Individual outcomes may be related to awareness, knowledge, or understanding related to the project topic following an informal science education approach; in particular, when participants take part in the design of projects they may also learn about the process of science and the scientific method, or requirements for monitoring programs (Bonney *et al.* 2009). Individuals may develop engagement or interest in topics and develop skills when the projects provide explicit opportunities for people to try something new or practice existing skills (Bonney *et al.* 2009). Individuals may find changes in attitudes, and behaviors following changes in value-orientations as a result of participating in science and monitoring activities, however, there were only a few examples where this change has been documented (Bonney *et al.* 2009). Additionally, participatory monitoring projects can provide power to individuals in negotiation efforts by generating quantified information that provides validity to complaints, for example, to counter maps made by government or corporate interests, in filing complaints against companies responsible for pollution, or working with urban planners to improve environmental conditions (Peluso 1995; Overdevest and Mayer 2007; D'Hondt *et al.* 2013). Scientific advances, may follow the availability of spatially and temporally extensive datasets that can be integrated and thus allow novel exploration and the formation of hypotheses related to many interrelated factors (Kelling *et al.* 2009; Hochachka *et al.* 2012). More effective resource management can be accomplished in communities when PPSR project provide extensive monitoring data that can be used for the iterative process of adaptive-management strategies (Cooper *et al.* 2007). Both management and scientific endeavors can gain local knowledge and creative insight from a broader audience (Goldman *et al.* 2009; Raddick *et al.* 2010). PPSR has been applied in fields such as ornithology to engage volunteers in projects and the data have been used to inform resource management. For example, Project FeederWatch (Bonney *et al.,* 2009) and eBird (Sullivan *et al.,* 2009) have engaged broad audiences to collect and share bird survey data by providing opportunities to learn about ornithology and share lists of sightings with other birder watchers.

In addition, approaches inspired by PPSR may provide opportunities to reach outcomes for individuals and communities that are desirable for forest management. For example, interactive and hands-on methods of engagement have been demonstrated as effective methods to increase public knowledge of fire management activities (Parkinson *et al.,* 2003) and for building relationships between forest management agencies and the public (Toman *et al.,* 2006a). Applying approaches inspired by PPSR to wildfire management could provide a mechanism for forest managers to interact with people in communities, share information to increase public understanding of wildland fire management, build agency trust by demonstrating tradeoffs in decision making in real-world situations, and foster a sense of shared responsibility. Recent advances in personal computing and mobile communications technology have increased the possibilities for public participation in science and natural resources management. However, for these opportunities to be realized, meaningful participation needs to be established which depends on the commitment and resources for natural resource managers to incorporate public participation data into management decisions (Harshaw 2010). Public participation in citizen science projects has been evaluated in terms of degree (the extent that participants can influence the processes that they engage in) and quality (how well the goals and activities of the project suite the needs and interests of the participants) (Shirk *et al.* 2012). If meaningful participation is not established (for example, if the participants have no power over the outcome of decisions), it may frustrate participants (Arnstein 1969), or erode citizen-agency trust (Toman *et al.* 2006a).

Finally, collecting observations of environments using mobile devices following PPSR practices can benefit Earth observation efforts. Sensors mounted on Earth observing satellites and airborne platforms provide measurements of Earth's surface patterns and processes, and interpretation and analysis of these data can lead to better-informed resource management decisions (Wulder *et al.,* 2008). In many cases, in-situ measurements by ground-based sensors, direct measurements by field crews, or recording observations of ground conditions are necessary for building or validating models that use remote sensing data. In other cases, in-situ measurements are required because the scale and location cannot be recorded using aboveground remote sensing due to sensor geometry and the spatial and temporal limitations of the platform and sensor. Therefore, collecting and using data from a variety of sources is critical to Earth observation systems. However, collecting in-situ data may require specialized sensors or employing field crews, and therefore, these data are available over limited spatial and temporal extents. Collecting datasets using mobile devices and PPSR methods may provide more extensive and up-to-date in-situ data for Earth observation.

1.1 Tools for PPSR

Several projects exist that use mobile devices (such as smartphones or tablets) to collect measurements of the environment (reviewed in detail in the following chapter). For example, an application developed by the British Geologic Survey allows the public to document temporary geologic exposures, for example, when soil strata or underlying bedrock are temporarily exposed to the surface by excavation for construction that would otherwise be "lost to science" (Powell *et al.,* 2012). Smartphone applications have been developed for professional geologists to aid in collecting notes, photos, and making field observations so that they are collected in a consistent and accessible manner (Weng *et al.,* 2012). A smartphone application was developed to facilitate community-based monitoring of forest carbon stocks, degradation, and disturbance by individuals who had been hired without previous experience in forest measurement (Pratihast *et al.,* 2013). For data collection, Open Data Kit (http://opendatakit.org) provides tools and templates for field data collection (Brunette *et al.,* 2012; Pratihast *et al.,* 2013). These approaches can be extended to forest management in communities for topics such as forest fuel loading in the wildland-urban interface (WUI). These projects and others are reviewed in detail in Chapter 2.

1.2 Case study: managing forest fuels in the wildland-urban interface

One forest resources management topic with potential to apply the principals of PPSR using mobile devices is forest fuels. PPSR using mobile devices could provide more data for forest managers to make decisions, increase knowledge and salience of wildfire topics in communities, and build citizen-agency trust. Forest fuels are structural components of forests that can combust in wildfires. In many WUI areas, where unoccupied forests meet human development, wildland fires can threaten human life and structures (Radeloff *et al.,* 2005). In recent years, policies of fire exclusion have led to changes in forest structure, including an accumulation of fuels. This, in turn, has led to more severe wildfires, which in combination with more people living in the WUI, necessitates the management of wildfire hazards (Agee and Skinner 2005). Forest managers engage in activities that aim to reduce or modify the fuel available to wildfires near priority areas (such as communities), thereby reducing the severity and size of wildfires and making fire suppression efforts more effective. Forest fuel management activities in the WUI may include controlled burns, thinning tree stems, pruning branches, clearing brush and other ground fuels, chipping, or planting fire resistant species. To effectively prescribe fuel management plans, in addition to knowledge of the ecology and fire history of a stand, fire managers require information about the amount and arrangement of fuel components (Agee and Skinner 2005). As forest fuels within broad, spatially heterogeneous areas can rapidly change (*e.g.,* fallen branches after a wind event), they require frequent re-measurements for effective monitoring (Keane *et al.,* 2001). Major challenges in prescribing treatments include (1) that forest fuels are spatially variable and can change rapidly due to storm windfall, or other natural changes in forest structure and (2) measuring forest structural components under dense canopies is difficult using remote sensing approaches, due to sensor geometry. Therefore, accurate characterization of forest fuels depends on frequent measurement by field crews (Keane *et al.,* 2001). Data collected about forest fuel loading are important inputs into forest management software, including geographic information systems (GIS) and fire behaviour models to plan, prioritise, design and implement fuels treatments and fire suppression strategies (Ohlson and Blackwell 2003; Lutes *et al.,* 2006).

Effective wildfire management also requires understanding, cooperation, and action by adjacent civic units (cities, municipalities, parks), private property holders, and other members of the community. For example, when municipalities apply fuels treatments to public lands, such as manually reducing the amount of fuels at a treatment site, the selected treatment(s) may not be effective unless adjacent property owners also reduce fuel loads on their land. Community members have an important role in reducing the ignitability of their residence by performing fuel reduction activities and using fire resistant building and landscaping materials (Cohen 2000). In Canada, Partners-in-Protection provides publications that recommend actions that homeowners can take to reduce the likelihood of their home igniting when wildfires occur. These actions include clearing a defensible space around the house, using fire resistant landscaping, and reducing brush around the perimeter of their property (Partners-in-Protection 2008). Currently in British Columbia, fire managers complete fuel assessments and prescribe fuel modifications on public lands (such as mechanical treatments and controlled burning), seek public support for fuel modifications on public land, and advocate for personal action on private lands (such as homeowners choosing fire resistant building materials and using fire resistant landscaping). Due to the complexity of land ownership and management responsibility in the WUI, fuels treatments on public land may not be effective unless strategies are coordinated across the mosaic of land jurisdictions (Radeloff *et al.,* 2005).

Fire managers in many regions also seek to build trust through citizen-agency relations, encourage community knowledge and engagement in protection planning and mitigation activities, and enhance a sense of shared responsibility for fire hazard in the WUI (Monroe *et al.,* 2006). In a survey of fire managers in Alberta, Canada, communication between municipal fire managers and community residents was achieved using a wide variety of strategies, including pamphlet and newsletter distribution, newspaper or radio advertising, website notices, tradeshow booths, open houses, door-to-door meetings, and providing wildfire mitigation advice to homeowners. However, despite many fire managers expressing an interest in more two-way communication with the public, they cited funding, time, and availability of personnel as limitations to engagement and communication with people in the community (Monroe *et al.,* 2006). Therefore new technical tools that facilitate public participation at low cost to forest mangers may provide possibilities to share ownership and responsibility of wildfire issues with a broader segment of the community, and in the process generate creative input (see section 6.5.1 for more discussion). Public acceptance of fuel management actions is generally associated with knowledge of wildland fire management, and it also depends on building trust through long-term citizen-agency relations (Olsen and Shindler 2010). Therefore, PPSR activities may provide more information for forest managers while increasing knowledge and support of forest management activities in communities.

1.3 Research questions and thesis organization

This thesis addresses the use of smartphones for remote sensing. To explore this research topic, a field trial was conducted using a smartphone application to record observations of forest fuels amounts and arrangements in the WUI by volunteers from Kelowna, BC. This thesis is an interdisciplinary study utilizing forest observations collected by volunteers using smartphones, questionnaire data collected from volunteers, observational notes collected by the research team, multispectral remote sensing data, and topography data. The research objectives were developed to meet data needs for remote sensing of forests by applying approaches and research priorities from PPSR (Bonney, Cooper, *et al.* 2009; Raddick *et al.* 2010; Shirk *et al.* 2012). The questionnaire design and analysis were developed from techniques in the social sciences (Dillman 2007). These data were interpreted in light of theory in environmental volunteerism (Moskell *et al.* 2010) and social research in wildfire management (Shindler and Toman 2003; Toman *et al.* 2006a; Harris *et al.* 2011). The data collected by volunteers was evaluated using theory from cartography, data-informatics, and forest measurement (Freese 1960; Moellering

1987; Sikkink and Keane 2008; Kelling *et al.* 2009). The volunteered data were used to make estimations over broader areas using techniques from remote sensing (Gitelson *et al.* 1996; Stage and Crookston 2007). Finally, the overall approach and research objectives were evaluated in light of current related projects, and this was used to reflect on the lessons learned and set future research objectives.

This thesis addresses the following research questions:

1) What are the related studies, terms, and concepts that can be used to define the field?

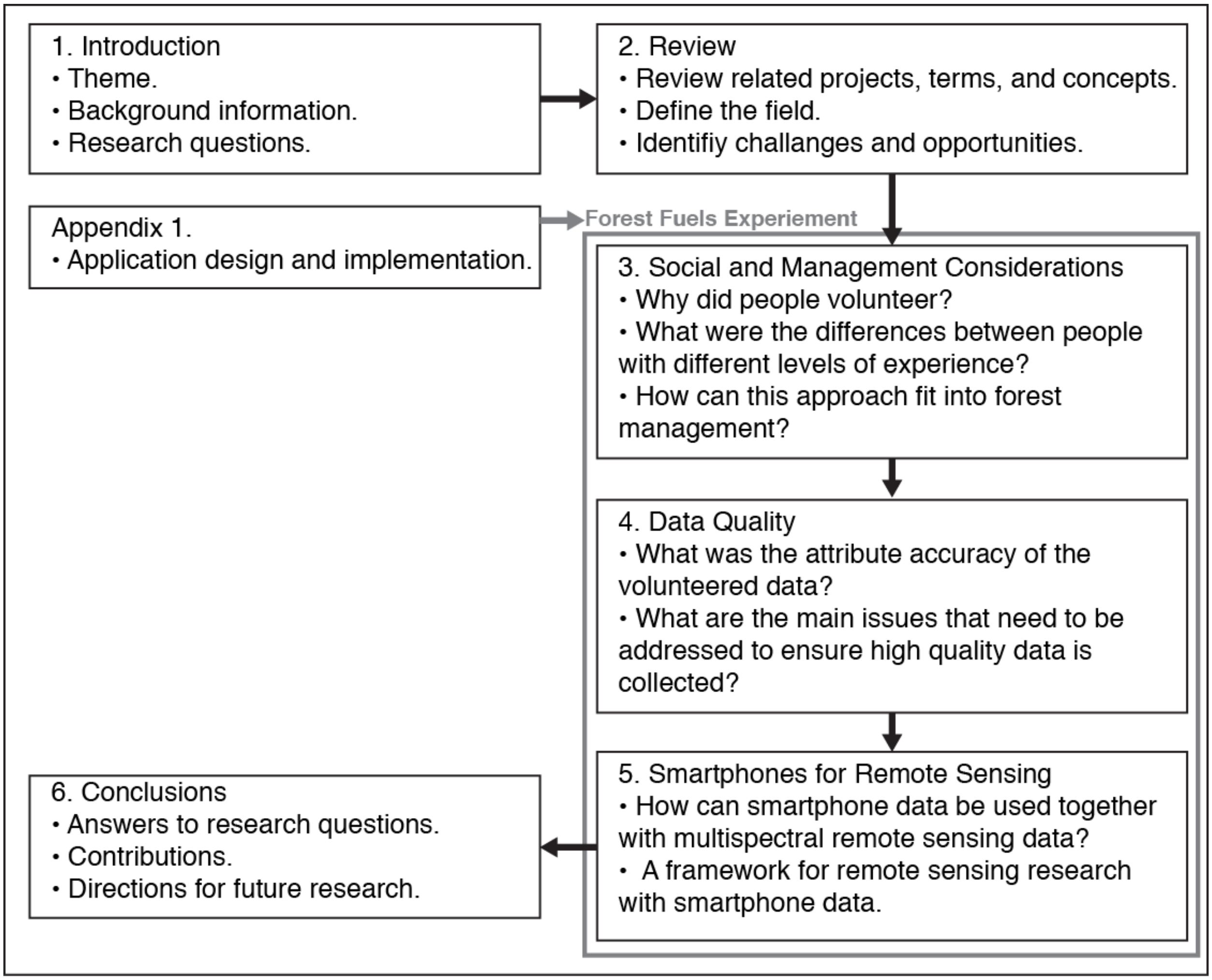
2) What are the social and management implications of using smartphones to collect data to inform forest management?

3) What is the quality of data collected by volunteers using smartphones?

4) How can forest observations collected by volunteers using smartphones be integrated with multispectral remote sensing data?

These research questions are answered in the following chapters (Figure 1.1). The first question is addressed in Chapter 2, a review of related literature, including a comparison and sorting of terms, concepts, and projects. As a result of the review, initial recommendations are provided to give guidance to future smartphone remote sensing projects. Chapters 3, 4, and 5 utilize data that was collected for a forest fuels experiment in Kelowna, BC. Methodologies for this experiment are described in the relevant sections, with the details of the application development in Appendix A. Social and management considerations of using smartphones to collect data to inform forest management decisions are addressed in Chapter 3. Questionnaire data collected from participants were analyzed to understand why participants chose to volunteer, what the differences were between people with different levels of experience, and how the approach can fit into forest management. Chapter 4 evaluates data quality collected by volunteers. Volunteer measurements were compared with reference measurements to lead a discussion of data quality and provide recommendations for developing approaches to collect high-quality data using smartphones. In Chapter 5, the smartphone data is integrated with multispectral remote sensing data. As a result of this exercise, a framework is presented for using smartphone observations together with multispectral remote sensing and topography data. The conclusion is presented in Chapter 6 where the research questions are answered, limitations are identified and evaluated, and future directions for research are discussed.

Figure 1.1 Thesis organization.



Chapter 2: Review and definitions

2.1 Introduction

Earth observation, the gathering of information about the planet's physical, chemical, and biological systems, often requires an integrated approach, where data are collected from spaceborne and airborne remote sensing devices, ground based (terrestrial) sensors, and in-situ measurements (GEO 2012). Remote sensing, classically defined as ''the science and art of obtaining information about an object, area, or phenomenon through analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation'' (Lillesand *et al.,* 2004 p.1), provides important Earth observation data for projects including measuring forests (Wulder *et al.,* 2008), atmospheric water vapour for meteorology (Newman *et al.,* 2012), geologic structure and the distribution of minerals (van der Meer *et al.,* 2012). A suite of remote sensing devices collect data at a range of spatial and temporal scales that often involve trade-offs in terms of spatial and temporal resolution, coverage, and viewing geometry. The global network of Earth observing satellites provides imagery of the Earth from an aerial perspective, with a temporal frequency determined by the platforms orbit paths and favourable acquisition conditions. When measurements of Earth surface features and processes from spaceborne and airborne sensors are difficult, prohibitively expensive, or are not of sufficiently high spatial or temporal resolution, in-situ remote sensing devices, and in-situ measurements provide critical complementary data. In-situ remote sensing measurements, such as those made using field spectrometers, compliment airborne and spaceborne platforms and have served an important role in the development of airborne and spaceborne remote sensing by developing, testing, and refining models and techniques relating biophysical attributes to airborne and spaceborne collected data (Milton 1987). In-situ remote sensing measurements made using field spectrometers also allow the acquisition of temporally frequent data at fine spatial and spectral resolutions for comparison and integration with spaceborne and airborne data, leading to more in-depth understanding of physical phenomena under study (Hilker *et al.,* 2009).

Spatially detailed measurements of forests have also been made using terrestrial LiDAR devices (Strahler *et al.,* 2008), providing measurements of the three dimensional arrangement of forest structural components near the ground and under dense canopies, which is difficult to acquire using spaceborne and airborne platforms, yet critical for investigation of ecological phenomenon (Vierling *et al.,* 2008). Both of these approaches provide data that are strongly complimentary to data acquired using airborne, and spaceborne remote sensing. However, the limitation of these approaches, is that they are time consuming, depend on specialized scientific equipment that is often expensive, and as a result, measurement from near-surface sensors are often limited in spatial extent and temporal frequency compared to measurements from airborne and spaceborne sensors. Due to advances in consumer electronics and communications networks, an increasing proportion of the general public has access to devices equipped with sensors capable of making measurements of the Earth's surface and processes, and an increasing number of opportunities exist for the public to volunteer measurements covering broad spatial extents (Goodchild 2007). Recent advances in mobile personal computing have resulted in a growing number of people carrying mobile personal communication devices, such as smartphones and tablets, with computing capabilities, networked data transfer, and equipped with sensors such as a camera and microphone (referred to as mobile devices in following sections). The global network of mobile devices offers opportunities to establish distributed networks of embedded sensors, capable of making a range of measurements (Burke *et al.,* 2006; Goodchild 2007; Lane *et al.,* 2010).

Finally, and most importantly, mobile devices provide opportunities to engage people in topics through projects that address their interests and concerns. For example, smartphone applications can provide a way for people to learn about a topic, practice a skill by downloading an application and partaking in activities, use the smartphone sensors and capabilities as a tool that can be applied to a hobby, interest, or project, and connect with other people who share similar interests through electronic communication tools and social media.

Developing methods to collect and analyze Earth observation data collected using mobile devices by engaging audiences in collecting and analyzing Earth observation data can lead to an increased knowledge of Earth surface features and processes by providing data at scales and perspectives that compliment measurements made using other sources of Earth observation data. For example, compared to Earth observing satellites, mobile devices provide a different viewing geometry that is close to the ground surface and from the human perspective. Compared to terrestrial remote sensing devices, mobile devices are lower cost and therefore can potentially be deployed over broader spatial extents and with higher temporal frequency. Compared to in-situ measurements by professionals, Earth observation data collected using mobile devices by networks of volunteers can be less expensive to collect and more quickly collected over broad areas. Networked data connectivity on the Internet allows rapid communication (learning about projects, receiving training, asking questions, and taking part in social networks), installing applications (or using web-applications), submitting data, and disseminating the results. Due to this connectivity, many people, covering a wide geographic range may take part in projects, encouraging a model of science that engages public participation.

However, Earth observation using mobile devices is a relatively new technique for collecting data. At present, Earth observation using mobile devices is defined by a range of terms and concepts that cross a broad range of disciplines including traditional remote sensing, terrestrial biology, geography, computer science, and citizen science. A critical review, evaluation, and sorting of these terms, concepts, and projects is needed to advance the state of the science and provide direction for future projects that use mobile devices for Earth observation. In this chapter, this need in is addressed three ways. In the first section, mobile devices are introduced for Earth observation and their utility for making measurements of Earth features and processes is examined. In the second section is a review of a range of related literature; terms and concepts, including citizen science, citizen sensing, participatory sensing, and opportunistic sensing; projects that use mobile devices for Earth observation; and projects that use related technologies which may be applied to advance mobile remote sensing projects. In the third and final section, as a result of the literature review, challenges and recommendations for the future of Earth observation using mobile devices are discussed.

2.2 Using mobile devices for Earth observation

In 2010, 5 billion of the Earth's population of 7 billion people, were estimated to have mobile cellular telephones, with 1 billion, a rapidly growing portion of the demographic, estimated to have mobile cellular phones with data connections, computing capabilities, and sensors for collecting data, commonly referred to as smartphones (ITU 2010). The common features of these smartphones provide capabilities for people to collect information about forest structure from the ground and human perspective using the touchscreen for viewing and entering data, sensors (including cameras to collect imagery), global positioning systems (GPS) to collect geolocation, compasses and accelerometers for measuring direction and angle, and the ability to store and transfer data over a network (Table 2.1). The key ability of smartphones for Earth observations is that when observations are made in the field, smartphones have the ability to store the data in memory and transfer it over a network to a server where observations are collected over broad areas. When network connectivity is not available, for example in remote locations where there is no cellular service, data may be stored in memory until network service is available again. This task may be accomplished manually, or using more advanced automatic methods. For example, Hull *et al.,* (2006) developed algorithms to deal with intermittent network connectivity by buffering data in the device's local memory, using call-backs to ensure successful delivery of data between the sending device and receiving server, and setting priorities for transferring buffered data to the server when network access is available. To record observations, graphical interfaces can be delivered on the touch screen to provide information to, and capture input from the user. Additionally, two very common built-in sensors with potential for measuring natural features are the camera and the microphone. The camera is of obvious interest for acquiring imagery for analysis, typically measuring energy in the visible range of the electromagnetic spectrum in three bands representing the red, green, and blue portions of the electromagnetic spectrum. Smartphone microphones have potential to measure acoustic signals, which have been used to identify ecosystem disturbance, incidence of human activity, and animal symphony (Porter *et al.,* 2005). Digital compasses are commonly built in to measure the device orientation relative to the Earth's magnetic poles. Accelerometers and gyrometers can measure the device orientation, and changes in the devices orientation in three dimensions relative to the Earth's gravity. Finally, two-way communication is possible, for example, in response to a query for assistance. Geolocation for observations made using smartphones can be acquired using the built in assisted global positioning system (A-GPS), and other location services. Assisted GPS uses additional information from the cellular network to more quickly acquire GPS signals and reduce energy consumption. Other location services are available where it is impossible to acquire a strong GPS signal (such as inside buildings) including triangulation of cell-phone towers, and WiFi positioning systems (where the MAC addresses of wireless access points have been mapped and are used to determine location). Zandbergen (2009) evaluated the accuracy of locations recorded by an Apple iPhone 3G compared to survey benchmarks, and found a median error of 8m for the AGPS, 74m for the wifi location services, and 600 m for cell-tower positioning, which was lower than for normal autonomous consumer GPS units. In a practical field test, Weng *et al.,* (2012) found that a smartphone GPS provided acceptable measurements for general geology fieldwork.

Table 2.1 Features of mobile devices that make Earth observation possible.

Characteristic	Potential Use
Built-in memory	Storage of pictures, sounds, and observations. Storage of reference material.
Network	Exchange of measurements with central server. Retrieval of reference material.
Touch screen, keyboard, and voice controls	Navigate menus, make selections, and enter textual information.
Camera	High spatial resolution imaging spectrometer (visible spectrum).
Microphone	Record sound.
Compass	Direction (relative to the Earth’s magnetic poles).
Accelerometer / Gyrometer	Orientation (pitch and yaw).
Global Position System (GPS)	Global position.
Assisted GPS (A-GPS)	Global position in locations with poor GPS signal, fast acquisition.

Compared with handheld tablet computers sometimes used for field data collection, smartphones have a several distinct features. First, smartphones have cellular network connectivity, so they are able to connect to the Internet where there is cellular data connection, while personal computers typically require a wireless network access point, or connection to another networked device. Second, smartphones are equipped with a compass, accelerometer and gyrometer, which provide the ability to measure directions and angles, while these features are not typically built in to a mobile handheld computer. Third, handheld computers specifically designed for field work, may feature a high accuracy GPS and the built-in ability to do differential corrections to provide GPS measurements that are of higher spatial accuracy than those acquired by common smartphones. Fourth, handheld computers may be specifically designed for field use, and may feature more rugged enclosures that provide resistance to damage in field conditions (for example heat, cold, impacts, and moisture), however this can be mitigated using aftermarket protective cases on common smartphone devices. Finally, smartphone devices are used by a large and growing segment of the population, while handheld computers specifically designed for fieldwork by professional field crews are not as ubiquitous. These technical characteristics provide insight into the types of measurements that are practical using smartphones. Since smartphones utilize cellular networks for data transfer, some of the most relevant applications are in urban areas, wildland-urban interface (WUI) areas, and along transportation corridors where cellular reception exists.

2.2.1 Terms and concepts

Since the envisioned network of mobile devices depends on volunteers from the public to collect and submit measurements, Earth observation using mobile devices has some similarities to citizen science, scientific endeavours where members of the public play an active role in collecting or analyzing data (Cohn 2008; Bonney *et al.,* 2009; Silvertown 2009). The disciplines of ornithology and astronomy both have relatively long traditions in citizen science, and recently citizen science has gained an increasing amount of attention by allowing researchers to collect data and perform analysis that would be prohibitively expensive and time consuming using traditional means because it covers broad spatial extents and requires fine temporal resolution (for example, Fink *et al.,* 2010), or processing the data that would be prohibitively labor intensive for a traditional research group (Raddick *et al.,* 2010). In astronomy, through the Galaxy Zoo project, more than 200,000 volunteers classified 100 million galaxies acquired by the Hubble telescope, a task which is difficult to perform automatically using computer vision techniques, and time consuming for laboratory staff (Raddick *et al.,* 2010). In ecological research, measurements contributed by volunteers in the eBird project have allowed researchers to collect and analyze temporally frequent data spanning North America (Trumbull *et al.,* 2000), providing opportunities to generate and test hypotheses for ecological inquiry at spatial and temporal scales that would be impractical using traditional methods (Dickinson *et al.,* 2010).

In meteorology, volunteers have collected extensive measurements of precipitation, providing more spatially detailed measurements than are available from the official network of weather stations and revealing previously undetected patterns of precipitation (Cifelli *et al.,* 2005). In mathematics, volunteers have donated processing time on their computers when not in use with other tasks, providing substantial distributed computing power to calculate very large prime numbers (Hayes 1998). To a large degree, these previously mentioned disciplines with successful citizen science initiatives are alike as they have a strong following of amateurs with considerable motivations and skill.

The term "citizen science" has gained widespread use and acceptance in the disciplines that practice it; however, there are several contradictions between the meaning of the term and common practice. For example, the word citizen is used to indicate that academic qualifications are not required to participate, while it may imply that citizenship in a particular state is a requirement to participate in a citizen science project (though this is seldom the case). Further, science is both a process, and a professional designation. While the efforts of volunteers can be of high value to scientific inquiry, performing these tasks does not fulfill the requirements placed on someone given a professional title of scientist (data collection and processing tasks are often the job of field and laboratory technicians).

Some have been critical of the unequal "use of citizens by scientists," drawing comparisons with 19th century specimen collection by British scholars using citizens in colonies (Lakshminarayanan, 2007). In response to this criticism, Cooper *et al.* (2008) distinguished citizen science from 19th century centralized specimen collection in that citizen science is typically framed in societies where there are many opportunities for citizens to enter scientific professions but few opportunities to participate as non-professionals, while acknowledging that present "informal science education" goals of citizen science projects may not readily lead to entry into scientific professions in developing countries. To promote equality between scientists and non-scientists, both Lakshminarayanan (2007) and (Cooper *et al.* 2008) call for open access and freedom for datasets collected by citizen scientists. Finally, while these projects often have the potential to inform policy and effect positive environmental change in the environments where they are practiced, Conrad and Hilchey (2011) identified a lack of documented examples where such change has taken place.

The term “Public Participation in Scientific Research” (PPSR) describes a broad range of activities that are often associated with citizen science, participatory sensing, and volunteered geographic information (Bonney *et al.,* 2009). PPSR is defined as “intentional collaborations in which members of the public engage in the process of research to generate new science-based knowledge” in projects that “aim explicitly to contribute to scientific research and/or monitoring” (Shirk *et al.,* 2012, p. 2). Shirk *et al.,* (2012) outline the main incentives to pursue PPSR approaches, including positive outcomes for science (by providing a dataset or analysis that would be difficult to otherwise obtain due to time, cost, or scale without the help of volunteers; volunteers helping with analyzing or interpreting data; and utilizing knowledge from volunteers in formulating research objectives, scientific theories or hypotheses), outcomes for management (by providing ecosystem monitoring data to inform management decisions), and outcomes for the volunteers themselves (by providing an opportunity to learn a skill, form part of their personal identity, or take part in an activity that they enjoy).

The meaning of the term “participation”, a key aspect of PPSR, has been critically evaluated, especially in development studies, where participation have been used to describe projects with a wide variety of outcomes, both positive and negative (Cohen and Uphoff 1980). Therefore specificity is needed to evaluate who participates (including who is excluded and who may exclude themselves), what they participate in (ranging from shallow and limited participation to deep and durable participation in which volunteers take part in all parts of the investigation; also, what decisions can the participants actually influence), and who can benefit from the participation (Cornwall 2008). Arnstein (1969) presented a ladder of citizen participation ranging from non-participation to degrees of citizen power (Figure 2.1), showing that power and control are tied to the nature of participation. More recently, some have raised concerns that volunteer efforts, such as "crowdsourcing", where information is volunteered by crowds generally perceived as interested armatures or hobbyists, in fact often originates from groups of people with considerable expertise requiring substantial amounts of effort with no consideration of fair compensation, worker's rights, and ethical treatment while potentially serving the profits of companies (Brabham 2012).

Figure 2.1 Arnstein's (1969) ladder of participation.

8. Citizen control 7. Delegated power 6. Partnership	Citizen Power
5. Placation 4. Consultation 3. Informing	Tokenism
2. Therapy 1. Manipulation	Non-participation

Researchers have evaluated the nature of the participation in PPSR. Conrad and Hilchey (2011) presented a framework describing different roles in PPSR as consultative/ functional (where the project is initiated, funded, and run by a central body), collaborative (where a project is led by a committee representative of stakeholders in an issue), and transformative (where a project is initiated, funded, and run by a community group, often in a time of crisis in an attempt to gain the attention of government). Similarly, Bonney *et al.,* (2009), presented a framework where PPSR projects are classified as contributory (designed by scientists for the public to contribute data), collaborative (designed by scientists, but the public also has some say in project design, data analysis, and dissemination of findings), and co-created (which are designed by scientist and the public working alongside each other, and public participants are involved in most or all of the steps of the scientific process). These classifications generally correspond with the steps of Arnstein's (1969) ladder of participation, with contributory projects equating to consultation or informing steps of the ladder, and co-created projects ranking closer to the steps of citizen power. Bonney *et al.,* (2009) provide a comprehensive listing and discussion of PPSR projects classified according to the levels of participation, however, there are limited examples of co-created or higher projects. Most PPSR projects collecting data covering broad spatial extents follow the consultative / functional model, where commonly, a lead researcher from a traditional academic institution determines the hypothesis and experiment design and volunteers collect or process the data, and the researcher then analyzes and publishes the results (Bonney *et al.,* 2009).

Similar to how citizen science includes the involvement of non-specialists, Goodchild (2007) referred to ‘‘citizens as sensors’’ in reference to the vast datasets of volunteered geographic information (VGI) collected by individuals and shared over the Internet. This approach is largely facilitated by technological advances that have provided large numbers of people with tools, such as consumer GPS, digital cameras, and Internet mapping services, to collect, record, and share spatial data about their environments on the Internet. These spatial datasets may be intentional, where citizens actively seek out measurements. Other sources of spatial data may be coincidental, where data is revealed from public data created for other purposes (for example, using datasets of georeferenced photos on photosharing websites), and there is debate about whether these type of data was voluntary because some is collected without consent (*e.g.,* if a toll-road operator collects information about the people paying tolls at each, the station the geographic data was not volunteered by the people crossing the toll stations) (Elwood *et al.,* 2012).

Participatory sensing (Burke *et al.,* 2006) is a more specific type of volunteered geographic information because it describes projects where the public actively participate by operating specially designed sensors and frameworks for purposes including urban planning, cultural identity and creative expression, and natural resources management. A great deal of research in participatory sensing is directed by researchers designing frameworks and technologies to facilitate grassroots sensing, a bottom-up process where non-specialists may initiate sensing projects without the direction of specialists. As a result, researchers have called for more research in participatory sensing to understand how to get people more actively involved in sensing projects, for example by understanding target audiences and designing services that meet their needs and motivations (Krontiris and Maisonneuve 2011). In contrast, participatory mapping was developed from participatory research in anthropology, sociology, and human geography, and in this context, the meaning of participation was rigorously debated. Involvement in participatory mapping includes non-academics defining research goals, designing research projects, collecting data, and analyzing data (Herlihy and Knapp 2003). In both participatory sensing and participatory mapping a guiding principal is that local people hold valuable knowledge that may be missed by top-down processes (Peluso 1995). In action research, an established social sciences research method, research is initiated to understand and systematically solve a social problem by studying it, initiating change, and reflecting on the changes (Lewin 1946). In participatory action research action is also initiated to both understand and solve practical problems with a stronger emphasis on participation and action from within the affected community and the underlying goal of empowering people to make decisions and take action, and drawing strong connections between participation and action (Whyte 1989).

In contrast to participatory sensing, where participants choose to contribute to a sensor network, Lane *et al.,* (2010) distinguishes opportunistic sensing where data are collected based on activities without participants actively choosing to submit data. An example of this type of activity is GSM tracing (Sohn *et al.,* 2006) where the movement of people is measured based on their regular mobile communication device usage. Another example is data mining from public social networks, for example images posted on photo-sharing websites. Lane *et al.,* (2010) suggests that opportunistic sensing may suit broad applications, since rates of participation are not directly dependent on volunteers actively making measurements for the purposes of the project. Lane *et al.,* (2010) describes participatory and opportunistic sensing as opposite ends of the spectrum, and at present there are too few broad scale examples to fully understand the trade-offs of each paradigm. Questions about empowerment and ownership that have been asked about active participation in mapping projects, including who may gain or lose (Chambers 2006), also need to be asked of passive or coincidental data sources, which may raise ethical concerns. For example information could be extracted that could be used against the people who created it, expose people to danger, or cause tensions within a community (Chambers 2006).

These terms, concepts, and definitions are summarized in Table 2.2.

Table 2.2 Terms and concepts related to mobile remote sensing using smartphones.

Term	Definition
Citizen Science	Science where citizens participate in any capacity, including data collection or analysis (Cohn 2008; Braschler 2009; Silvertown 2009).
Volunteered Geographic Information	Geographic data provided voluntarily by individuals (Goodchild 2007)
Participatory Sensing	Remote sensing where citizens participate by operating sensors (Burke *et al.,* 2006).
Opportunistic Sensing	Remote sensing using devices not necessarily designed to collect remote sensing data (Lane *et al.,* 2010).
Public Participation in Scientific Research	"Intentional collaborations ... to generate new science-based knowledge" in projects that "aim explicitly to contribute to scientific research and/or monitoring" (Bonney *et al.,* 2009; Shirk *et al.,* 2012 p. 2)

2.2.2 Projects using mobile devices for Earth observation

In this section, a selection of projects that use mobile devices to collect Earth observation data are reviewed. A review of published studies was conducted using the following criteria: (1) The study must use common mobile devices to collect Earth observation data without the attachment of specialized scientific equipment and (2) Public participation is encouraged. From the suite of eligible studies, eight studies were highlighted to cover a range of disciplines, locations and approaches. Given that this is a dynamic field with new and innovative studies being developed and published rapidly, these studies are indicative rather than exhaustive.

2.2.2.1 eBird

The eBird project was established by the Cornell Lab of Ornithology and National Audubon Society to gather, organize, and disseminate bird-sighting data to citizens and scientists alike (Sullivan *et al.,* 2009). This project has been very successful in initiating high levels of public engagement and subsequent use of eBird data in scientific publications, including building complex exploratory models integrating a range of estimation monthly estimates of species distribution over a broad spatial extent (Fink *et al.,* 2010). The success of eBird is attributed to the design of an approach that aims to provide a useful resource for birders based on the interests and desires of the birding community, engage them in science, and, at the same time, provide tools to collect scientific data (Sullivan *et al.,* 2009). Resources provided to birders in this project include the ability to query a vast database for bird observations and display results on maps and in tables, a permanent place to store and share checklists, and alerts for notable and rare sightings that attribute recognition for birders' accomplishments. Bird surveys may be completed using three effort-based sampling schemes (time, distance, or area), or less rigorous casual observations. Submitted data are first automatically checked against species limits for the time and locations, unusual observations are sent to regional editors for review, and supporting evidence may be requested. Open access to data is maintained for participants, scientists, and the general public. Registration and a login code are needed to submit data, but not to download data, view maps, or view graphs. Through the open access to data and access to information about the scientific process, the designers claim that citizen participants may go beyond data collection to become more informed and engaged in science (Cooper *et al.,* 2008). Additionally, several mobile applications for mobile devices have been developed and provide field-based queries of the eBird database to display the time and location of bird sightings and bird sighting hotspots, including BirdsEye (http://www.getbirdseye.com/), and the Audubon guide to birds (http://www.audubonguides.com/ index.html) (where eBird queries are supported in addition to a multimedia field guide). Other applications, such as The Bird-Watcher's Diary (http://www.stevenscreek.com/birdwatchersdiary.htm) have been developed to streamline the process of completing checklists by automating repetitive aspects, such as recording time, data, and GPS data, providing multi-modal dataentry methods (for example, touch-screen, keyboard/ buttons, or voice controls) for consistently recording field observations, and providing export options compatible with the eBird data structure. BirdsEye is able to submit directly from the field to the eBird database.

2.2.2.2 The National Phenology Network and Project Budburst

The U.S.A. National Phenology Network (USA-NPN) monitors the influence of regional climate on the phenology of plants, animals, and landscapes, based on observations collected by volunteers across the United States. These in-situ observations collected by volunteers have the potential to provide long term records with the precise timing of phenological events, including leaf out, flowering, migrations, and egg laying. Volunteers in the National Phenology network are required to register for the program and are provided with measurement protocols. Observations are uploaded to the project database and aggregated across spatial extents. The project designers identify the motivation for participants as the rewards of making observations, and knowing that they are making a contribution to research and climate monitoring (Mayer 2010). Access to submit and download data is provided to participants and researchers after registration. Project Budburst is an offshoot of the USA-NPN developed by the National Environmental Observatory Network (NEON) and the Chicago Botanical Garden, where volunteers make measurements of plants, kept in a separate database from the USA-NPN. School groups are encouraged to participate through the availability of curriculums for teachers to use in classes. Through a collaboration with the University of California Centre for Embedded Network Sensing (CENS), in Project BudBurst Mobile, applications were developed to make and submit measurements of phenological timing using mobile devices. Using mobile platforms and protocols designed for volunteer data collection, Project Budburst Mobile demonstrates the foundations of a mobile remote sensing project with the potential to reach a wide audience with mobile devices, given enough interest and motivation by volunteers to build a large enough database to analyze at a national scale. The motivations of participants have been explored by adding game elements to increase motivation. (Han *et al.,* 2011) designed a game called Floracaching (a play on the word ‘‘geocaching’’, an activity where participants use GPS devices and other navigational equipment to hide and seek hidden caches). In Floracaching, participants are awarded points for finding floracaches (plants given a special designation) and recording the phenology. Participants are able to create new floracaches once they reach a certain number of points by visiting existing foracaches. Results indicated that participants were motivated by game elements, followed by the making a contribution to science, and finally followed by the desire to share pictures and observations with peers (Han *et al.,* 2011).

2.2.2.3 NatureServe

NatureServe is a network of programs comprised of independent centres that collect and analyze data about plants, animals, and ecological communities of the western hemisphere, in particular by identifying and keeping track of ecologically important, and threatened, components of the terrestrial biosphere (Regan *et al.,* 2004). A recent initiative in the NatureServe program aims to develop a ‘‘Mobile Observations System,’’ for gathering, collecting, managing, and sharing information about plants animals, and habitats using a mobile platform with a built-in camera and GPS. This digital collection method is designed to be a more efficient and accurate way of collecting data by reducing data entry errors (for example translating field notes to digital format) and automating repetitive and tedious tasks such as collecting metadata and recording GPS readings. Consistency is improved by the use of standardized data collection templates and protocols, allowing integration and synthesis between datasets. The collection forms and workflow are designed to be extendable for a variety of projects and objectives. In addition, a desktop environment is also in development to assist with data cleanup and submission to the spatial data server for long-term storage. These tools are available to scientists and professionals, and additionally, they are also available to grassroots initiatives with access to mobile devices.

2.2.2.4 Leafsnap

Leafsnap provides software to identify tree species based on describable physical attributes, including leaf shape, color, and size, using computer vision algorithms to search from a large reference database of samples, with the aim to assist field ecologists, field assistants, and citizen scientists to make more timely and accurate species identifications (Belhumeur *et al.,* 2008). Extensive reference libraries were built with high quality digital images and descriptions for common and rare species, making this information more readily available to botanists and the public using computers and mobile devices. As samples are collected and analyzed using the application, spatially referenced data are uploaded to a central server, which as the database builds in volume, may be useful for monitoring species distribution across landscapes. The software is designed to provide wide access to the reference database, and the ability to collect samples and record classifications more quickly and easily than using traditional methods. Additionally, for non-expert users, several tools are provided to reduce the barriers to making accurate taxonomic classifications, including training games, intuitively designed delivery of information using clear pictures and text, and the assistance of computer-vision searching, which may be less daunting than learning to use traditional field guides. Users identify a specimen with the application by capturing an image of a leaf on a contrasting background, such as a piece of paper on a clipboard, using a mobile device. Then, computer vision algorithms are used to segment the shape of the leaf and the segmentation information is sent over a network to centralized servers and compared to reference measurements in the sample database to generate a number of likely matches. Finally, the participant uses other identifying characteristics, such as appearance of flowers, leaves, petiole, fruit, bark and habitat, to identify and verify the species. This human-in-the-loop approach can reduce the amount of work required by participants by using computer algorithms to query large databases, while using human input to improve accuracy of classifications (Branson *et al.,* 2010).

2.2.2.5 GeoTools

GeoTools (Weng *et al.,* 2012) is an application for geology field observations using mobile devices. The applications major features include the ability to record text, sounds, and photos; measure strike and dip of geologic features; measure geolocation; create thorough and consistent metadata for all measurements; and output data in a consistent and well-documented format. Traditionally, these tasks were accomplished using an autonomous camera, compass (with inclinometer), GPS, notebook, paper, and pen. After data collection, the entries in the notebook must be digitized. From the perspective of the researchers, for geology fieldwork, the mobile device application collected data with as much precision and accuracy as the traditional tools, while avoiding data entry errors during digitization and reading instruments, and keeping the data in a consistent data format. While this project has not been released to the public yet, it is indicative of the type of tools that will soon become more common for field crews and amateur geologists.

2.2.2.6 GeoExposures

GeoExposures is a citizen science project by the British Geologic Survey, where volunteers document temporary exposures, for example trenches, pipelines, foundation excavations, road cuttings, and embankments. As these exposures are temporary, and are therefore often ‘‘lost to science’’ (Powell *et al.,* 2012). The authors utilized a publicly accessible web database, accessible to anyone who wants to submit or view. The public is asked to volunteer photographs and geographic coordinates of these temporary exposures using an application for mobile devices or a web form. No registration is needed to submit data. A web-map is provided on the webpage for viewing data. To ensure data quality, an employee of the BGS filters submitted measurements, and a forum is provided for discussion about submitted data. A potential future area of research is understanding who submits data to GeoExposures, what are their motivations and experiences, and how does this compare with other citizen science projects.

2.2.2.7 Open Data Kit (ODK)

Open Data Kit (ODK) is a platform for collecting data using smartphones (Brunette *et al.,* 2012). Originally designed as a tool for public health projects in developing countries, ODK can also be used for collecting ecological data such as forest measurements (*e.g.,* Pratihast *et al.,* 2013). The first version of ODK, utilized extensively by a range of projects (over 11,000 installations from the Google Play store in 2013) featured three applications to 1) build forms for data collection, 2) collect data using smartphone platforms, and 3) aggregate measurements from multiple devices. Version 2.0 of ODK featured several changes and extensions. For example, Brunette *et al.,* (2012) describe that in many developing countries tablets and smartphones are used for tasks that are accomplished using desktop computers in earlier adopting countries, therefore, more of the administrative tasks have been made possible on mobile devices, allowing participation for more organizations that would like to use the application. Finally, the second version has extended functionality, including the ability to connect to and log measurements from external sensor, scan paper forms using a smartphone's camera, and the ability to view tables and graphs of collected data. Tables 2.3 and 2.4 summarize the features of the previously described projects that use mobile devices to collect environmental data.

Table 2.3 Projects that use mobile devices for Earth observation.

Project	Agency	Description	Motivations and rewards	Platform
eBird (Sullivan *et al.,* 2009) http://ebird.org (retrieved 2 September 2012)	Cornell Lab of Ornithology and National Audubon Society	An online database for avian surveys with access for citizens and scientists alike. Field sampling protocols and guidelines provided for volunteers.	Tools for searching and viewing database useful for birders. Prestige for enthusiasts sharing lists of sightings.	Web and mobile
National Phenology Network (Miller-Rushing et al 2010) http://www.usanpn.org/ (retrieved 2 September 2012)	Partnership of scientific and government organizations.	Infrastructure to share phenology observations and support research on regional climates.	"[Tools] for researchers, students, and volunteers... to discover nature". "Making phenology data, models and information freely available to empower decisions by scientists, managers and public" (https://www.usanpn.org/about#)	Web
Project Budburst (Reddy et al., 2008) http://neoninc.org/budburst/ (retrieved 2 September 2012)	NEON and CENS	A mobile application to record the timing of phenological events; partner with National Phenology Network	"Make a meaningful contribution to understanding environmental change [and] contribut[e] to research", "ask a scientist", and "download data"	Web and Mobile
NatureServe http://www.natureserve.org/projects/handheld/index.jsp (retrieved 2 September 2012)	NatureServe	An extensible mobile framework and supporting backend for digital field data collection.	Tools for scientists and project managers to coordinate data collection using mobile devices.	Mobile
LeafSnap http://leafsnap.com (retrieved 2 September 2012)	Columbia University, University of Maryland, and the Smithsonian Institution	Computer visions algorithms to search plant leaf database and display high quality images and plant information.	An electronic field guide. Access to detailed descriptions and high-resolution images of leaves, flowers, fruits, petioles, seeds, and bark.	Web and Mobile
GeoTools	Ball State University	A mobile application for geology fieldwork, automating and synthesizing common tasks for field geologists.	Field tools for geologists. Collect integrated and consistent field data.	Mobile
GeoExoposures http://www.bgs.ac.uk/citizenScience/geoexposures.html (retrieved 2 September 2012)	British Geologic Survey	A tool for documenting temporary geologic exposures.	"Provide the geoscience community with a website to enable recording of temporary geological exposures, and to make the information available to all"	Web and Mobile
Open Data Kit	University of Washington Department of Computer Science; Google.org	A toolkit for building forms for mobile data collection, collecting data on mobile platforms, and aggregating data collected by distributed devices.	Tools for mobile data collection in developing countries. Make data collection accessible to people with a range of experience and employ local people to collect data.	Mobile (with desktop admin.)

Table 2.4 Attributes of projects that use mobile devices for Earth observation.

Project	Database	Login	Maps	Tools	Scope	Games	Schools
eBird	Web	Needed to submit data	Public	Data entry and query, keep personal lists	Continental (North America)		
National Phenology Network	Web	Needed to submit data	Public	Training, phenology data entry, visualization of data.	Continental (North America)		Extensive
Project Budburst	Web	Needed to submit data	Public	Phenology data entry	National (USA)	Floracaching	
NatureServe Mobile Observation System	Private (for mobile data information system), public for Data Explorer	Needed to submit data		Data dictionary programming, data entry	Continental (North America and Latin America)		
LeafSnap	Web	Needed to submit data	Maps of where measurements were made	Image based leaf-identification, search database, training games, keep personal lists	Eastern North America	Training	
GeoTools	Personal	NA/	Personal	Measure strike, dip, pictures, sounds, and notes	Regional		
GeoExoposures	Web	Not needed	Public	Report observations	National (United Kingdom)		
Open Data Kit (ODK)	Web	Depends on application	Depends on application	Design forms for data entry; collect data using smartphones; aggregate data from multiple smartphones; log data from external sensors; scan paper forms; and generate tables and graphs on smartphone.	Depends on project; available internationally in multiple languages		

2.3 The future of mobile devices for Earth observation

As a result of the literature review, the following considerations are provided for Earth observation projects using data collected using mobile devices. First, the utility of mobile devices to provide Earth observation data is evaluated. Second, considerations for collecting data are discussed. Third methods for analyzing data are discussed, and finally using and sharing Earth observation data collected with mobile devices is addressed.

2.3.1 Earth observation using mobile devices

Earth observation using mobile devices is the collection of data about the Earth's physical, chemical, and biological systems, using smartphones or tablets to collect the data. This activity generally falls under the category of VGI, because it depends on the populations of people with mobile devices to voluntarily submit measurements. Due to the scientific nature of these investigations, Earth observation using mobile devices also overlaps with citizen science. Volunteered data collection using mobile devices depends on the population having access to mobile devices to make measurements, cellular data connectivity to transfer the data to servers (although approaches are available to collect data and store them until network connectivity is available), the local availability of monitoring projects to partake in, awareness of these monitoring projects by volunteers, and motivation by volunteers to contribute measurements. Therefore, the logical application area of mobile devices is in urban and suburban areas and along transportation routes that have cellular data service (*e.g.,* highways). Wildland-urban interface areas provide an ideal combination of people available to participate in projects, natural areas to measure, and well-serviced infrastructure including cellular data networks. Additionally, these areas are high priority areas for monitoring efforts because at this interface human populations are growing and many anthropogenic impacts on environments are found (Leu *et al.,* 2008). Given that mobile devices are handheld, mobile, and ground based, they demonstrate suitability for making measurements of objects and processes near the ground surface. For example, forest structural components near to the ground (including coarse woody debris, dead standing trees, and understory vegetation) and some geological features may be difficult to measure using airborne and spaceborne platforms due to viewing geometry, forest canopies obscuring the view, and the relatively small size of features compared to the spatial resolution of sensors. Image data may be supplemented with observations made by the device operator, providing the opportunity to record measurements that are difficult to acquire using sensors or to analyze using automated methods. These human entered observations and judgments may serve to establish the context of the measurements and place constraints on the data (based on factors such as conditions at the time of acquisition and the experience of the operator). It may also help to measure cultural land uses that are impossible to measure using satellites, for example place names, identification of communities, human use of resources, and the social values. Furthermore, mobile devices are less restricted by atmospheric conditions than space or airborne platforms, due to the shorter path from the sensor to the measurement surface, and may offer opportunities to make measurements with higher temporal resolution; for example, when cloud cover obscures the view of aerial sensors. In a well-coordinated project, due to the ubiquity of mobile devices, measurements may be collected over extensive areas and deployed quickly to record limited time occurrences such as natural disasters, or rare events.

2.3.2 Recruiting and retaining volunteers

Recruiting and retaining volunteers is the act of finding volunteers to contribute high quality data to a project. Building sufficiently large databases in Earth observation project depends on the effective recruitment and long-term involvement of participants. In contrast to citizen science projects that provide tools that are based around hobby activities that members of the public actively engages in, such as bird watching, other types of Earth observation projects may require volunteers to partake in activities that are much different than their typical daily activities. Also, in contrast to activities that are based around volunteers using their personal computers in their free time, such as the Galaxy Zoo, Earth observation using mobile devices requires volunteers to actively enter their environments and take measurements. Therefore, these types of projects using Earth observation using mobile devices may require different approaches and more closely follow a volunteerism and environmental stewardship model. Cooper *et al.,* (2007) suggested that partnering with existing organizations, such as civic groups, neighbourhood organizations, non-profit environmental protection groups, and outdoor recreation groups is an effective way to reach target communities, and providing constant support, through email list-servers and online discussion boards is needed to retain participants. These findings are supported by research in environmental volunteerism by Moskell *et al.,* (2010), who found that volunteers in an urban environmental stewardship project were more likely to arrive at events with a friend, coworker, or acquaintance from a stewardship organization than arriving alone having found the event through Internet advertising. Given that volunteers are likely to have a history of volunteering in previous projects and networked connections to other individuals in volunteer organizations, automated methods of selecting and targeting participants based on availability and performance when collecting data, such as those developed by (Reddy *et al.,* 2010), may also help target participants for new projects. Participation levels were examined in detail by (Reddy *et al.,* 2008) who described participation levels as consistent, bursty (showing concentrated bursts of contribution), or sporadic, and highlighted a significant risk in participatory sensing projects, abandonment, where participants begin a project and then fail to complete the project. A number of approaches have been developed to address these challenges. For example, the eBird project provides a number of services to contributors, by helping birders keep track of sightings, publishing bird checklists, attributing credit to bird watchers accomplishments, and establishing a sense of community through email lists and discussion forums (Sullivan *et al.,* 2009). In the GalaxyZoo project, engagement with other participants using online forums to form a sense of community was cited as a motivating factor for many participants to make a sustained effort in the project (Raddick *et al.,* 2010).

2.3.3 Collection of field measurements using mobile devices

The collection of field measurements using mobile devices is the act of acquiring data in the field using mobile devices. Similar to the traditions of remote sensing, which are image-based, for Earth observation using mobile devices the camera may be one of the most important sensors. The challenge of developing methods to extract quantitative measurements from photographs taken using mobile devices, given the high spatial resolution, oblique geometry, and human based perspective, may be met by incorporating human observation and judgment-based information collected in the field with automatic classifications. These tasks may range from simple questions for quality control (for example, asking a participant to double check a measurement), to more complex operations that require human input to improve automatic classifications, such as setting thresholds, interpreting shapes, and making comparisons to reference observations. These tasks can be led and facilitated through a graphical interface (for example, Raddick *et al.,* 2010). Furthermore, the range of mobile device sensors, including those that measure device orientation, such as compass, accelerometer, and gyrometer can be used to provide context to constrain computer vision problems, which in turn can facilitate more accurate classifications (Bradski and Kaehler 2008). Measurements over broad spatial extents using networks of mobile devices depends on building databases of comparable observations made by a dispersed network of participants, including a large number of different mobile device software and hardware platforms and device configurations. Bioinformatics techniques applied to remote sensing data collected using mobile devices, such as consistent protocols for data collection, standardized data models, and detailed metadata are needed so that spatially and temporally dispersed data on a range of subjects can be integrated and synthesized (Jones *et al.,* 2006). Consistent data models can be promoted by establishing data warehouses and web based front-ends to relational databases (Mcguire *et al.,* 2008), and providing open application programming interfaces (that allow access to the data and software tools for other applications) may allow other developers to extend projects for a range of platforms.

2.3.4 Sampling strategies

Sampling strategies determine where and when measurements are acquired through space and time. While strict probabilistic samples provide the highest efficiency per datum, datasets with less structured sampling schemes with large volumes of data may provide unique information, though more rigorous analysis and modeling are needed to utilize these data (for example, Munson *et al.,* (2010)). Volunteered geographic datasets often contain biases that can be categorized as temporal or spatial (Dickinson *et al.,* 2010). Biases in time are related to the effort of the observers, the times when volunteers are available to make observations, and the types of observations that volunteers submit in contrast to those that they do not submit. Biases in space are related to where volunteers collect measurements. For example it was demonstrated by Betts *et al.,* (2007) that the areas sampled in roadside breeding bird surveys had undergone different rates of landscape change than surrounding landscapes. Additionally, substantially more opportunities to collect measurements exist in populated areas, and there is a bias towards higher density sampling in populated areas and areas with more supporting infrastructure (to provide access) (Fink *et al.,* 2010). A common source of bias through space and time in volunteered datasets is the observer effect, where participants submit measurements that they find interesting, and fail to report common measurements (Cuff *et al.,* 2008). These effects can be mitigated by correcting for sampling effort (Link and Sauer, 1999). Finally, volunteers may have a range of levels of experience and cultural backgrounds, and whether these effects have significant spatial or temporal effect and bias warrants further investigation.

2.3.5 Privacy

Privacy is important in projects that use mobile devices so that the people collecting data do not inadvertently disclose information about themselves or others as a result of the design of the project. Researchers have called for clear guidelines to be set in terms of what levels of privacy are acceptable in VGI (Elwood *et al.,* 2012). In contrast to remote sensing measurements made from spaceborne and airborne platforms, near-surface remote sensing measurements collected using mobile devices have distinct privacy considerations (Slonecker *et al.,* 1998). It may not be possible to collect near-surface remote sensing measurements using mobile devices where public access is not permitted, such as private property, unless the owners agree to cooperate.

Furthermore, in the process of volunteering measurements, volunteers may reveal information about themselves, their property, or their community with which they are not comfortable. Lane *et al.,* (2010) describes how even if volunteers are comfortable and consent to revealing personal information, they may fear that they are unfairly revealing information about people around them, who have not consented to share information, termed the ‘‘second hand smoke’’ effect. These concerns come as an additional cost to participants and may deter participation. Several approaches have been developed to address privacy concerns. In the PoolView project, algorithms have been developed to degrade personal information before submitting to a public database, while still allowing calculation of aggregate community level values from the submitted data (Ganti *et al.,* 2008). Another approach used computer vision algorithms to filter for confidential information before sharing measurements (Reddy *et al.,* 2007). Providing open access to datasets to ensure transparency may build trust for participants, if privacy is reasonably protected. If trust is well established with participants, volunteered datasets may be a tool to collect measurements from private property, having the owner’s consent, which may not be practical to obtain using traditional field crews. Another challenge is that by building communities that may increase motivations for participation such as expected reciprocity and recognition for efforts, may also lead to tension due to privacy concerns (Krontiris and Maisonneuve 2011).

2.3.6 Data quality

Data quality can be described as the lineage, positional accuracy, attribute accuracy, logical consistency, and completeness (Moellering 1987) that makes data fit for a given use (Chrisman 1984). Data lineage is related to the history of the dataset and is usually recorded in the metadata.

Collecting data digitally using mobile devices offers opportunities to automate aspects of metadata creation during data collection. There are limitations in the positional accuracy of mobile devices that are different than for equipment explicitly designed for field data collection. For example, Zandbergen (2009) found that the accuracy of GPS devices on common mobile devices was lower than for autonomous GPS devices. This limitation may be partially addressed by including relative descriptions of the locations of where measurements are made as a second double check. Higher accuracy aftermarket GPS units may be connected to mobile devices, though because these units are not standard, this may be a barrier to participation for some volunteers. Attribute accuracy may be influence by both sensor and user errors. Similar to the GPS sensor, measurements made with the camera, microphone, and accelerometer may include errors due to the limitations of the accuracy of these sensors. Additionally, the people collecting data may introduce error into datasets by misunderstanding directions given to them, lacking the expertise to make accurate measurements, or mistakenly submitting incorrect data. Reddy *et al.,* (2008) developed metrics to quantify participant expertise and participation. In their experiment, participants were asked to take pictures of damaged sidewalks in a well-inventoried area using a mobile device to measure participant accuracy, and all participants contributed varying amounts of measurement errors including blurry, dark, or otherwise unusable images. Logical consistency may suffer with different interpretations of classifications (however this should be mitigated using clear instructions and criteria for classifications). The completeness of a dataset is dependent on having a sufficient number of observations to adequately record the condition of a site. To mitigate data quality issues, multiple sensors, such as compass and inclinometer can be used to ensure data consistency, for example, that imagery is acquired at consistent angles and directions. Designers may consider a stepped approach where experienced contributors are given more complex instructions than those first starting out (Dickinson *et al.,* 2010). One quality control approach taken in the eBird project is the application of regional and temporal filters to submitted data. If an observation is unusual in a given region at a given time, it is forwarded to a regional editor for review, and supporting evidence may be requested from the submitter (Sullivan *et al.,* 2009). In the DietSense project (Reddy *et al.,* 2007), where participants wore camera phones around their neck to record dietary habits, software tools were developed to automatically reject, without recording any data, images meeting the following criteria: blurry, dark, or out-of-focus images; those containing personal information, such as computer screens or papers which may contain personal information; and faces of people not participating in the project. Projects using mobile devices to collect ecological data have opportunities to provide immediate feedback from this filtering process. For example, Pundt (2002) evaluated methods of providing realtime feedback on data semantic integrity during data collection for mobile GIS applications that could improve attribute accuracy compared to traditional methods.

2.3.7 Analyzing datasets covering broad spatial extents

By building networks of mobile devices to collect Earth observation data, massive volumes of data can be collected covering broad spatial extents and combined with other data sources. This may require new approaches to analysis. Remote sensing using volunteered measurements, citizen science, and participatory sensing represent new research models in contrast to traditional models of scientific research (Cooper *et al.,* 2007), and offer opportunities to amass large volumes of data, but require different approaches to analysis. Kelling *et al.,* (2009) proposed a new paradigm for data-intensive science, where data-driven analysis techniques such as visualizations, simulations, and model building in volumes of data from multiple sources allow exploration of complex relationships and patterns to generate hypotheses for the underlying biological phenomena. These approaches depend on the synthesis of data from a wide variety of sources that have recently become available.

2.3.8 Sharing datasets

Sharing datasets involves establishing who owns the data, who has access to it, and what are acceptable uses. Data sharing is an important consideration in a citizen science project to establish trust, fairness, and value for data contributors (Bonney *et al.,* 2009). Sharing data under open licenses may alleviate concerns that data are being sold for profit to third parties, or that data are being disclosed against the wishes of participants. The GeoExposures project uses a Creative Commons license that is designed to spell out very clearly the legal requirements for open access to the data (Powell *et al.,* 2012). In addition, providing motivation to volunteers will help maintain a base of individuals willing to contribute to future citizen science projects. However, analyzing volunteered data sets may require considerable expertise and computing power (for example, Fink *et al.,* 2010), so analysis of these datasets may be beyond the capabilities of the majority of volunteers without specialized training and access to powerful computers. Sharing other types of information, such as general reference information and training along with generalized reports in a more accessible format may be rewarding to volunteers (for example, Trumbull *et al.,* 2000; Raddick *et al.,* 2010).

2.4 Conclusion of review

An increasing number of studies, from a broad range of disciplines are embracing Earth observation using mobile devices as a new type of monitoring. The examples reviewed in this study demonstrate a number of advantages of this approach, including the ability to rapidly collect data, collect data over broad extents, collect consistent metadata, provide scientific tools to a broad audience, and provide opportunities to engage the public in science. The field is rapidly growing and changing, and dramatic changes are expected in the coming years. Some challenges in this field include a lack of unity between the many different disciplines and projects. Both technical and social factors are important for the state of Earth observation. Technical advances, for example designing more robust and effective sampling schemes and reliable data collection methods, will result in higher quality data sets. Social advances, such as gaining a better understanding of the range of experiences and motivations of individuals who contribute volunteered data, will help scientists engage the public in a meaningful way, and build new records of Earth observation.

Chapter 3: Social and management considerations

3.1 Introduction

Wildfire management in the wildland-urban interface (WUI) protects property and life from wildland fire. One approach that has potential to provide information about the amount and location of fuels to forest managers and, at the same time, increase public knowledge and engagement in reducing wildfire threats is PPSR inspired approaches using smartphones to collect data. However, there is a need to evaluate the role of these types of programs in communities, including challenges such as volunteer participation incentives, risk, liability, and personal privacy.

In addition, there are similarities between recent PPSR efforts and environmental volunteerism (such as urban tree planting) that may be analyzed to better understand the links between volunteering, collecting data for PPSR, and the expanding role of technology. For example, the Volunteer Function Inventory (VFI) has been employed to understand the motivations of volunteers in an urban tree planting project (Moskell *et al.,* 2010). The VFI is a model that hypothesizes six functions that are served by volunteerism, and these may be used as a tool to assess individual motivations for volunteering (Clary *et al.,* 1998). The functions in the VFI are values (*e.g.,* humanistic or altruistic), understanding (providing new learning experiences, or a chance to practice skills), social (building relationships with others), career (seeking career related benefits), protective (volunteering to escape negative feelings), and enhancement (focused on personal growth). In this study, the answers to open questions were classified using the VFI categories (similar to Moskell *et al.* 2010). In future work, to better understand the motivations of volunteers in more advanced use of the application beyond this preliminary work demonstrated in this study, the full set of indicators developed by Clary *et al.* (1998) could be applied to get a more in-depth understanding of the motivations (five indicators for each function, representing 30 indicators total), however this would result in a much longer questionnaire limiting the possibility to investigate other topics. Utilizing the VFI to analyze motivations in PPSR projects may allow researchers to understand and compare the motivations of volunteers and may also enable project designs that engage the target audience for recruitment and continued participation by volunteers.

The purpose of this chapter is to increase understanding of the social and management implications of a PPSR-inspired smartphone application for wildfire management. Public involvement may provide additional forest fuel loading data to forest managers both on public land (where ongoing monitoring of conditions takes place), and on private land (which forest managers may not typically have access to) and a smartphone application may provide a mechanism with which the public can gather and provide information. However, the role the application may fill needs to be evaluated for each potential use. In this study, a smartphone application was developed and examined for whether it was a suitable technology for forest fuel loading data acquisition by people with a range of experiences living in a wildfire-affected community. Participants were asked to complete paper- based questionnaires before and after using the application to collect forest fuel loading data in order to help us to understand their experiences. In this manuscript three main points are addressed. First, the smartphone application is addressed. Second, participants' demographic characteristics and previous experiences related to wildfire are considered and how these influenced motivations for getting involved with the project and experiences using the application to collect data, including how professionals and non-professionals approached a similar task. Third and finally, using these results as a guide, the ways that a smartphone application inspired by a PPSR approach may fit into wildfire management in communities in the WUI are discussed. This chapter describes exploratory research that was conducted as a first step in understanding the challenges and possibilities of applying a smartphone application inspired by PPSR methods as a tool for measuring forest structure to inform wildfire management decisions in the WUI. The findings of this work are not meant to be conclusive, given the limited sample at a single location at a single point in time. Rather, this chapter aims to provide insight to, or a proof of concept of, an approach which has many challenges, but which also holds considerable potential for both providing more information to forest managers and providing a way for members of communities that are vulnerable to forest fires to participate in forest and wildfire management.

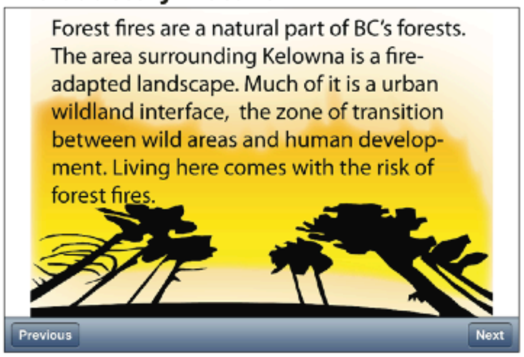
3.2 Methods

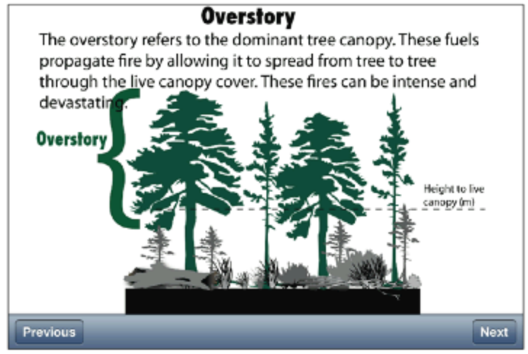
3.2.1 The Forest Fuels Application

The application was designed and implemented with three activities (the details of implementation are given in Appendix A). The first activity was an introductory slideshow with definitions for terms and concepts related to forest fuels (Figure 3.1). The second activity was a visual rapid classification of fuel conditions, aided by reference images and illustrations (inspired by the Photoseries and Photoload rapid assessment techniques evaluated by Sikkink and Keane (2008); Figure 3.1B). In the third activity, participants took six pictures of the fuel components at the site (in four directions at right angles relative to the direction of ground slope, straight up at the forest canopy, and straight down at the forest floor) and measured the location using the global positioning system (Figure 3.1C). The data collected by participants can be exported to a spreadsheet format so the data from multiple devices can be collected over a network for analysis. The application was designed so the data collected was compatible with the official protocol for professionals measuring forest fuels in British Columbia, Canada (Morrow *et al.,* 2008). The protocol uses five classes for each forest fuel component, and assigns a point value to each class; allowing foresters to prioritize stand fuels treatments. Background material along with illustrated instructions were developed and provided both as a set of introductory slides and in a series of help screens available at each step, with the intent of teaching non-professionals to take the measurements and collect data. The application was implemented for Apple iOS 6.0 on an iPhone 4 device, but it could be implemented on any smartphone platform with a touchscreen, camera, GPS, accelerometer, data storage, and networked data transfer. Also, the application was designed to function where cellular service is not available by saving the data on the device while in the field; however, GPS acquisition can take longer when out of cellular range, and network connectivity is required to transfer measurements to a central server for collection and analysis.

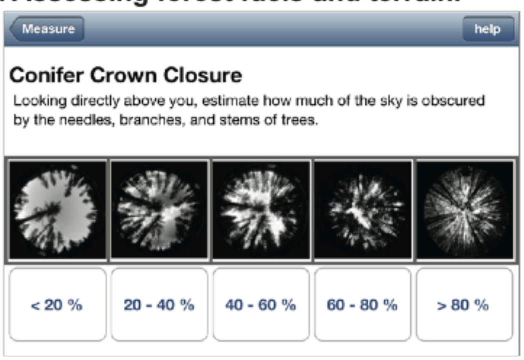
Figure 3.1 Examples from the forest fuels application, including (A) introductory material, (B) rapid visual assessment and measurement, and (C) collection of geolocation and imagery.

A. Introductory material



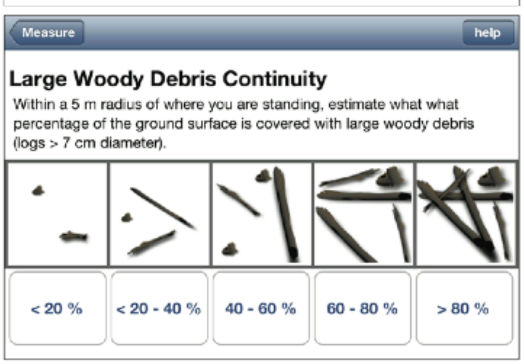


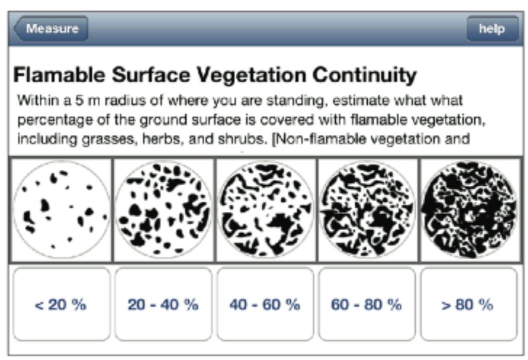
B. Assessing forest fuels and terrain.



Visual estimation:
- Conifer crown (% closure)
- Conifer crown base height (height in meters)
- Large woody debris (% coverage)
- Fine woody debris (% coverage)
- Understory vegetation (% coverage)

Measurement
- Slope (%)
- Aspect (cardinal direction)





C. Geolocation and site imagery.

3.2.2 Application testing, observational data, and questionnaires

The study area was located in a WUI area in Kelowna, British Columbia. In this region, risk of wildfire is highest during the dry summer months. For example, the Okanagan Mountain Fire of 2003 necessitated the evacuation of 27,000 people and consumed 239 homes. The project was staged at the University of British Columbia Okanagan (UBCO) campus, where a range of forest structure conditions and forest fuel loadings are accessible within a short walk from campus on publicly accessible land endowed to, and managed by, the University of British Columbia, along right-of-way trails managed by the City of Kelowna, and in a city park managed by the City of Kelowna.

For this preliminary study where the degree of user uptake, and the degree of public interest in participating in the study was unknown, (resulting in an unknown target-audience), a “build-it-and-they-will come” strategy was employed. This type of strategy has key limitations, as discussed later in the thesis. In general, as recruitment strategies that are specifically focused on the needs and motivational characteristics of the target-audience may result in highly targeted recruitment campaigns, which in turn engage more volunteers than efforts that were designed for unknown audiences. As a result, there are limits to the approach in this thesis and further consideration are needed to scale these recruitment strategies, in particular, to more sustained efforts if the project were continued on a longer basis. For a discussion of limitations associated with the recruitment approach see sections 6.4.2, 6.4.3, and 6.4.5. For a discussion of possible strategies to address these limitations, see section 6.5.1.

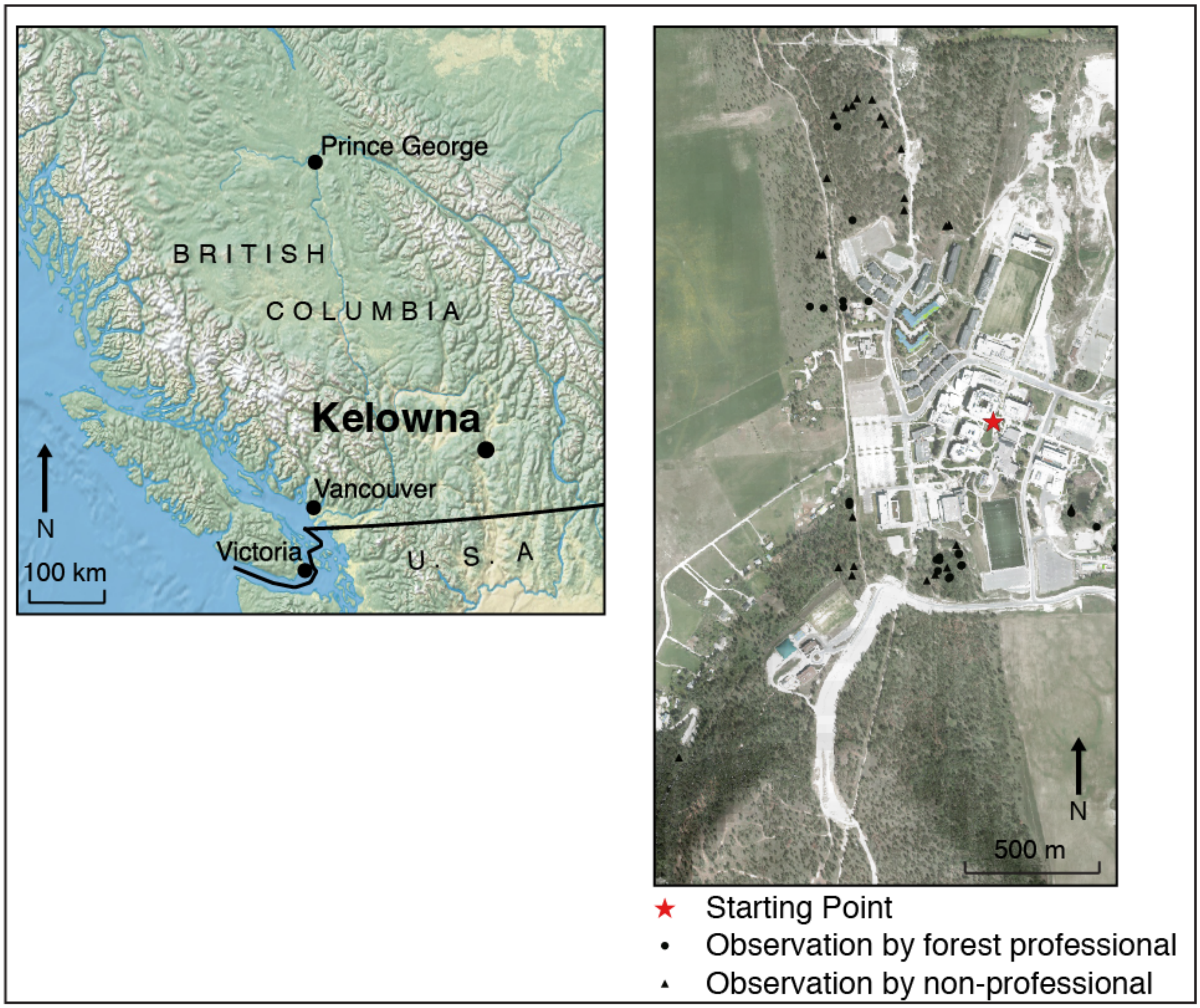
Posters were placed at local coffee shops, public bulletin boards, and in local classified advertisements. These were placed one month in advance of the study and were maintained for the duration of the study. Neighborhood associations and recreation groups in the surrounding area were found using local listings available on the City of Kelowna website and using Internet search terms “Kelowna outdoors club” and “Kelowna hiking club” and were contacted by email two weeks in advance of the first visit. Professional contacts were made by email, which were subsequently forwarded to a broad group of wildfire professionals throughout British Columbia. Finally, stories about the research were published by several local newspapers (Vancouver Sun 30 July, Kelowna Daily Courier 2 August, Vernon Morning Star 3 August, Barrier Star Journal 5 August), radio stations (CBC 30 July, CKNW 16 August), and a television station (CHBC 8 August), and these stories included links to the project webpage (or mentioned the project webpage) which contained the recruitment information. Any inquiries about participation were followed up by contact by email or telephone and all possible efforts were made to accommodate any interested participants. Refreshments were offered as a token reward for participation. The demographic characteristics of the participants are summarized in Table 3.1. Participants were met individually between June and October 2012 at the UBCO campus and asked to complete an initial paper-based questionnaire to provide information about previous experiences, behaviors, and attitudes related to wildfire and wildfire management. Participants were then provided with a smartphone with the forest fuels application running and asked to collect forest fuel loading data in areas adjacent to the campus while accompanied by at least one researcher. Participants spent between 25–120 min collecting data (Figure 3.2), depending on how many locations they visited, the data they collected and the length of discussion and interaction with the research crew. The length of time spent by each participant at each location was not recorded and could be investigated in future research. The participant who spent the shortest time collecting data indicated that she wanted to use the application to collect data over a larger area (since it was her day off and wanted to go for a hike), so she spent a short time collecting data and then departed to go hiking. Other participants who spent longer amounts of time collecting data visited multiple sites and engaged in discussions with the research team. Several of the participants mentioned that they expected (and were prepared) to spend more time collecting data with the smartphones and over more rigorous conditions. None of the participants complained about the time commitments or the conditions for collecting data. The possibility of providing physically challenging data collection tasks may be an effective recruitment strategy for some participants. Future implementations could allow more flexibility in the amount of time required and the number and locations of sites to collect data to accommodate people who wanted to collect data at a few locations quickly, as well as people who wished to collect data over broader areas and be more physically active. Additionally, opportunities should be provided for interaction with other people (including forest professionals, for example at meet-ups), if it is desired.

Observational data (for example, participants' reactions, statements, and questions about wildfire and the use of the application) was collected throughout the course of the experiment. After collecting the forest fuels data using the smartphone application, the participants completed a second paper-based questionnaire investigating their experiences collecting data with the application.

Table 3.1 Demographics of participants. The mean reported age was 45 years.

Item	Response (count)	Response (%)
Gender		
Male	13	72%
Female	5	28%
Education		
High school	1	6%
Some college or university	5	28%
College or university degree	10	56%
Graduate degree	1	6%
No answer	1	6%
Occupation		
Retired	5	28%
Student	4	22%
Provincial wildfire manager	2	11%
Provincial forester	2	11%
Regional/civic forester	2	11%
First nations wildfire manager	1	6%
Store manager	1	6%
Bookkeeper	1	6%
Place of residence		
Rural	6	33%
Suburban	7	39%
Urban	5	28%

Figure 3.2 Location of study area, and location of volunteered observations.



Respondents indicated their answers using five-point Likert scales (from 1 = "Strongly Agree" to 5 = "Strongly Disagree"), checked boxes with discrete answers (for example, "Have you been evacuated in a wildfire before?"), or wrote longer answers to open-ended questions (for example, "The part of the project I enjoyed most was…"). Student t-tests for independent samples were used as a tool for comparing means between groups for the Likert scale questions ($\alpha = 0.05$), which were determined directly from answers to questionnaire items (Table 2). Due to the small sample size, only groupings with at least a 60% / 40% or better proportional balance were compared. One section of questions that asked about attitudes and behaviors related to wildfire management was repeated in the first and second questionnaires to evaluate whether there was a change in the way participants answered questions before and after using the application to collect forest fuels data. For these repeated questions, Student t-tests for paired (dependent) samples were used to compare means ($\alpha = 0.05$). Open-ended questions about motivation and enjoyment were coded using the definitions of the five VFI categories by Clary *et al.,* (1998) which are values, understanding, social, career, protective, and enhancement. The definitions of these categories along with examples from the project are indicated in the following section to show how the VFI was operationalized. The "values" category includes motivations that allow an individual to express altruistic or humanitarian concerns for others (*e.g.,* "to help with research and assist students"). "Understanding" includes motivations related to the chance to learn a new skill or practice skills that might otherwise be un-used (*e.g.,* "interested in how to protect interface areas" or "the technology looks fascinating"). "Social" motivations are related to relationships with others. The "career" category included seeking career-related skills (*e.g.,* "[I] work with wildfire protection and assessment so access to new methods to define wildfire threat is important"). "Protective" motivations aimed to protect the individual against negative feelings (*e.g.,* "concern for the care of the outdoors"). Finally, "Enhancement" was defined as striving for positive personal growth and development (*e.g.,* "bored, and thought, why not?"). The research team interpreted the statements by participants and all applicable categories were tallied. A two-sample proportion test was used to test if there were differences in the proportion of responses for each VFI category for the different groups ($\alpha = 0.05$). The statistical tests and significance levels were used as a tool for comparing means and proportions, and results significant at the stated levels are reported below. However, due to the limited and self-selected sample, the results should not be used to infer trends to a larger population. In addition, some of the responses were non-normal in distribution. While the t-test is generally "accurate to a high degree, even [when] the assumptions of homogeneity of variance and normality of the underlying distribution are untenable", where the two samples have differently skewed distributions, this can lead to a bias in probability statements (Boneau 1960, p. 60). In these cases, the bean-plots were used to describe and discuss the distributions of responses directly. We reiterate this exploratory research was conducted as an initial trial to gain insight into how a smartphone application can be used as a fire management tool, and the statistical tests were used as a tool to explore the data rather than make inferences about larger populations.

Table 3.2 Groupings used to compare questionnaire responses by different groups. Groups marked with an (*) had sufficiently balanced proportions for comparison.

Grouping	Yes	No
Aware of actions by others to reduce wildfire risks *	10 (56%)	8 (44%)
Fire Professional *	9 (50%)	9 (50%)
Has been evacuated due to a wildfire	5 (28%)	13 (72%)
Lives near the forest	15 (83%)	3 (17%)
Owns a smartphone	11 (69%)	5 (31%)
Owns property	15 (83%)	3 (17%)
Under the median age (50.5 years old) *	9 (50%)	9 (50%)

3.3 Results

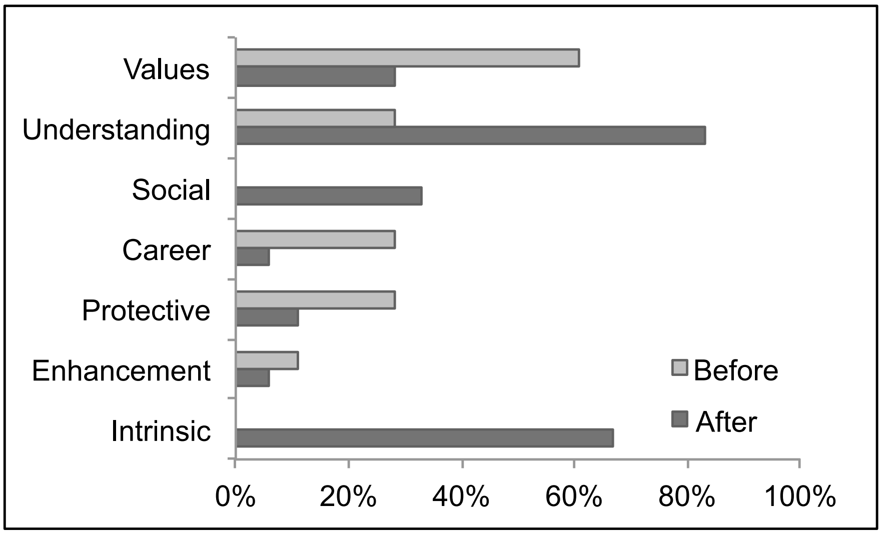
3.3.1 The application

The 18 participants collected forest fuel loading data at 46 separate forest fuel sample plots. In the questionnaire, all of the participants agreed or strongly agreed that they were satisfied with the experience of collecting data. None of the participants had previously used a smartphone to collect data in other projects; however, several wildfire professionals reported regularly using smartphones at work to collect and share images and GPS coordinates. Many of the participants had ideas to extend the functionality of the application. Amongst the suggestions were taking measurements of other non-fire related aspects of the forest (for example, forest health), feedback on where other participants had taken measurements (so that measurements could be taken in less-frequently visited areas), and feedback on how volunteered measurements compared with other volunteered measurements. In the field setting, there were three main challenges encountered: difficulty selecting the correct button (even though the buttons were much larger than in standard application design), lighting of the screen in a bright sun-lit environment, and minor technical errors. Finally, several of the participants offered, without prompting, to spend more time using the application to collect data over a broader area.

3.3.2 Motivations for volunteering

Reported motivations and rewards for project participation changed during the period prior to, and after, the use of the application (Figure 3.3). Before using the application, the three most frequently mentioned motivations were “values”, “protective measures”, and “understanding”. Fire professionals indicated higher career motives (56%) compared to non-fire professionals (0%). After using the application the three most frequently mentioned factors respectively were “understanding”, “social”, and “values”. In addition, the majority of participants expressed in their answers some form of intrinsic enjoyment while completing the activity.

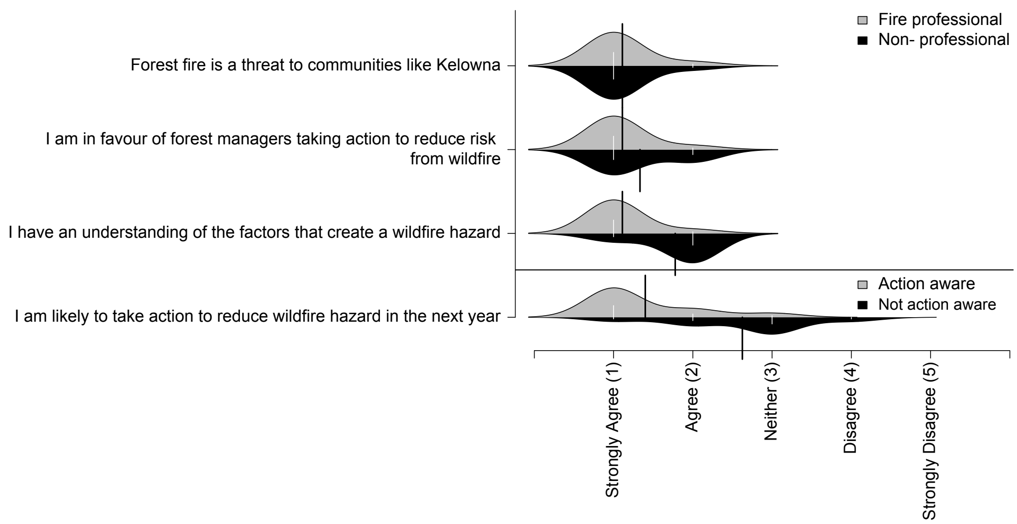
Figure 3.3 The proportion of participants' responses to open-ended questions classified using VFI categories. Before using the application, participants were asked "What is the most important reason you volunteered for this project?" After using the application, participants were asked "What was your favorite part of the project?" and "The part of this project I enjoyed most was…". An intrinsic enjoyment category was added for the responses after using the application to collect data (*e.g.,* "I enjoyed walking in the forest and collecting data").



3.3.3 Experiences and attitudes related to wildfire

All respondents agreed or strongly agreed that wildfire is a threat to their community, and were in favor of fire managers taking action to prevent wildfire (Figure 3.4). There was a range of responses from all groups regarding whether or not fire managers were doing enough to prevent wildfire for all groups (including forest professionals). As expected, fire professionals reported greater familiarity and knowledge than non-professionals for each question about fire knowledge. Finally, people who were aware of actions by others to reduce a wildfire threat agreed more strongly that they themselves were likely to take action to reduce a wildfire threat themselves compared to those who were not aware of actions by others. Very few of the non-professionals were aware of the Partners-in-Protection FireSmart Manual for Homeowners (22%), and none had used it. In contrast, many of the professionals were aware of the Partners-in-Protection FireSmart Manual for Homeowners (88%) and the majority had used it (78%).

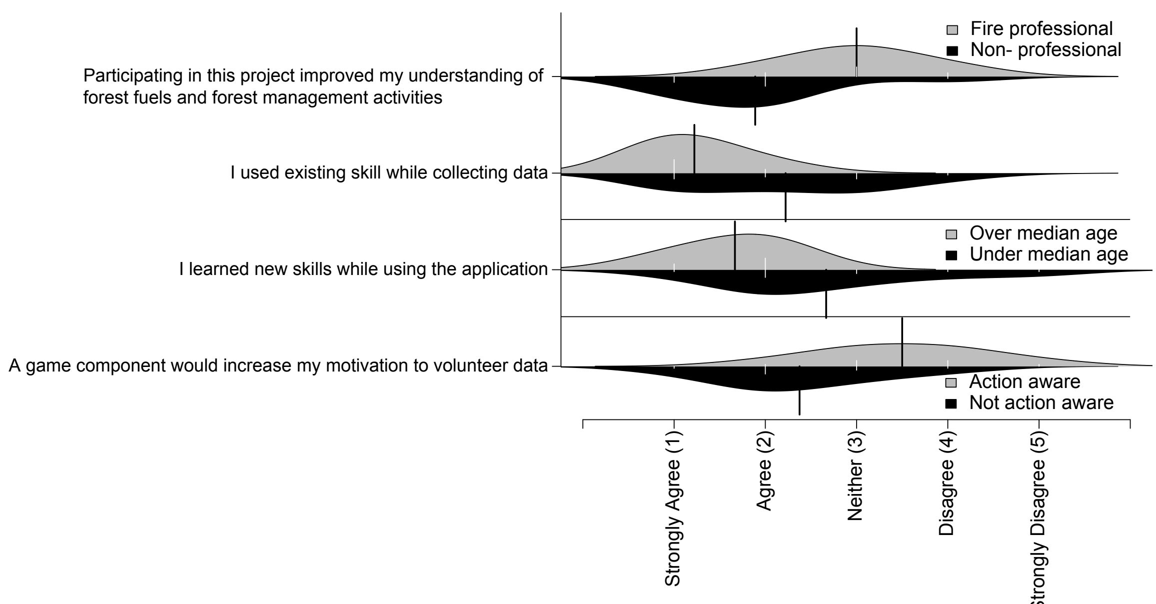
Figure 3.4 Experiences, attitudes, and behaviors related to wildfire. The black bars represent the means for the respective groups, the white bars represent individual responses, and the curve represents the density of responses for the group.



3.3.4 Experiences collecting forest fuels data using the smartphone application

Non-forest professionals reported an improved understanding of the principals of forest fuels management compared to forest professionals, who reported using an existing skill while collecting data compared to non-professionals (Figure 3.5). Most non-professionals reported learning a new skill with most in agreement, one neutral, and one strongly disagreeing answer. The forest professionals' were also mostly in agreement about learning a new skill, and was not significantly different than the non-professionals (the question did not specify whether it was a technical skill related to using the smartphone, or a forestry skill related to understanding forest fuels). Respondents who were under the median age more frequently disagreed that they learned a new skill while collecting data. People who were aware of actions by others to reduce wildfire hazards were generally less in agreement that a game component would increase their motivation to collect data. In contrast, participants who were not aware of actions by others to reduce a wildfire risk in their community, were somewhat in agreement that a game component may increase their motivation to collect data. For both professionals and non-professionals, there was a range of responses about whether a game component would increase motivation to collect data. Several participants, who were enthusiastic about the possibility of adding game elements mentioned similarities with other activities for which they used smartphone, such as geocaching (a location-based activity using GPS).

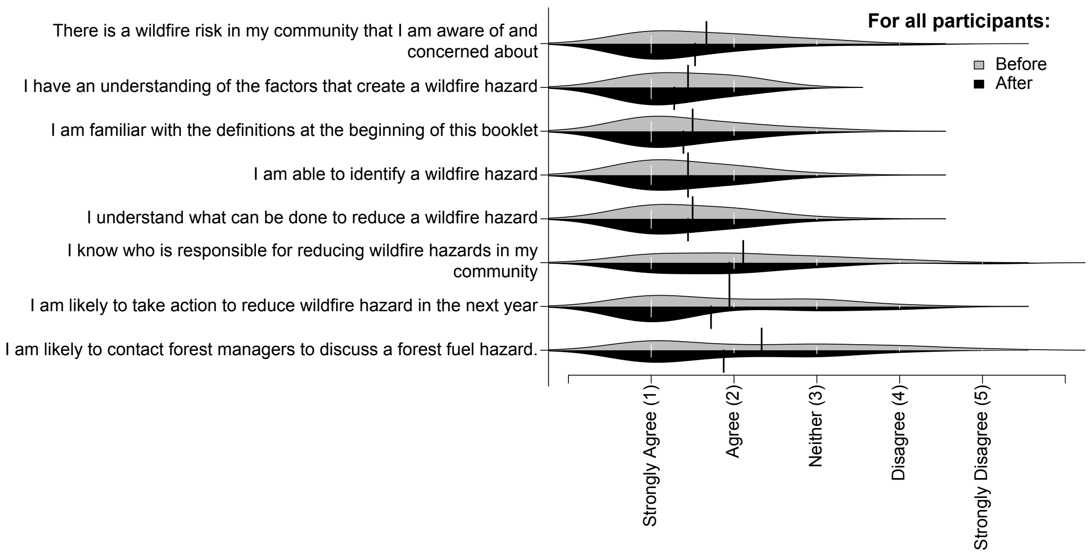
Figure 3.5 Questionnaire responses about using the application. The black bars represent the means for the respective groups, the white bars represent individual responses, and the curve represents the density of responses for the group.



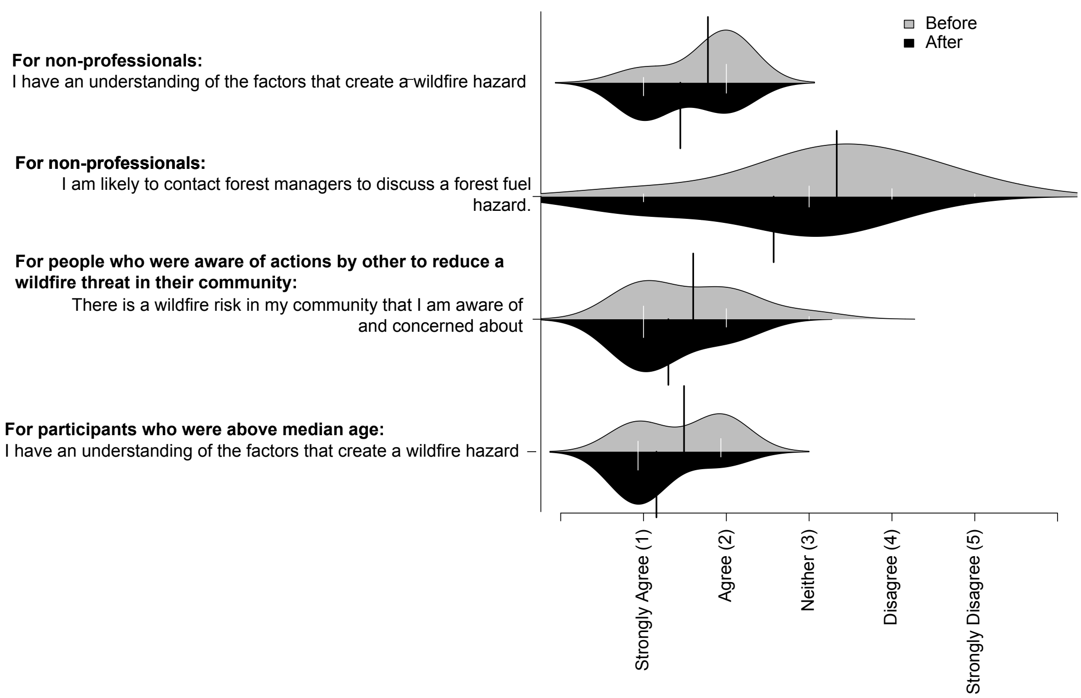
3.3.5 Changes in awareness, knowledge, and planned behaviors after using the application

From the set of questions that were asked before and after using the application assessing awareness, knowledge, and planned behaviors related to wildfire, there were no significant differences. A small but notable shift was observed in the distribution of responses that would be considered a desirable outcome of the project, including increased understanding, awareness, and communication about wildfire threats (Figure 3.6). This was supported by statements such as one non-professional's comment that "by doing field data collection, you think about the issue and become more likely to act". Another commented that "tools are needed for people living in the [WUI], including communication, steps, and actions. I could see this being useful for work parties in the community." In contrast, there were several comments that people living in the area already "had an intuitive idea" of the factors that lead to a wildfire hazard. Another participant commented, "I was already inspired to take action—the study did not change that".

Figure 3.6 (a) Changes as a result of using the application for all participants, and (b) highlights of changes for subgroupings. These highlights were identified using α = 0.1, due to the small magnitude of the differences. The black bars represent the means for the respective groups, the white bars represent individual responses, and the curve represents the density of responses for the group.



a.

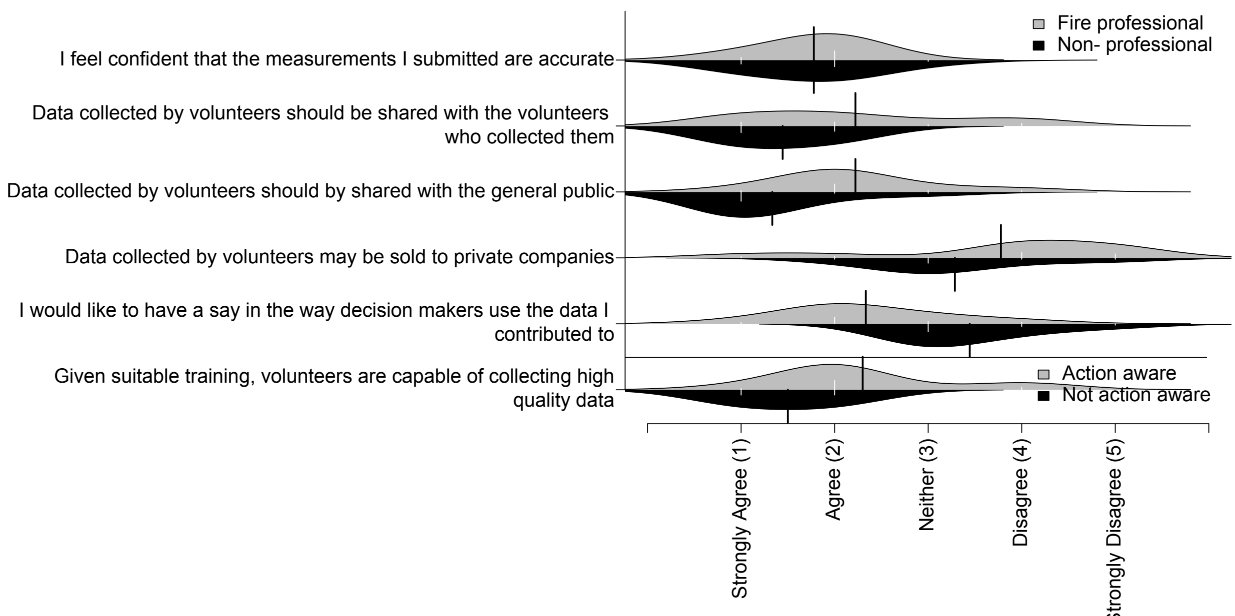


b.

3.3.6 Ideas about fitness of use of the data, fairness of use of the data, and expectations of privacy

Most participants agreed or strongly agreed that they were confident in the measurements that they made and there was no significant difference observed by group (Figure 3.7). Participants aware of actions taken by others to reduce wildfire threats were less strongly in agreement that volunteers could collect high quality data or that given suitable training, volunteers were capable of collecting high quality data.

Figure 3.7 Responses about the fitness and fairness of use of the data. The black bars represent the means for the respective groups, the white bars represent individual responses, and the curve represents the density of responses for the group.



Most of the participants agreed that data collected by volunteers should be shared with the volunteers who collected them, and most also agreed that the data should be shared with the general public. However, some fire professionals had reservations about sharing data. In the interview notes and open-ended questions, the forest professionals indicated some of the reservations in more detail. The main concern was distributing data without professional interpretation of the results, which may lead to unrealistic or poorly-informed demands by the public for fuels treatments. For example, one professional commented that the “data collection and complaints can be taken out-of-context” and the application could provide a way to “complain without face-to-face interaction”. Another concern was that doing fuels assessments was the job of forest managers, and that public outreach efforts using smartphones should be focused within the domain of existing outreach programs, rather than expanding into the realm of professional responsibilities. Forest professionals more frequently expressed that they wanted a say in the way that data they contributed were used. Most, but not all, participants were opposed to volunteer-collected data being sold to private companies.

Responses regarding expectations of privacy were mixed, with 16% of respondents expressing an objection to forest fuel loading data, including observations, images, and GPS coordinates, being both collected in their community and shared with the public on the Internet, as long as the measurements were not collected on their personal private property. When asked about data being collected on personal private property and shared on the Internet, 58% expressed an objection. Numerous comments were made and collected in the observational data, ranging from having no objection or discomfort sharing data collected on personal property and concerns about home security due to sharing pictures (for example, if personal property displayed in the pictures becomes more vulnerable to theft) to some forest professionals expressing concern that sharing measurements on personal property could expose home owners to liability if a fire hazard is identified, nothing is done about it, and a wildfire occurs, or leading to "neighbor-to-neighbor conflict".

3.4 Discussion

A major challenge in wildfire management in the WUI is establishing understanding and cooperation for fuels treatments and other preventative measures amongst the numerous stakeholders, including municipalities, parks, and private property owners (Radeloff *et al.,* 2005). Fire managers seek communication, understanding, and incentives for individuals to take action on their properties, such as clearing brush, cutting grass, and using fire resistant landscaping at their home residence (Cohen 2008). A further challenge in the management of forest fuels is collecting timely data about forest fuel loading, as these forest structure components can rapidly change. These components are often near to the ground and under dense forest canopies, making them difficult to measure using airborne and spaceborne remote sensing platforms (Keane *et al.,* 2001). Public participation in data collection may provide additional or complimentary forest fuel loading data to forest managers both on public land (where ongoing monitoring of conditions takes place), and on private land (where forest managers do not typically have access). However, the exact role of smartphone applications applied to measuring WUI forest fuels needs to be tested and examined for the range of uses that they may be suitable to provide.

In this chapter, people from a wildfire-affected community tested a smartphone application to collect forest fuels data in the WUI following a PPSR inspired approach. Ideally, PPSR approaches are "explicitly for non-scientists" (Cooper *et al.,* 2008), and by extension, explicitly for non-professionals in a natural resources management context. In practice, there may be a range of professional involvement, ranging from setting project objectives, organizing data collection, and collecting data itself. For example, the North American Breeding Bird Survey enlists volunteers (some of whom are professional biologists) and provides training to facilitate data collection (Sauer *et al.,* 2005); these data are commonly considered PPSR data (Dickinson *et al.,* 2012). Many other projects with voluntary participation include contributions by people with considerable expertise (Brabham 2012). In this study, participation in data collection was voluntary, and despite extensive efforts to recruit participants without professional experience related to wildfire (for whom the application was designed), half of the participants had professional backgrounds in wildfire. Although the professional involvement was not intended or expected to be as large, it represents a willingness by professionals to engage with the community about wildfire topics and provides insights into the ways that professionals and non-professionals approach similar tasks. Professional participants had higher career related motivations for their involvement, indicated higher previous knowledge and skills related to measuring forest fuels, and wanted more input in how the data are used. On many other topics, forest professionals answered questions in a similar way as non-professional participants, demonstrating many shared values with other people in the community. Our initial experience suggests that substantial professional involvement may be beneficial or necessary in a wildfire PPSR project to address and mitigate some of the inherent risks related to wildfire management and also as a public outreach opportunity.

Motivation to volunteer is critical to the success of PPSR projects and also for public outreach projects for wildfire protection. The number of participants in this study was lower than expected, especially considering the generally positive reception of the research by the community and local media coverage that occurred during the recruiting campaign. Based on the findings of this research evaluating the VFI categories, to motivate more people to volunteer, a focus should be placed on sending messages that appealing to the volunteer's sense of values, and to a lesser degree protective measures in reducing wildfire threats to the community. In the context of wildfire management, these messages could promote that helping to measure and monitor forest fuels loading is an act of citizenry that can help reduce forest fuels hazards. For people with professional experience making forest measurements, an appeal to career motivations could also be effective. This study did not address sustaining participation, however, in order to motivate volunteers to continue their participation, messages could target developing a sense of understanding (of both forest fuels topics and technology), social factors (taking part in the group), and the intrinsic enjoyment of the activity (spending time in the forest).

Another factor for the limited levels of participation was that the research team was located in a different city than the field site, restricting the number of scheduled visits. If the research team were closer to the study site, or participants were free to use the application on their own time, several more potential participants' schedules could have been accommodated. In other efforts, such as volunteer mapping of streets, a small number of volunteers have been able to thoroughly map areas and provide very high quality data, especially if those volunteers are motivated to accurately represent an area, and the products developed from the volunteered data are distributed to a much broader audience (Haklay *et al.,* 2010). Despite the small sample size in the present project, the number of participants was realistic for a community-mapping project. In future research, sharing the volunteered data over the Internet and inviting participation in other ways, such as viewing or analyzing the collected data, could attract a potentially larger group of people.

Non-professional respondents' awareness of other existing public outreach wildfire programs (such as Partners-in-Protection) was surprisingly low, considering that they are the target audience of the programs. In contrast to many other PPSR projects that are targeted to hobbies (such as birdwatching or astronomy), this study dealt with preparatory actions to avoid a hazard. As such, there are differences in the implementation from an organizational and participant perspective. Other volunteer projects have addressed risk-related issues with considerable recruitment of volunteers, however most have dealt with responses to disaster situations and not prevention (Meier 2012; Cross 2013). Likewise, for wildfire hazard reduction, salience for wildfire issues is highest soon after the occurrence of a wildfire (Monroe *et al.,* 2006). Smartphone applications and public participation data collection projects may serve a different role in wildland fire management. For example, long-term interactions are also important for positive citizen-agency relationship building (Olsen and Shindler 2010). Similar to how the experiment in the present study was structured, in a PPSR inspired project, community foresters may interact with participants on an ongoing basis in person, at workshops, and through electronic communications thus providing an environment to build citizen-agency relationships, and potentially increase knowledge over a longer time period.

The retention of citizen volunteers is another factor that is critical to the success of PPSR projects. Some PPSR projects have utilized game elements and social network services in an effort to increase motivation and engagement for collecting data (*e.g.,* Han *et al.,* 2011).

Volunteers in other PPSR projects have indicated that game elements and electronic communication tools that provided social interaction and recognition of achievements were important for the ongoing involvement of volunteers in projects, but were not a factor in recruitment (Iacovides *et al.,* 2013). In addition, factors related to understanding were the most frequently reported motivations in the Galaxy Zoo project, an astronomy project where volunteers classified the shape of galaxies in images acquired by the Hubble telescope, with a strong following of an estimated 20,000 volunteers (sample of 20 volunteers) (Raddick *et al.,* 2010). These exploratory research suggests that the factors identified after using the application (understanding, social, and values) could be further developed to retain volunteers in PPSR projects related to wildfire. Electronic communication tools can be easily incorporated into the application to support the retention of volunteers through social incentives, and in addition provide opportunities for interactive communication with fire managers.

Previous research linked perceived risk and threat assessment with homeowners taking wildfire mitigation action (McFarlane *et al.,* 2011). Therefore, increased perceived risk and improved threat assessment are desirable outcomes for this project. The changes observed in the repeated questions related to awareness of forest fuel hazards, knowledge about forest fuels, and planned behaviors for forest fuels hazard reduction after using the application to collect forest fuels data were small in magnitude. These changes were small, likely in part because most of the participants had already agreed or strongly agreed with most of the statements prior to using the application to collect forest fuels data, leaving little room for improvement and many of the participants were already aware of fire hazards and motivated to take action as indicated through volunteering for the project. In addition, the participants used the application for a short amount of time and did not have the opportunity to use the application more than once. Price and Lee (2013) found an increase in scientific literacy along with a negative change in personal evaluations of knowledge over a six-month astronomy project, which they attributed to participants gaining a greater appreciation for what they had yet to learn. Nonetheless, our exploratory findings indicate that there is promise to use PPSR as a tool with the potential for positive outcomes for the participants and for communities where wildfires occur.

While using the application, some of the participants raised considerations that need to be addressed before the application could be released to the public. First, operational uses and restrictions would need to be defined, for example, if different procedures are required to use the application on public lands with data sharing, or if usage on private lands would necessitate data being held in confidence. The second consideration was risk or liability associated with wildfire. For example, could the project organizers be held liable for damages if volunteered assessments lead to the decision not to treat an area and a wildfire occurred? Alternatively, if the assessments indicated that a treatment should be performed but were not financially possible, would the responsible person or organization be held liable for damage caused by the fire? Careful legal consultation would be needed in any region where the application was released to the public. Third, a concern was raised about adversarial or malicious measurements. For example, a participant cited an example of one resident illegally cutting trees to improve his view under the guise of fuel reduction; however, any indication of this type of behavior was not observed in this study. The images collected by the application would provide evidence that could be reviewed against any inflated claims, and observations from the same area conducted by different, independent observers could provide further corroborating evidence. In the study region, municipal bylaws restrict the removal of large trees without permitting. Finally, a concern was raised about rapidly distributing data without professional interpretation, leading to unreasonable public pressure on community foresters to perform treatments that are beyond operating budgets or do not match priorities. While this may be a source of tension for the forest managers, who may feel their traditional role is threatened, it would be indicative of an increased awareness of wildfire issues in the community and greater incentives for action by both individuals and government departments. In the an ideal case, PPSR inspired projects may provide a mechanism to share information about forest management decisions and build participant knowledge, including tradeoffs, costs, and compromises in making decisions, which are activities that are associated with increased support and trust for agencies making forest management decisions (Parkinson *et al.,* 2003). All forest professionals indicated that they would like to be consulted about how the data were used, which is reasonable given their expertise, in prescribing treatments to improve safety and maintain forest health. It is unknown whether moderation or filtering of the data by professionals would affect the motivation of participants and how this would affect the perception of the project and agencies involved in the project. In addition, if participants feel that agencies do not recognize or use information that they receive from interactions with the public, it may erode trust in the agency (Shindler and Toman 2003), which is a potential risk for agencies engaging in PPSR inspired wildland fire projects. In future work, systems will be needed to store and analyze the data, and the previously mentioned expectations of fairness of use of the data may provide guidance in developing approaches for data stewardship (Michener and Jones 2012).

3.4.1 Limitations

This was an exploratory study, conducted under controlled conditions in a limited area and over a short time period. Conducting the study with more participants, over a broader area, and over a longer time period would provide more robust information. Statistical methods were used only to explore the data, and larger sample sizes and more controlled experiments would be needed to make inferences about larger populations. This study was not intended as an inferential study, but a proof of concept of a new application. More work is needed to define markets and targets for success so that, in the future, it is possible to assess if this smartphone application would see market success and uptake (more discussion is provided in section 6.5.1).

Chapter 4: Data quality

Several methods for the rapid assessment of forest fuels have been developed. The photo series technique involves measuring fuels in reference plots and taking oblique reference photographs allowing field crews to visually match observed site conditions with the photos and record the corresponding quantitative values for fuel loading (Maxwell and Ward 1976). Another method is the photoload technique, where synthetic fuel beds with known fuel loadings are photographed (downward and oblique), also creating a visual guide for assessment (Keane and Dickinson 2007a). Sikkink and Keane (2008) compared rapid assessment techniques with traditional direct measurements, such as planar intersect and fixed area plots, and found that there are trade-offs between the methods in terms of measurement accuracy, experience and time required to complete each assessment. All of these methods lay a solid foundation for new approaches that may be advanced by technology. Recent advances in communication technology, including smartphones, have led to new possibilities for collecting data. A growing proportion of the population use smartphones with Internet connectivity to widely and rapidly share information. These devices are generally less expensive than electronic devices that are purpose-built for forestry and they provide opportunities to easily install applications; deliver instructions and enter data on a touch screen interface; acquire images using the camera; measure location and direction using the global positioning system (GPS) and compass; measure angles using an accelerometer; store data and transmit it over a network. These devices also have the potential to collect forest structural data to compliment Earth observation data collected by satellite remote sensing devices (Ferster and Coops 2013). Several previous projects have utilized smartphones to collect Earth observation data (Powell *et al.,* 2012; Weng *et al.,* 2012; Pratihast *et al.,* 2013; and others including several commercial offerings).

The purpose of this chapter is to evaluate the quality of forest fuels data collected by volunteers using a smartphone application. In addition, needs and general issues are identified to guide and inspire further development for data collection with smartphones and public participation methods, which may offer considerable potential for wildfire management. Volunteers were recruited from a wildfire-affected community, including professional and non- professional participants, who used a smartphone application to record observations of forest fuels amounts and arrangements in a WUI area. The data acquired by participants with different levels of forestry experience is assessed and used to lead a discussion of the fitness of the data for informing wildfire management decisions.

4.1 Methods

The study area was located at the University of British Columbia Okanagan campus, in Kelowna, British Columbia, Canada (described in previous chapter). The study site contained a variety of WUI forest stands, including areas where stems had been thinned and woody debris removed; there was debris from insect-killed trees that had been felled and de-limbed on site; and where no recent stand modifications were observable and the accumulation of forest fuels was considerable. Through contact with local neighbourhood associations, recreation groups, professional foresters and local media, 18 volunteers were recruited. Nine of the 18 volunteers (50%) had extensive working experience in forest fuels management or wildfire suppression. The application was developed for a common smartphone without any additional instruments (see Appendix A for details). The application was inspired by rapid visual assessment techniques such as photo series and photoload (Sikkink and Keane 2008). Each participant was assigned a random, non-personally identifying code, which was recorded and linked to the volunteered plot data and reference data. The assessment included three parts. First, a series of slides introduced the general concepts of forest fuels management. Second, visual estimations of the quantity and arrangement of fuels on site were made using diagrams and illustrations for reference and, for each component, the closest matching category was selected using menus and buttons. The categories and definitions followed the regional protocol in British Columbia (Morrow *et al.,* 2008) (Table 4.1), making the results compatible with previous datasets. Third, participants acquired location information from the GPS, slope, aspect and images of the fuel loading at the site (including overall site pictures of each stand and photos of the specific components). The data generated were exported as a comma separated value (CSV) file and JPEG images transferred either by email or attaching the device to a computer with a cable. Participants, accompanied by at least one member of the research team, walked to WUI areas and used the smartphone application to collect data at locations of their choice (to simulate a volunteered, opportunistic dataset). The research team collected observational notes. The 18 volunteers collected data from a total of 46 plots. A flagging tape marker was placed for revisit by the research team to collect reference measurements. The reference measurements were collected in a similar way to the volunteered measurements and where practical, quantitative direct measures were taken of conifer crown base height, understorey conifer stem density and large woody debris coverage. However, because of equipment limitations, this was not possible for all components. Furthermore, all forest measurements contain error that can be attributed to the device or operator in addition to practical considerations of collecting measurements. (Freese 1960). For example, Sikkink and Keane (2008) compared five measurement methods of for forest fuels in terms of precision, accuracy, time required to collect measurements and the amount of experience required use the method. Therefore, the reference measurements served as a relative baseline for comparison, and a more thorough analysis to bound and compare the estimates to other methods was deemed beyond the scope of this research. Nonetheless, the comparisons of repeated measurements were sufficient to lead a discussion of issues of data quality.

Table 4.1 Description of forest structural components measured as adapted from Morrow *et al.*, (2008).

Component	Unit	Description	Categories
Conifer crown closure	Percentage coverage	Percentage crown closure of overstory conifer trees. Volunteered and reference observations were made using visual estimates with crown closure diagrams for reference (Appendix A).	A, <20%; B, 20–40%; C, 40–60%; D, 60–80%; E, >80%
Conifer crown base height	Metres	Estimate in metres in height to base of dominant and co-dominant veteran stems. Volunteered observations were visual estimates. Reference measures were taken using a pole and measuring tape to measure the height from ground level to continuous live conifer crown.	A, >5 m; B, 3–5 m; C, 2–3 m; D, 1–2 m; E, <1 m
Understorey conifers	Stems per hectare	An estimate of the number of suppressed and understory coniferous trees. Volunteered observations were visual estimates. Reference measurements included stems within a 5-m measured plot radius.	A, <100; B, 100–200; C, 200–400; D, 400–600; E, >600
Understorey vegetation coverage	Percentage coverage	The total surface area coverage of all flammable vegetation surface fuels. For both volunteered and reference observations, a visual estimate was made using diagrams from reference (Appendix A).	A, <20%; B, 20–40%; C, 40–60%; D, 60–80%; E, >80%
Large woody debris coverage	Percentage coverage	Coverage and depth of dead and down particles greater than 7 cm in diameter and with less than 50% of its circumference buried. Volunteered observations were visual estimates using diagrams for reference (Appendix A). For reference measurements, the ground area covered by large woody debris was measured with a tape within a 5-m radius plot.	A, <1%; B, Scattered, <10%; C, 10–25%; D, >25% not elevated; E, >25% elevated
Fine woody debris	Percentage coverage	Coverage of dead and down particles larger than conifer needles and less than or equal to 7 cm in diameter. For both reference and volunteered observations, a visual estimate was made using diagrams for reference (Appendix A).	A, <1%; B, Scattered, <10%; C, 10–50%; D, >50%, <10 cm deep; E, >50%, >10 cm deep
Slope	Percentage ratio of vertical change to horizontal change	The angle of the average ground slope in the area. Measured with device inclinometer.	A, <15%; B, 15–30%; C, 30–45%; D, 45–54%; E, >55%
Aspect	Cardinal direction	The direction of slope, relative to true north, or flat. Measured with device compass.	A, north; B, east; C, flat; D, west; E, south

Comparisons between the volunteered and reference data were made by calculating the root mean squared difference (RMSD) for the quantitative value (determined by the midpoint of the range of values in each category) and the difference in categorical ranking (the number of categories separating the volunteered and the reference observations). Finally, the proportion of measurements within ± 1 category of the reference measurements were counted and a one-sample Chi-square proportion test was used to evaluate if there was a significant difference between the proportion of observations that were above and below the reference value ($\alpha = 0.05$). This statistical test was completed as an exploratory test only, with a more representative (and larger) sample required to draw more conclusive statements about larger populations.

4.2 Results

Of the 46 plots measured by 18 participants, 22 were measured by participants with professional experience in forestry, and 24 by participants with no previous experience in forestry. Most of the measured components, classified into one of the five ordered categories, had a RMSD between 0.7 and 1.5 categories compared with the reference measurements, whereas larger RMSDs (1.5 categories or greater) were observed for understory conifer stem density, height to live conifer crown, and slope and aspect (for non-professional participants) (Table 4.2). In measured units for professional participants this translated to a RMSD of 15% for understory vegetation coverage and a RMSD of 436 stems per hectare for understory stem density. In measured units for non-professional volunteers, the RMSD was 25% for conifer crown closure and the greatest RMSD was 427 stems per hectare for understory stem density. The details of these differences and why they occurred are examined below. For most components, the professional measurements were slightly closer to the reference measurements than were the volunteered measurements, but for some measurements, such as slope and aspect, the professional volunteers were notably more accurate than the non-professional volunteers. This was likely due to previous experience using a compass and inclinometer (the application interface was styled after these instruments). Non-professional participants overestimated slope and aspect. With further training, non-expert data collectors could be expected to improve. Likewise, for fine woody debris, professional measurements were closer to the reference measurements than were non-professional measurements, and this was likely due to greater familiarity identifying fine woody debris and estimating surface coverage. For height to live conifer crown, the non-professional participants provided measurements closer to the reference measurements than did professional participants. This most likely occurred because, in general, non- professionals were observed to closely follow the instructions given in the application, while some of the forestry professionals, already familiar with the terms, did not refer to the instructions as closely, and used working definitions that differed from the instructions given and the definitions used by others. These issues could be problematic for building databases using measurements from multiple sources. Many of the participants (including professionals and non-professionals) underestimated the number of understory conifer stems, and only a small number of volunteers were able to consistently estimate the density of stems. Therefore, this component requires greater skill to make reasonable visual estimations. One possible approach to overcome this issue may be to provide more extensive training for new volunteers. Some of the experienced volunteers suggested that using a low-cost plot measurement cord and diameter gauge (to determine eligibility of stems), and providing more specific criteria on what constitutes understory trees would have improved their estimates and thus reinforced logical consistency across users and locations. For the other components – conifer crown closure, large woody debris, fine woody debris and surface vegetation continuity – the RMSD ranged between 0.7 and 1.5 categories. For fine woody debris, participants underestimated coverage. For the other components, no systematic bias in either direction was observed. The measured RMSD may be partly attributed to variation in visual interpretation. Several incomplete plots were submitted, so adding an alert may help make participants aware of missing fields before submitting the data.

Table 4.2 Metrics for comparison of the volunteered measurements with the reference measurements. Comparisons were made for all volunteered measurements, measurements volunteered by people with professional experience (Pro) and people without professional experience (Non-pro). The metrics include (1) root mean square difference (RMSD) in measurement units, (2) RMSD in number of categories separating the volunteered data and the reference measurements (CRMSD) and (3) the proportion of measurements within ± 1 category of the reference measurement or greater than two categories difference (a higher category number indicates a higher fuels load). A one-sample Chi-square test of proportions was used to evaluate if there was a significant difference (α = 0.05) between the proportion of measurements that were over and the proportion of measurements that were under the reference measurement (asterisks indicate significance).

	Metric	Fine woody debris continuity (%)	Large woody debris continuity (%)	Surface vegetation continuity (%)	Understorey conifers (stems per hectare)	Conifer crown base height (m)	Conifer crown closure (%)	Aspect (degrees)	Slope (%)
All	RMSD	34.6	21.2	21.7	431.7	2.6	23.5	113.8	22.5
Pro	RMSD	33.3	14.6	14.5	436.9	2.9	21.6	87.7	14.8
Non-pro	RMSD	35.9	25.8	26.5	426.8	2.2	25.1	135.0	28.2
All	CRMSD	1.2	1.2	1.1	2.0	1.7	1.2	1.3	1.6
Pro	CRMSD	1.1	1.1	0.7	2.0	2.0	1.1	1.1	1.0
Non-pro	CRMSD	1.2	1.3	1.3	2.0	1.4	1.2	1.5	2.0
All	+2 or more	0	9	4	9%	26%	9	13%	5
All	±1	75	80	87	57%	59	83	80%	65
All	−2 or less	25*	11	9	35%*	15	9	8%	30*
Pro	+2 or more	0	5	0%	9%	36%	5	0%	10
Pro	±1	77	91	100	64%	45%	86	90%	85
Pro	−2 or less	23%*	5	0	27%*	18%	9	10%	5
Non-pro	+2 or more	0	13	8	8%	17%	13	25%*	0
Non-pro	±1	73	71	75	50%	71%	79	70%	45
Non-pro	−2 or less	27*	17	17	42%*	13%	8	5%	55*

4.3 Discussion

When using a rapid visual assessment method, variations in measurements are expected because of differences in visual interpretation. However, in this study, several consistent differences were observed between users, which points the way to improving the approach. Initially, the motivation for this study was to design and provide a tool that could be accessible to a large number of people with minimal equipment and training, and that allowed users to make forest measurements related to fuel loads. Nonetheless, more precise yet potentially more time-consuming data collection methods may also be feasible. For example, measuring devices could be used for a subset of measurements to provide feedback about the accuracy of visual estimates. Attribute accuracy of data collected by professionals and non-professionals has been compared in other studies. For example, (Pratihast *et al.,* 2013) found that forest inventory and land use change data collected using mobile devices by untrained personnel were comparable to data collected by professionals. Other studies reported similar findings (*e.g.,* See *et al.,* 2013). Additionally, many voluntary projects use self- selected volunteers with considerable expertise (Brabham 2012). The findings of this study indicated that data collected by professional participants were somewhat more similar to reference measurements than were the data collected by non-professional participants. Where differences were due to experience and training, inexperienced participants could be expected to improve over time with suitable feedback and access to training. In other cases, where differences were due to logical interpretation of instructions, making instructions for measurement protocols more clear could improve the consistency and comparability of observations contributed by professionals and non-professionals alike.

4.3.1 Limitations

A limitation of this study is that some of the reference measurements were collected in a similar way to the volunteered measurements. In particular, some of the components that were assessed using visual assessment methods rather than direct measurements (identified in Table 4.1; for example, % ground coverage of fine woody debris is very difficult to measure directly) are high priorities for comparison with other methods. In future studies, the measurements could be compared with multiple measurement methods to bound the observations (following Sikkink and Keane 2008), and collected over a broader range of sites and with more participants. It is important to note that several major considerations in implementing a public participation project involving wildfire are risk, liability and personal privacy. This work is intended as a starting point to demonstrate proof of concept for an approach that has considerable potential for data collection in forestry and wildfire management.

Chapter 5: Integrating smartphone data with multispectral remote sensing data

5.1 Introduction

PPSR may serve a variety of roles in the context of remote sensing. First, volunteers may help with data collection. Lillesand (2002) utilized data collected by volunteers in combination with spectral remote sensing measurements to calibrate models of water clarity that were used by resource managers. Modern electronic communication devices, such as smartphones provide increasing opportunities for volunteers to collect data, in particular because of the following factors: they are available to an increasing number of people; they are equipped with a touchscreen for delivering instructions and entering data; they are equipped with sensors such as a camera, accelerometer, gyrometer, and global positioning system; they have the ability to store data in memory and transfer them over a network; and they have the ability provided by application stores to distribute an application to a wide audience for rapid installation (Ferster and Coops 2013).

A small but growing number of remote sensing projects have used smartphones to collect data or PPSR inspired approaches. For example, Pratihast *et al.,* (2013) tested a smartphone application for inexperienced forestry workers to collect land cover and land cover change information. The study showed that inexperienced data collectors were able to collect data that was comparable to more highly trained workers. Gumley *et al.,* (2010) designed a smartphone application and distributed publicly to record atmospheric conditions and land cover coinciding with satellite overpasses. In the GeoWiki project, volunteers assessed land cover from remotely sensed imagery to help with model building and validation (See *et al.,* 2013).

One natural resource research area where there is potential to apply the principals of PPSR to collect field data in combination with data from satellite remote sensing, is the measurement of forest fuel loading. Forest fuels are forest structural components that provide fuel for wildfire thus presenting a hazard to communities (Hardy 2005). Wildland-urban interface (WUI) areas, where human development meets wild areas, are expanding in North America and in these areas homes and other community infrastructure can be threatened by wildfire (Radeloff *et al.,* 2005). In addition, policies of wildfire exclusion in fire-adapted landscapes have led to an accumulation of fuels, resulting in more intense and severe wildfires; therefore, fuels reduction treatments, which aim to reduce or modify the amount and arrangement of fuels at a location, are necessary to mitigate hazards to communities where wildfire occurs (Agee and Skinner 2005). In order to identify fire hazards and coordinate fuels treatments, fire managers need data on fuels loading as input to fire behaviour models and geographic information systems (Arroyo *et al.,* 2008).

Several studies have utilized remote sensing approaches to estimate the spatial distribution of forest fuels. Falkowski *et al.,* (2005) employed a multifaceted approach including maximum likelihood classification of cover type and structural stage, potential vegetation type from the classification of edaphic conditions, and linear modeling of the forest canopy using multispectral remote sensing from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor using bands with 15 m spatial resolution. Peterson and Franklin (2012) utilized topographic variables and multispectral remote sensing from Landsat Thematic Mapper and

Enhanced Thematic Mapper to map forest fuels in Yosemite National Park. However, despite the fact that remote sensing approaches can utilize data covering large areas, allowing rapid and efficient monitoring of forest fuel loads, there remain challenges in measuring forest fuels using remote sensing from above-canopy platforms because many of the fuels components are located near the ground and can be obscured by overstory trees (Keane *et al,* 2001). Therefore, collecting ground-based measurements is still essential to understanding the quantity, arrangement, and spatial distribution of forest fuels. While ground collection is thus necessary, collecting these measurements is also a major challenge given the broad areas that are influenced by wildfire, the large spatial variation within stands, and the rapid changes that can happen in fuel loadings, for example, blowdown after a storm (Keane *et al.,* 2001).

The RapidEye remote sensing platform has potential to meet several of the challenges of remote sensing forest fuels because of its relatively fine spatial resolution, frequent temporal resolution, and the multi-spectral resolution of its bands. RapidEye provides imagery with a nominal spatial resolution of 5 m, providing the potential to map variations in canopy cover at a detailed scale that may be suitable for providing information about small vegetation patches that may pose localized hazards in communities. Additionally, the data are provided by a constellation of five satellites equipped with push-broom scanners with a 77 km swath, providing a unique ability to acquire fine spatial resolution imagery with a relatively rapid 5.5 day revisit time, or as soon as 1 day if off-nadir imagery is used. This approach has been used to track disturbance in near-real time with finer spatial resolution than is allowed using other sensor (such as Landsat ETM or MODIS) (Arnett *et al.,* 2014). Therefore, methods that are developed for forest fuels mapping can be applied for monitoring for rapid changes in conditions. The sensor provides five bands

(440 – 850 nm), notably, including a "red-edge" band (690-730 nm) which measures a region of the electromagnetic spectrum associated with a rapid increase in reflectance for vegetation between the trough in the red region by chlorophyll absorption and the reflectance peak of near-infrared reflectance related to leaf-structure. In vegetation studies, the use of the RapidEye red-edge band and indices related to the red-edge band has potential to detect stress earlier than using the near-infrared bands (Eitel *et al.,* 2011), and help with classification, especially for open vegetation types such as bush vegetation and perennial herbs (Schuster *et al.,* 2012). The ability to distinguish understory and conifer crown vegetation is useful for fuels mapping by separating the canopy from other components (Riaño and Chuvieco 2002; Falkowski *et al.,* 2005), and therefore, the RapidEye red-edge band and derived indices may be useful for fuels mapping by helping to distinguish the conifer canopy from understory shrub and herb layers when they are in, or approaching, a senesced state.

In addition to requiring data about forest fuels loading, forest managers also run public outreach programs that are necessary to encourage home owners to practice fire reducing landscaping (Cohen 2000), and to gain public support for treatment programs on public land (Harris et al., 2011). Public perceptions of trust in forest manager's actions have been related to knowledge of wildfire processes (Toman *et al.,* 2006a), and trustworthy relations over time (Shindler *et al.,* 2009). Utilizing PPSR inspired approaches may provide an opportunity to collect more information for wildfire managers, while concurrently increasing public knowledge and engagement related to wildfire issues and build citizen-agency trust. To explore this theory, a smartphone application was developed to measure forest fuel loading by volunteers in a WUI area (Appendix A). Volunteers made observations about the quantity and arrangement of fuels based on reference images following the photo load and photo series approaches (Sikkink and Keane 2008), and collected images using the camera and location using the GPS. The observations were then exported in tabular format and collected for analysis on a central server. The volunteers were given questionnaires before, and after, collecting data to better understand how technologies can fit into a forest management activities, including the volunteers' motivations for volunteering, previous experiences with wildfire, experiences using the application, and expectations of privacy and fairness of data use (Chapter 3). The volunteered measurement plots were revisited by the research team to collect reference measurements, and the quality of the data was assessed (Chapter 4). For many components (*e.g.,* large woody debris, surface vegetation coverage, and crown closure), the measurements by non-professionals were comparable to measurements by professionals. However, to gain a more complete picture of how data collection by volunteers using a smartphone application can fit into a forest management context, these data need to be integrated with data from other sources, such as remote sensing and topography, and used to estimate fuel loading over broader areas.

The purpose of this chapter is to identify and evaluate methods of integrating ground-based observations collected by volunteers using smartphones with remote sensing data to estimate forests fuels loading within a WUI area. Volunteers used a smartphone application designed by the research team to collect observations of forest fuels loading. The observations were used to perform a K-MSN imputation of multiple forest fuels components using vegetation indices derived from multispectral RapidEye imagery (5 m spatial resolution). Geolocation was matched using canopy imagery collected by the smartphone's camera and the RapidEye imagery to evaluate the differences in distance related to GPS precision. To provide practical insights into the professional and non-professional data, independent subsets were selected and modeled, to evaluate the effects of different levels of volunteer experience. Lastly, based on the experience from this project, a framework is developed and presented to help coordinate future volunteer efforts when considering use of these types of data in Earth observation studies.

5.2 Methods

The study area was located in Kelowna, British Columbia, Canada. In this region, there is substantial development in WUI areas in the Ponderosa Pine biogeoclimatic zone, which is characterized by a mix of grassland and forest with vegetation that is adapted to wildfire (Hope *et al.,* 1991). A study area boundary was delimited to include forested areas covering 52 ha within comfortable walking distance of the study meeting point, within the approximately 1 hour allocated to each participant. The study start point was accessible by car or public transportation. Details of recruitment strategy to obtain volunteers, the smart phone application, and the experiment are provided in the preceding chapters and Appendix A., and a short summary follows. Volunteers were recruited by contacting nearby neighbourhood associations, outdoors clubs, and through placement of posters, classified advertisements, and local media coverage. A substantial proportion (50 %) of the participants indicated that they had extensive working experience in forestry including operational foresters, wildfire specialists, and community foresters (the separation was based on statement of experience rather than professional title). To simulate an opportunistic dataset, volunteers were directed to collect data in publicly accessible areas of interest. While collecting data, participants were accompanied by at least one member of the research team. While collecting data, a flagging tape marker was placed, and the research team revisited the volunteered plot immediately after the volunteer measurements to collect reference measurements for comparison. Where possible, direct quantifiable measurements were taken, while for some components visual estimations were made similar to how the application was used (see Ferster and Coops, 2014 for details). The forest fuels components and associate activities are given in 4.1. The procedures and generated output were designed to be compatible with regional protocols (Morrow *et al.,* 2008) so that the data may be used with other previously collected sources. Following a forest fuels photoseries inspired approach (Sikkink and Keane 2008) the participants made visual estimations based on reference diagrams and estimated the appropriate fuels loading category. For the analysis, the quantitative mid-point of each category was assigned to the observation.

Rapid eye multispectral imagery was acquired on 28 July 2013, coincident with the field program (Table 5.1). The image was orthorectified by the vendor using nearest-neighbour resampling. A dark object subtraction was applied to correct for atmospheric scattering using ENVI 5.0 (Exelis Visual Information Solutions, Boulder Colorado) (Chavez 1996), and vegetation indices were calculated (Table 5.2). Additionally, a digital elevation model (DEM) was acquired (Canadian Digital Elevation Data 2003) with a 30 m spatial resolution.

Table 5.1 Remote sensing and topography data specifications.

Sensor	Provider	Acquisition Date	Spatial Resolution	Bands	Processing
RapidEye	Blackbridge Geomatics	28 July 2013	5 m	Band 1: Blue 440 - 510 nm	• Vendor orthorectification with nearest neighbour resampling (level 3 product)
				Band 2: Green 520 - 590 nm	• Dark object subtraction (Chavez 1996)
				Band 3: Red 630 - 685 nm	
				Band 4: Red Edge 690 - 730 nm	
				Band 5: Near-infrared 760 - 850 nm	
Digital Elevation Model	Canadian Digital Elevation Data (geobase.ca)	7 July 1995	30 m	Elevation in meters relative to Canadian Geodetic Vertical Datum 1928	• Reprojected to Universal Transverse Mercator North American Datum 1983 Zone 11 North

Table 5.2 Calculation of vegetation indices.

Predictor	Source	Formula	Reference
NDVI	RapidEye Image	(Band 5 - Band 3) / (Band 5 - Band 3)	Tucker (1979)
GNDI	RapidEye Image	(Band 5 - Band 2) / (Band 5 + Band 2)	Gitelson et al., (1996)
NDRE	RapidEye Image	(Band 5 - Band 4) / (Band 5 + Band 4)	Barnes et al., (2000)
GRVI	RapidEye Image	(Band 3 - Band 2) / (Band 3 + Band 2)	Tucker (1979)
SR	RapidEye Image	Band 5 / Band 3	Tucker (1979)
RSR	RapidEye Image	Band 4 / Band 3	Tucker (1979)
Slope	Digital Elevation Model		
Aspect	Digital Elevation Model		

To develop an understanding of the potential errors in horizontal positional accuracy using the smartphone GPS measurements and to ensure that the volunteered smartphone measurements were reasonably matched in location with the RapidEYE imagery, several steps were taken. First, the GPS coordinates were compared between those collected by the participants and those collected by the research team. From the two sets of measurements, the set with the lowest device reported error was used to position the measurement on the map. Second, Event Visualization Tool (eVis) v 1.2.0 software (Ersts *et al.,* 2013) was used to review the five site photographs of each plot and compare them with vegetation patterns visible in the RapidEye imagery. This tool allows easy viewing of the collected data, captured images, and geolocation on a map within a GIS environment (for comparison with remote sensing imagery). Where volunteered measurements were observed in locations very different than the canopy cover or landcover observed in the RapidEye scene the plot was moved to the locally optimal location that best represented the vegetation patterns visible in the site pictures. Finally, the distance moved was calculated as the Euclidian distance from the original volunteered location to the location that was determined to be the best match for the remote sensing imagery. Therefore the images collected by the smartphones along with the eVis tool were the basis of a valuable quality control step.

To estimate the spatial distribution of forest fuels at the study site, a K-MSN (k=3) imputation was performed using R version 3.0.3 (R Core Team, 2011) and the package yaImpute 1.0-20 (Crookston and Finley 2008). K-MSN is a classification technique that uses predictor variables that are available for a wide area (such as remote sensing or topography cover ages) to estimate the quantity of an unknown target variable that was measured at a subset of the locations (in this case, forest fuels loading). A distance measure is used to calculate similarity between the targets and the predictors, and the attributes can be calculated as an inverse distance weighted mean of the K nearest neighbors. For this study, the Mahalanobis distance (Mahalanobis 1936) was used, because of its demonstrated ability to predict forest attributes (Hudak *et al.,* 2008), intuitive interpretation, and since the distances are calculated using only to the predictor variables, it allows direct comparison of distances for models that were built with different training data, which for this application provides utility in directing sampling effort. All predictor variables were used in the imputation and a canonical correlation analysis (using the procedure in Sherry and Henson (2005)) was undertaken using SAS 9.3 (SAS Institute, Cary NC) to understand the relationship between the predictor variables and the targets (as recommended in Packalen *et al.,* (2012)). In addition, the Mahalanobis distance was mapped to see how well areas were represented by the reference observations. Finally, the imputed surfaces for the entire extent and distance maps were used with an orthrorectified aerial photograph for presentation (City of Kelowna Open GIS Catalogue 2013).

An initial examination of the distribution of the volunteered plots indicated that almost all of the plots were collected in closed-canopy forested areas. Even in relatively open areas of forest, the volunteered plots were located in small isolated patches of closed canopy, indicating potential for significant underrepresentation of open-canopied forested areas. As a result, to augment the volunteer observations four additional image-based plots were established in more open areas, directly adjacent to existing plots by experts where it was possible to observe site conditions from site photos from the adjacent observations (not more than 20 m distance and a clear line of sight).

To evaluate the K-MSN models, the root mean squared difference (RMSD) was calculated using a leave-one-out cross-validation approach for the data used to build the model augmented with the RMSD between imputed and measured values for all of the reference data collected by the research team. The models were built with subsets of the data (for example, only observations by professionals), and the RMSD was calculated using the reference observations collected by the research team (including the data used to build the model following a leave-one-out-cross-validation approach, augmented with all other available reference data using the RMSD between the imputed value and the reference measurement). Following Stage and Crookston (2007), the RMSD contains error from the following sources of error: 1) measurement error, 2) pure error (due to the predictor variables not representing the pattern or error in the spatial resolution), 3) the availability of observations to act as a surrogate for the target (related to the spatial representativeness of the training data), and 4) the choice of K (the number of near neighbours used in the imputation), number of reference observations, and the relative weights. By evaluating these sources of error, it is possible to evaluate the "relative gains of reducing measurement error versus increasing the density of sampled observation units" (Stage and Crookston 2007). In this study, all of the sources of error were evaluated using K-MSN imputation as a tool to integrate the remote sensing, topography, and volunteered smartphone data sources for larger area predictions and to evaluate sources of error to improve future volunteered-data collection efforts. In order to assess the predictive capacity of the RapidEye spectral bands and the additional elevation data to the six forest fuels components a canonical correlation analysis was then conducted. Finally, the K-MSN model was performed and evaluated with different combinations of professional and non-professional volunteers. Random combinations of volunteers were selected from 0 to 9 of the professionals and non-professionals, each repeated 10 times. These comparisons were evaluated by calculating the RMSD using the full suite of reference observations.

5.3 Results

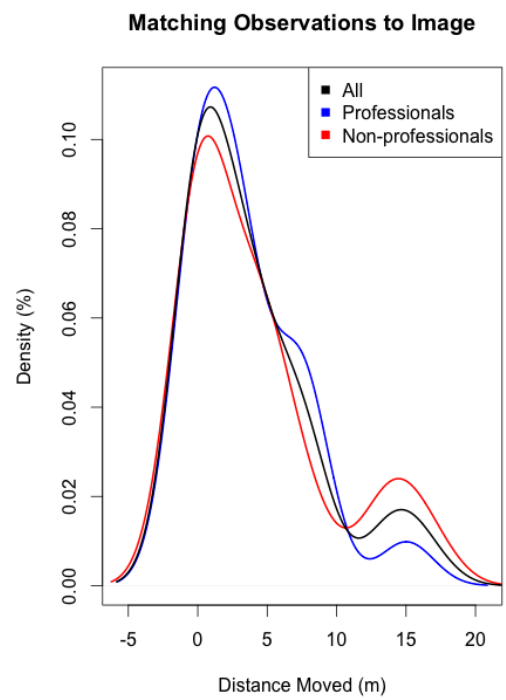
5.3.1 Spatial registration

The median distance needed to match the location of the smartphone data with the RapidEye imagery was 3.0 m, and was slightly further for forestry professionals (3.6 m), and slightly closer for non-professionals (2.9 m) (Figure 5.1 and Table 5.3). The mean differences were much larger than the medians due to a small number of observations which required very large positional shifts (one for a forest professional at 209 m and one for a non-professional at 564 m). The positional shift had a week positive correlation with canopy cover (Pearson's r = 0.18).

Table 5.3 Amount observations were moved to match the image.

	Movement needed to match image			
Grouping	Min	Median	Mean	Max
Professional Forestry Experience	0	3.6	14.0	209.7
No Professional Forestry Experience	0	2.9	28.9	564.0
All	0	3.0	21.6	564.0

Figure 5.1 Distance observations were moved to match the remote sensing imagery. For clarity, several very large movements were not illustrated.

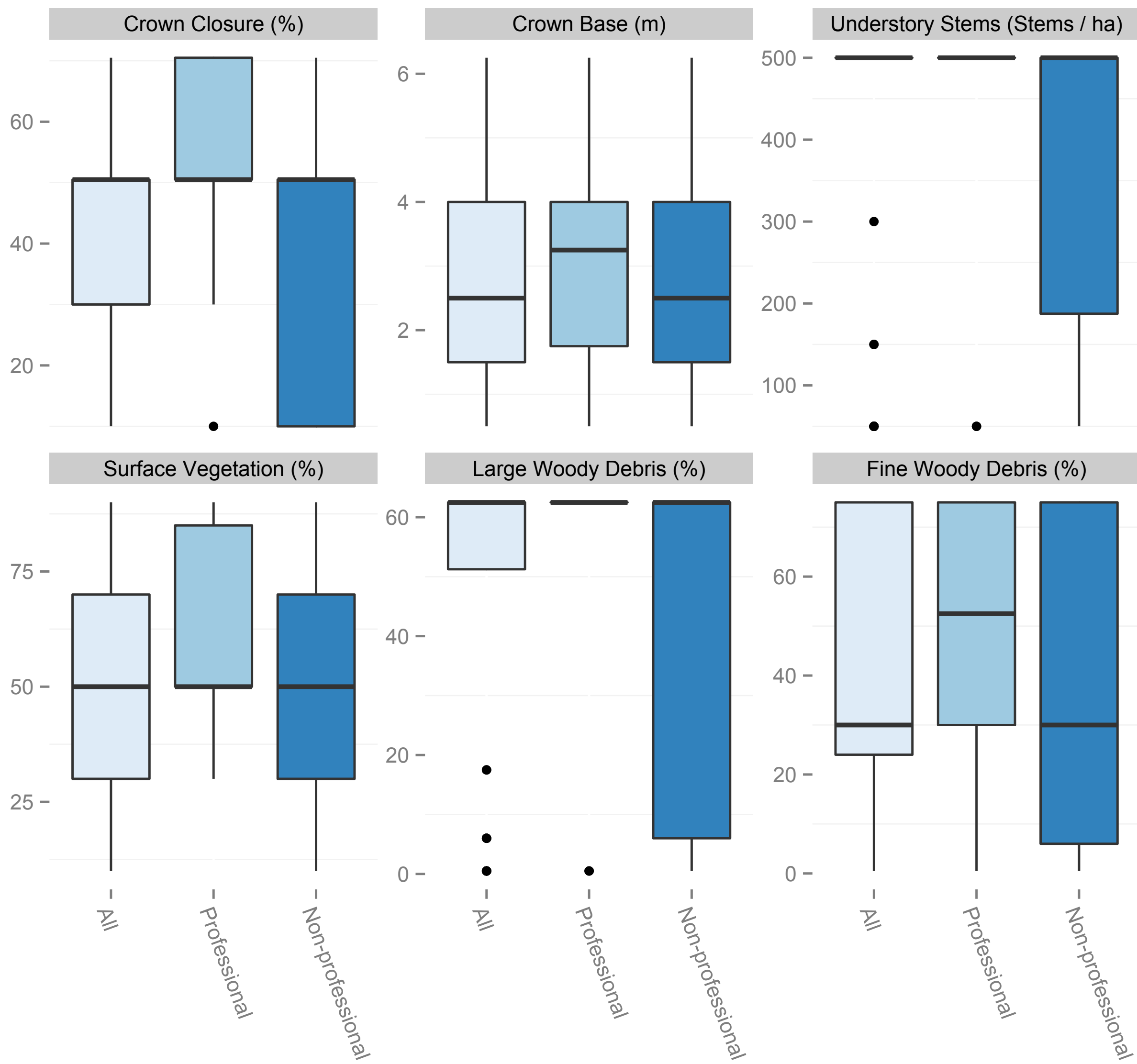


5.3.2 Field data

Several patterns were evident in the observations of forest fuels loading collected by the volunteers. High canopy closure was associated with high amounts of woody debris, higher understory stem densities, and lesser amounts of understory vegetation. Locations with high amounts of large woody debris also had high understory stem densities. The previous two conditions may be related to the woody debris providing higher soil moisture, which in turn promotes tree growth that restricts light for understory vegetation. Locations with high amounts of understory vegetation also had lower amounts of fine woody debris, likely due to the presence of more open canopies, and less literfall. Sites at higher elevations typically had lower canopy closure, and high amounts of fine woody debris and only moderate amounts of large woody debris. These sites were typically very dry with relatively small trees, and little understory growth. Low elevation sites typically had higher amounts of understory conifers, high amounts of understory vegetation, and abundant large woody debris.

In general, the volunteers with professional forestry experience more frequently chose sites with high levels of fuel loading, and non-professionals chose sites with a broader range of conditions, and were more evenly spread across these conditions, including some with lower levels of loading (Figure 5.2). In particular, the volunteers with professional experience chose very few sites with lower levels of conifer crown closure, large woody debris, surface vegetation coverage, and understory stems. The overall pool of observations included a wider range of conditions.

Figure 5.2 Boxplots for volunteered observations collected by all participants, participants with professional experience (Professional), and participants without professional experience (Non-professional).



Extracting the remotely sensed and topography variables from the observation locations confirmed that professional participants generally collected locations with high canopy and vegetation cover (indicated by higher vegetation indices), while non-professionals collected data from sites with broader ranges of spectral index values (Figure 5.3). Notably, non-professionals collected observations at sites with steeper slopes and higher elevations. Comparing the distances from the starting point (Table 5.4), non-professionals on average, collected measurements that were further away from the starting point, and the furthest distance measurements were collected by non-professionals. However, the assets at highest risk from wildfire (*e.g.,* buildings) were closer to the starting point, and the volunteers with professional experience collected their measurements closer to these high priority locations.

Figure 5.3 Boxplots for environmental predictors collected by all participants, participants with professional experience, and participants without professional experience.

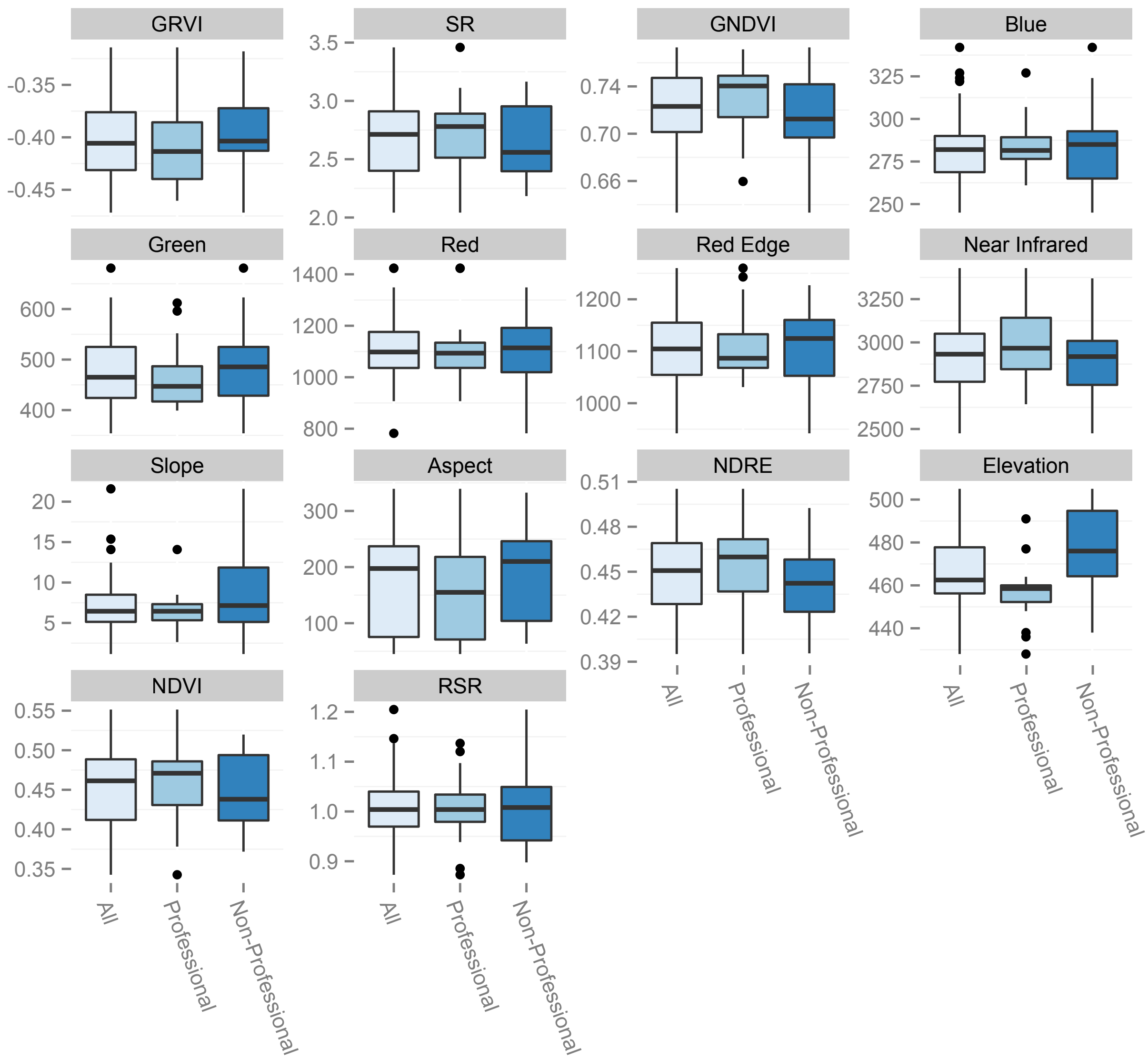


Table 5.4 Summary of Euclidian distance (in metres) of volunteered observations from the starting point, including mean, standard deviation (SD), Median, maximum (max), minimum (min), and range of values.

Forestry Experience	Mean	SD	Median	Min	Max	Range
All	467	176	421	259	1024	765
Yes	382	104	357	267	744	477
No	548	193	492	259	1024	765

5.4 K-MSN Classification

The K-MSN model was built for the full set of measurements, measurements by forest professionals, and measurements by non-professionals using the validation data (Table 5.5) and the raw volunteered data and the reference data (Table 5.6). For most of the components (with the exception of crown closure, which was slightly lower for non-professionals), the pool of all observations had a lower RMSD error than the observations by professionals or non-professionals alone. This was expected because in these cases only a subset of the measurements were used to generate the model while all observations were used to test it, increasing the number of similar neighbours. For conifer crown closure, the RMSD for observations by non-professionals was lower than for professionals and slightly lower than the total pool, although it was only by chance that less representative sites in terms of the predictor variables had conifer crown closures that were close to the reference measurements. For most of the other components, the measurements by professionals and non-professionals were similar, with the RMSD of models built by data from professionals being slightly lower. The largest difference between the models developed by professional and non-professional measurements was for woody debris.

Comparing the RMSD for the raw, uncorrected data and the reference data showed larger RMSD values for the uncorrected data with the exception of conifer crown closure for professional participants. The raw data were closely examined to explore why the model built with uncorrected professional measurements were closer to the reference measurements than the model built using the reference measurements themselves. The data points where the raw model outperformed the corrected model had relatively high Mahalanobis distances to the nearest neighbour (75th percentile and higher). Therefore, it was by chance that the uncorrected canopy closures more closely matched the reference measurements, and the RMSD for the other components was much higher. Another of the most notable differences between the volunteered and the measured observations was for suppressed and understory conifers, due to lower levels of visual observation accuracy and an overestimation of the number of stems (Ferster and Coops 2014), the model using the reference data showed considerably lower counts. Using the data quality procedures recommended in Chapter 4 would substantially increase the accuracy of these estimations.

Table 5.5 RMSD for Mahalanobis model with reference data.

	All	Pro	Non-pro
Conifer Crown Closure (%)	23.2	29.7	22.5
Conifer Crown Base (m)	1.9	2.3	2.4
Suppressed Conifers (stems/ha)	144.0	188.3	184.7
Surface Vegetation (%)	21.6	28.6	30.7
Large Woody Debris (%)	28.3	29.1	34.8
Fine Woody Debris (%)	33.2	36.7	40.4

Table 5.6 RMSD for Mahalanobis model with raw, uncorrected data.

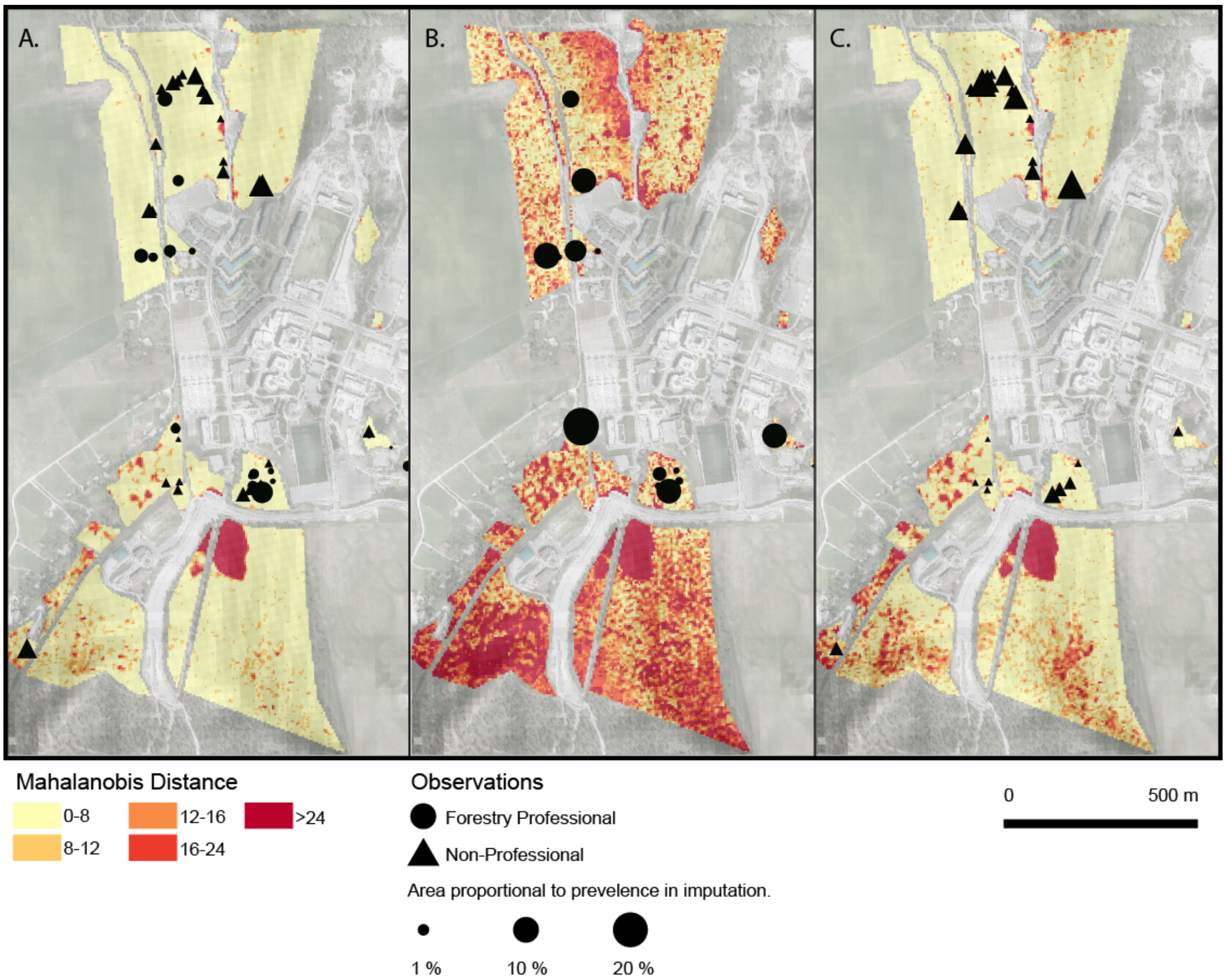
	All	Pro	Non-pro
Conifer Crown Closure (%)	29.9	26.8	31.7
Conifer Crown Base (m)	2.5	2.2	2.7
Suppressed Conifers (stems/ha)	402.9	327.6	399.3
Surface Vegetation (%)	27.7	29.6	35.6
Large Woody Debris (%)	47.5	48.7	42.6
Fine Woody Debris (%)	39.3	38.3	40.2

Using the imputation of conifer crown closure as an example, the estimation based on observations by forest professionals shows higher conifer crown closure near the buildings than the imputation from non-professional observations (Figure 5.4). However, some areas that had been treated for fuels, including thinning of the canopy, such as the linear segment of forest at the Northwest of the study area had conifer crown closure over-estimated by the professional's observations. There were also large differences in the southern section of the image, with the non-professional estimate showing higher conifer crown closure. Evaluating the map made by non-professional participants shows lower canopy closure in the center parts of the study area, nearest buildings. The imputation based on the combination of professional and non-professional observations shows the greatest variation in canopy closure throughout the scene, including areas with high amounts of canopy closure and areas with lower levels of canopy closure.

Figure 5.4 K-MSN imputation of conifer crown closure using (A) all observations, (B) observations by professional, and (C) observations by non-professionals.

Examining the map of Mahalnobis distances shows larger distances for the professional observations mostly in open parts of the stand, since there were fewer observations representing those conditions (Figure 5.5). For the combined measurements, areas of greater Mahalanobis distances included patches in the lower center of the study area, near the edges of stands. Additionally, the estimates by professionals had larger Mahalanobis distances further away from the center of the study area. To improve the spatial representation of the volunteered observations, areas with large Mahalanobis distances could be targeted.

Figure 5.5 Mahalanobis distance for the nearest neighbour in the K-MSN imputation which shows how similar each pixel is to the most similar reference observation in terms of the predictor variables for (A) all observations, (B) observations by professional, and (C) observations by non-professionals.



5.4.1 Evaluating relationships between the target and predictor variables

A canonical correlation analysis was conducted using the 14 environmental predictor variables and the six forest fuels components (Table 5.7). Considered together, the full model across all dimensions (1-6) was statistically significant ($F=2.77$ and $p<0.001$), with a Wilk's $\lambda = 0.007$, indicating a strong effect size and confirming the model explained a large amount of the observed variance. Functions 2-6, 3-6, and 4-6 were also significant at $\alpha = 0.05$. The first four functions, representing canonical correlations (comparable to Pearson's R for the canonical functions) of 0.89, 0.83, 0.76, and 0.72 were chosen for interpretation.

Table 5.7 Tests of canonical dimensions.

Function	Canonical Correlation	Mult. F	DF1	DF2	p-value
1	0.89	2.77	84	162.4	<0.001
2	0.83	2.29	65	141.0	<0.001
3	0.76	1.94	48	117.6	<0.001
4	0.72	1.66	33	92.0	0.03
5	0.64	1.22	20	64.0	0.27
6	0.35	0.50	9	33.0	0.87

Mult. F = Multiple F value for Wilks' λ, DF = degrees of freedom

Considering the scaled loadings for the canonical functions (Table 5.8), in the first dimension, low green irradiances with high GNDVI, RSR, and elevation, were associated with greater amounts of suppressed and understory conifers, understory vegetation, and large woody debris. This implies that understory conifers and vegetation play a large role in driving visible reflectance (darker greens) and were associated with large woody debris, especially at relatively higher landscape positions. In the second function, low irradiance in all bands except the near-infrared, high SR, GNDVI, NDVI, and certain aspect orientations were related to greater amounts of crown closure, understory conifers, and large woody debris, with lower amounts of understory vegetation. This relationship shows that areas with high amounts of canopy closure and high amounts of understory conifers were associated with plentiful large woody debris, less understory vegetation, and the best predictors for these types of conditions were spectral vegetation indices (such as GNDVI), and reduced visible and red-edge reflectance, with aspect. In the third function, increasing elevation was associated with lower amounts of canopy closure and higher amounts of woody debris and suppressed and understory conifers. In the fourth function, higher NDRE, and GNDVI were associated with higher conifer crown closure and higher amounts of fine woody debris (likely windfall from these very dense canopies). Similarly, Falkowski et al., (2005) found that high GNDVI was an effective estimator of canopy fuels components, due to its ability to distinguish between the canopy and senesced vegetation. Evaluating the h^2 coefficients, the predictors with the highest capabilities were the visible and red-edge remote sensing bands, GNDVI, NDRE, and Elevation. In terms of the target variables, the strongest relationships were for suppressed and understory conifers, conifer crown closure, and surface vegetation, with lower amounts for fine and large woody debris. For conifer crown base height, there was very low potential for making the estimation using the predictor variables, so other methods using different predictors or considering other methods of analysis may be more effective.

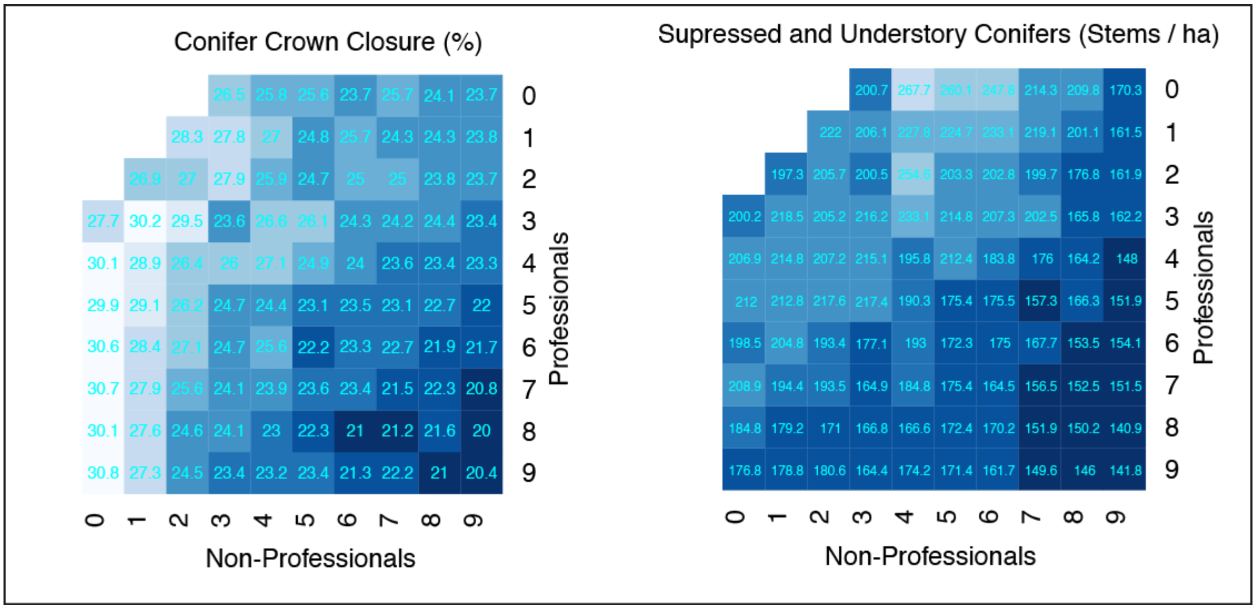
Table 5.8 Standardized canonical coefficients.

	Function 1			Function 2			Function 3			Function 4			
Predictor Variables	*Coef.*	r_s	r_s^2	*Coef.*	r_s	r_s^2	*Coef.*	r_s	r_s^2	*Coef.*	r_s	r_s^2	h^2
Blue	1.08	-0.33	0.11	-0.57	$\underline{-0.67}$	0.45	0.70	-0.07	0.00	-0.06	-0.16	0.02	$\underline{0.59}$
Green	0.50	$\underline{-0.48}$	0.23	-2.22	$\underline{-0.69}$	0.47	0.75	-0.07	0.01	-10.16	-0.05	0.00	$\underline{0.71}$
Red	10.37	-0.41	0.16	-3.40	$\underline{-0.58}$	0.34	4.32	0.12	0.01	-2.20	0.05	0.00	$\underline{0.52}$
Red-Edge	-9.21	-0.25	0.06	1.85	$\underline{-0.63}$	0.39	-1.74	0.04	0.00	6.62	-0.02	0.00	$\underline{0.46}$
Near Infrared	4.02	0.04	0.00	0.93	-0.13	0.02	-0.64	-0.11	0.01	-1.88	0.38	0.14	0.18
GRVI	4.13	-0.26	0.07	1.58	-0.35	0.12	6.61	-0.27	0.07	1.23	-0.10	0.01	0.27
SR	3.66	0.42	0.17	-4.21	$\underline{0.45}$	0.20	4.96	-0.21	0.04	-7.20	0.16	0.03	0.44
GNDVI	7.82	$\underline{0.55}$	0.30	0.67	$\underline{0.65}$	0.43	12.59	0.01	0.00	-7.92	0.24	0.06	$\underline{0.78}$
NDRE	-16.52	0.25	0.06	10.15	0.41	0.16	-6.92	-0.17	0.03	15.86	0.44	0.19	$\underline{0.45}$
NDVI	12.37	0.40	0.16	-15.67	$\underline{0.45}$	0.21	-2.56	-0.20	0.04	-9.18	0.19	0.03	0.44
RSR	-5.47	$\underline{0.45}$	0.20	7.96	0.39	0.15	-4.19	-0.20	0.04	6.34	-0.13	0.02	0.41
Slope	-0.54	-0.21	0.04	0.13	0.11	0.01	-0.42	-0.20	0.04	0.11	-0.14	0.02	0.11
Aspect	0.33	0.07	0.00	-0.62	$\underline{-0.45}$	0.20	0.42	0.41	0.16	0.67	0.19	0.04	0.40
Elevation	-0.29	$\underline{-0.62}$	0.38	0.39	0.05	0.00	1.13	$\underline{0.48}$	0.23	-0.54	-0.16	0.02	$\underline{0.64}$
Target Variables													
Conifer Crown Closure	0.09	0.23	0.05	0.32	$\underline{0.49}$	0.24	-0.92	$\underline{-0.47}$	0.22	0.59	$\underline{0.67}$	0.44	$\underline{0.96}$
Conifer Crown Base	-0.12	0.04	0.00	-0.05	0.06	0.00	0.11	0.19	0.04	0.43	0.23	0.05	0.10
Suppressed Understory Conifers	1.16	$\underline{0.72}$	0.52	-0.09	$\underline{0.45}$	0.20	0.59	0.42	0.18	0.17	0.30	0.09	$\underline{0.99}$
Surface Vegetation	0.59	$\underline{0.53}$	0.28	-0.85	$\underline{-0.62}$	0.39	-0.31	-0.33	0.11	0.18	-0.29	0.09	$\underline{0.86}$
Large Woody Debris	-0.37	$\underline{0.47}$	0.22	0.89	$\underline{0.48}$	0.23	-0.09	0.41	0.17	-0.74	0.27	0.07	$\underline{0.69}$
Fine Woody Debris	-0.15	-0.02	0.00	-0.90	0.08	0.01	0.47	$\underline{0.50}$	0.25	0.97	$\underline{0.74}$	0.54	$\underline{0.79}$

Coef. = Standardized canonical coefficient; r_s = structure coefficient; r_s^2 = squared structure coefficient; h^2 = communality coefficient for functions 1-4. Structure and communality coefficients greater than 0.45 are underlined.

Evaluating the random combinations of volunteers (Figure 5.6) reveals several patterns in the way that professionals and non-professionals collected the data. Because the models were built with the data from the reference measurements, the RMSD should mostly be due to the location of the plots, however, these values likely still contain some measurement error, and this is indicated that in some cases models made with less than the full set of measurements had a slightly lower RMSD. This indicates that as a filtering step, plots with very large distances to their neighbours should be examined and either removed from the model if they are determined to contain a large amount of measurement error, or left in the model and possibly more plots could be directed towards similar conditions if they were determined to be a valid representation of an underrepresented condition. Secondly, as the number of non-professionals increased, the RMSDs decreased in a more linear manner than for professionals - indicating that the non-professionals collected data in more random fashion compared to the professionals who followed a more similar method. In some cases, combinations of volunteers less than the full set were able to make estimations with RMSDs close to the full set of volunteers. This indicates that given the knowledge gained from the exploratory analysis future sampling could be directed more efficiently.

Figure 5.6 RMSD for models using random combinations independent volunteers for combinations of at least 3, mean from 10 iterations.



5.5 Discussion

Several studies have used smartphones (*e.g.,* Pratihast et al., 2013) or public participation to collect data used in remote sensing analysis (See *et al.,* 2013). In this study, volunteered observations of forest fuels were collected using a smartphone application, and extrapolations over broader areas made by combining the smartphone data with predictor variables from remote sensing and topography. As a result of performing this exploratory analysis, insight can be provided into how to direct and analyze future volunteer efforts.

5.5.1 GPS accuracy

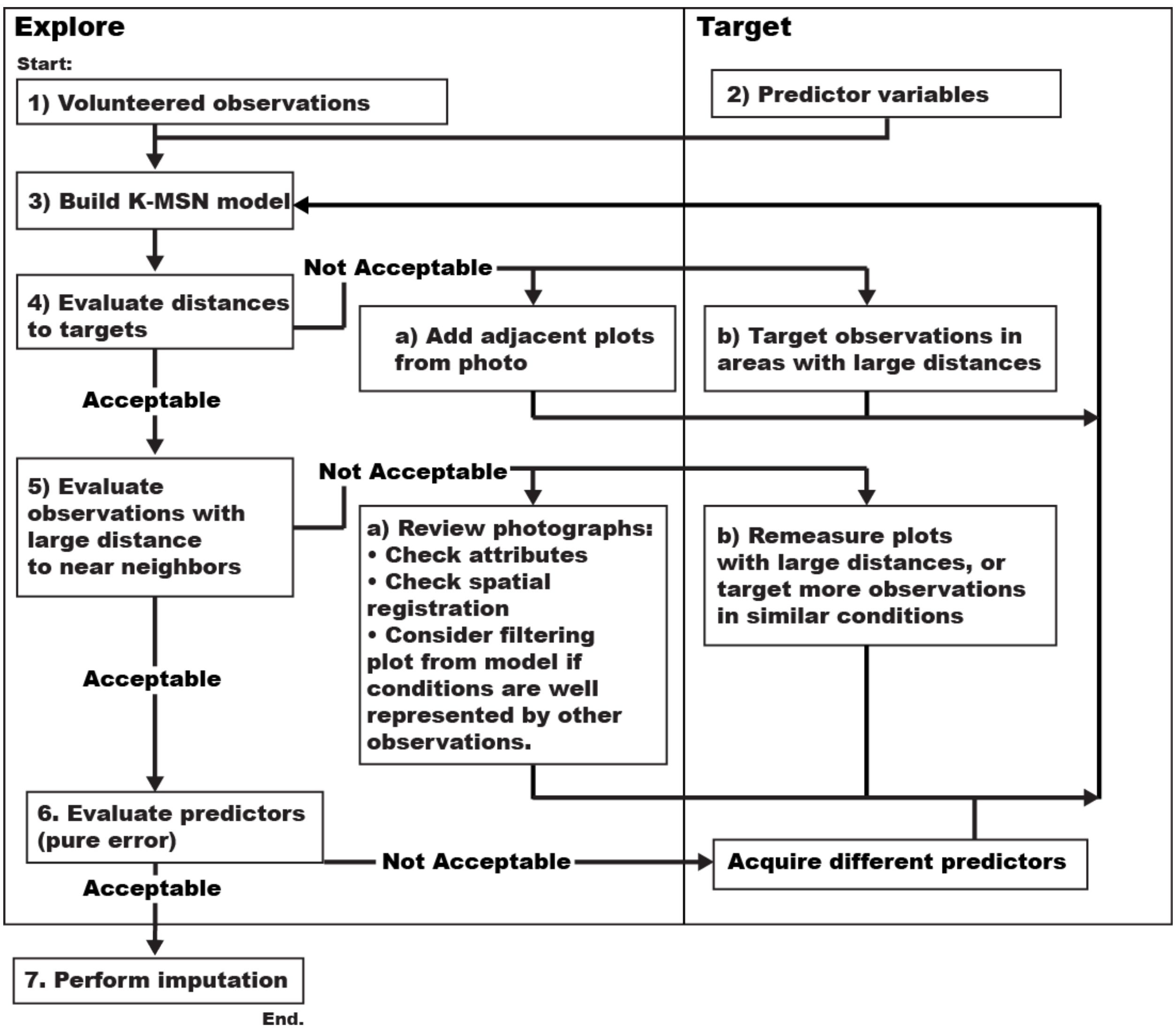
GPS accuracy of smartphone devices was tested extensively by Zandbergen (2009) and Zandbergen and Barbeau (2011), who found a median error of 8 m, however very few measurements with large differences (greater than 30 m) were found in a predominately urban setting. In contrast, the present study was undertaken in a forested environment, and survey benchmarks were not available to test the locational accuracy with as much certainty. As a result, patterns of vegetation visible in imagery were used to match the two sources as closely as practically possible. The distance moved was weakly positively correlated with canopy closure, indicating that this factor may warrant further investigation, however, given the weak correlation, there may be other factors to consider. For example, the application was designed to continuously acquire GPS positioning information while observations of the forest components were being collected, and locational information was recorded as the last step of the process. As a result, non-professional participants had a lower median error, who were observed to take more time to complete each assessment, compared to professional participants who were already familiar with the protocols and terms used in the application and took less time to complete an assessment at each location and therefore, less time to secure a positive GPS signal. Several very large distances (> 100 m) were submitted, and the secondary manual-screening phase was important for identifying and correcting these locations. More error checking should be built into the application, for example where a participant compares the reported GPS location against a map and confirms whether it matches or not. Finally, more work is needed following Zandbergen (2009) and Zandbergen and Barbeau (2011) at known locations (*e.g.,* cadastral survey markers) under forest canopies to better understand what the performance of smartphone GPS devices are in field conditions, and this may help researchers understand what spatial resolution of imagery is appropriate to compare with smartphone-collected measurements (Hengl 2006).

In previous work by Pratihast *et al.,* (2013), non-experts hired to collect forest data using smartphones were able to collect data that was nearly equivalent to data collected by experts, but at considerably less cost. Additionally, people from local communities were more effective at monitoring local forest degradation from fuel wood collection than from remote sensing or aerial monitoring approaches. Similarly, See *et al.,* (2013) found that data collected by non-experts for validating remote sensing models were very close to measurements acquired by experts, however, there were some components where experts outperformed them. These findings were supported by Ferster and Coops (2014) who found that in some cases people with forestry work experience collected more accurate data than non-professional, however, in other cases, non-forestry professionals collected data that was more consistent with the instructions given in the application. In the present study, a volunteered and opportunistic dataset was analyzed to give insight on where forestry professionals and non-professionals chose to collect data. Participants with professional forestry experience were found to submit observations in higher priority areas with higher fuels loading, while non-professionals covered a broader range of conditions and collected observations over a wider area. Models built with the professional's observations alone indicated higher fuel loadings across the landscape. Considering that an overestimation of the fuels load may lead to fuels reduction or modification treatments, while an underestimation may lead to a stand with high fuels loading not being treated, the overestimation is a more conservative outcome. These trends point to a symbiotic relationship between the observations submitted by users of different expertise, where professional measurements are collected in high priority areas, and non-professionals provide a broader range of observations that may make more subtle trends apparent. For both professionals and non-professionals, very few observations were submitted from open areas. This likely could be improved by simply providing instructions to collect observations in a wider range of conditions. The six images acquired in a consistent manner at each site made it possible to add additional plots using photo-interpretive methods.

Similar to Falkowski *et al.,* (2005), indices such as GNDVI and high pigment absorption were associated with increasing canopy closure. However, in the present study, understory vegetation had a strong signal and similar response, indicating that canopy classification could have been more accurate if the remote sensing imagery were acquired when the vegetation was in a further senesced state. Using the NDRE, derived from the red-edge and red bands available in rapid eye imagery was useful to distinguish conifer crown closure and suppressed and understory conifers from surface vegetation. Riaño and Chuvieco (2002) used imagery collected in two phenological states to map forest fuels using remote sensing, leading to a significant improvement in the ability to classify fuels types, especially for classifying different understory vegetation compositions under deciduous forest canopies. In future work, the approach in the present study could be adapted to incorporate satellite images taken in different phenological states, which may help obtain both more accurate crown and understory vegetation estimates. The multivariate canonical correlation analysis provided insight into complex relationships between site conditions and forest fuel variables. While the study area contained a large amount of variation in forest structure in a small area, species composition was very similar throughout the site. Future work may test this approach over areas with greater variation in species composition, possibly adding a classification or stratification step.

The K-MSN approach used in this study provided tools for the simultaneous imputation of multiple forest fuels components and also for coordinating volunteer efforts. Future efforts can be directed to maximize the efficiency of the volunteers to cover the entire area and collect re-measurements as conditions change due to forest growth and disturbance. Based on this exploratory analysis, we present one possible framework for starting with a volunteered, opportunistic data source and directing future efforts (Figure 5.7). The framework starts with a body of volunteered observations from opportunistic sources and with unknown error. In the second step, predictor variables are collected that are related to the targets (the order of the first two steps are interchangeable). In the third step, the predictors and targets are used together to build a K-MSN model, and the following steps assess the model for three of the types of error described by Stage and Crookston (2007) including measurement error, pure error, and similarity of the reference observations, as described in the following steps. In the fourth step, the spatial representation of the observations is examined using the Mahalanobis distance approach to assess the spatial representation of the sample with respect to predictor variables, which demonstrates the similarity of reference observations to the target pixels. If there are large areas that do not have similar observations, they are unrepresented, and future sampling should be directed to those areas. Alternatively, the analysis can be focused to exclude areas with large distances. In the fifth step, the distance of each observation to the other nearest neighboring observations is considered. If observations are collected under similar conditions and have inconsistent measurements, they will be flagged for error checking. This step assesses the measurement error of the observations and the GPS measurement of spatial registration. Finding this source of error requires the assumption that the dataset includes valid measurements (evaluation of attribute quality of the dataset by Ferster and Coops (2014) indicated that a majority of the volunteered observations were within an expected boundary of the reference measurements). In the sixth step, the predictor variables are assessed to better understand the capability of the model. This step is related to pure error in the model and may help managers choose and test more effective predictors. In the final step, the final K-MSN imputation is performed for the study area.

Figure 5.7 A framework for starting with an opportunistic data source and directing future observations. The diagram is divided into to halves: explore and target. The explore side involves operations involving data that was already collected, and the target side involves targeting the future efforts of participants or acquiring new data.



Aspects of this framework are iterative and scalable, allowing them to be completed automatically in real time - for example, Mahalanobis distance for the target pixels across the study area could be calculated and displayed as each additional observation is collected and presented to participants to show where volunteered observations are most beneficial. Additional research is needed to see if this could be a motivating approach for participants, and potentially could be combined with approaches that utilize game elements with more points awarded for collecting observations in high-distance areas (Iacovides *et al.,* 2013). Additionally applying this type of framework to measurement programs over time to observed changes also requires addition research. For example, with the present framework, as more volunteered measurements are collected over time, changing forest fuels loadings will trigger the re-measurement or targeting of new measurements in similar conditions, and the filtering of outdated measurements.

The North American Breading Bird Survey (BBS) is a citizen science project that utilizes a strategic sampling design (along major roads once a year during breeding season) and similar to this study, includes many volunteers with considerable expertise (Sauer *et al.,* 2005). In contrast to the BBS, this study presents a more flexible and scaleable framework incorporating opportunistic data. One possibility is to incorporate design ideas from the breeding bird survey. For example, data collection could take part of a pre-fire season spring-cleanup campaign led by local fire managers. Additionally, strategic sample points could be established as a starting point if these efforts were coordinated from the beginning.

5.5.2 Limitations

This chapter includes exploratory work, conducted over a limited area and timeframe under controlled conditions. One of the main limitations of this chapter is that the area where estimations were made was relatively small. While classifying even a small area can be difficult (a commonly cited challenge in forest fuels mapping is that the variation in forest fuels within a single stand often exceeds the variation between stands, see Keane *et al.* 2001), estimations should be made over larger areas with a wider variety of stand conditions to more fully understand how well the approach can work with different aged stands and a wider range of conditions (such as elevation). The analysis presented in this chapter is exploratory and is intended to describe the data collected in this chapter and inspire future research effort and topics. More research over broader areas with more participants is required to draw broader conclusions. Implementation to a wider audience would require careful consideration of risk and liability, which are inherent in wildfire issues. Therefore, caution is warranted in applying these new techniques.

Chapter 6: Conclusion

This thesis used a case study of forest fuels management to demonstrate the viability of a multidisciplinary approach for collecting forest information using smartphones and PPSR methods integrated with multispectral remote sensing. In the first section of the conclusion, the main findings of each chapter are presented to answer the research questions posed in the introduction (Chapter 1.). In the second section of the conclusion, the work in the thesis is reflected on in light of current literature and current research priorities. In the third section of the conclusion, the significance and the contribution of each section of the thesis is discussed. In the fourth section of the conclusion, the limitations of each chapter are summarized, and the overall limitations of the approach and research questions are discussed and these are used to identify the overall lessons learned. In the fifth and final section of the thesis, as a result of the work to answer the research questions, reflection on current literature and the strengths and limitations of the work, future research topics are identified and discussed.

6.1 Answers to the research questions

6.1.1 What are the related studies, terms, and concepts that can be used to define the field?

An increasing number of studies, from a broad range of disciplines utilize mobile devices to collect Earth observation data. The examples brought forward in the review chapter demonstrated a number of advantages of this approach, including the ability to rapidly collect data, acquire data over broad extents, obtain consistent metadata, provide scientific tools to a broad audience, and provide opportunities to engage the public in science.

The practices of PPSR and collecting Earth observation data using mobile devices is rapidly growing and dramatic advances are expected in the coming years. A challenge is that many separate disciplines have similar objectives for volunteered or public participation data collection, leading to a wide range of terms and concepts that require definition and sorting. For example, there are projects with similar principals and areas of overlap that include (but are not limited to) volunteered geographic data, participatory GIS, PPRS, citizen science, and participatory sensing. Both technical and social factors are important for the advancing the state of Earth observation using mobile devices to collect data. Technical advances, for example designing more robust and effective sampling schemes and reliable data collection methods, will result in higher quality data sets. Social advances, such as gaining a better understanding of the range of experiences and motivations of individuals who contribute volunteered data, may help scientists engage the public in a meaningful way while building new records of Earth observation.

6.1.2 What are the social and management implications of using smartphones to collect data to inform forest management?

Forest fuels treatment in the WUI is important to reduce the threat of wildfire to communities. This exploratory study applied a PPSR approach to forest fuels treatment in the WUI using an application for mobile devices to collect forest structural data related to forest fuel loading. This study applied PPSR approaches to wildfire management with the aim of testing the potential for generating positive outcomes for communities and volunteers and for building a more extensive fuel loading dataset. Through questionnaires, the relationship of demographics and experiences of participants to their awareness, knowledge, and planned behaviours related to wildfire were examined in relation to technology-driven PPSR projects. Initially, personal values were a main motivator for getting involved, and after collecting data the main motivations were related to building understanding and social factors. Efforts to recruit more participants may target their sense of values and to a lesser degree protective motivations (*i.e.* participating is a way to help out the community and reduce wildfire threats). Efforts to sustain participation may target the participants' sense of understanding (of forest fuels and technology related topics), as well as social factors, and highlighting intrinsic enjoyment in the activity (spending time outside in nature). Forest professionals initially had high career-related motivations for getting involved, so these motivations are a target for achieving professional participation. Many of the participants without professional forestry experience indicated that they learned about forest fuels and forest management, while people with professional forestry experience indicated that they used an existing skill, and both indicated that they learned new skills (related to wildfire and technology).

Finally, several logistical considerations were identified that should be addressed before this approach is implemented outside of an experimental setting, including risk and liability, and fear of distributing results without professional interpretation leading to undue pressures on fire managers. Measuring forest fuels data is usually the domain of forest professionals. Some forest professionals expressed concern in extending the public's role into collecting forest fuels data, and forest professionals indicated that they wanted to have a say in how the data were used in management decisions. This tension is created by challenging the traditional role of forest managers and may meet opposition, however public participation methods require that the public have input in order to increase meaningful dialog and participation for the participants and promote the positive aspects of greater awareness and shared responsibility. Additionally, if volunteers submitted data, and forest managers are perceived as not acting appropriately using the information, it could erode citizen-agency trust. Initially, forest managers may wish to engage more limited audiences, for example, rather than distributing the application widely to the general public, the application could be given to smaller groups who have received training. Issues such as legal liability associated with the use of data collected using this application would also require ongoing attention over time.

This approach differs in that non-professionals were invited to engage in this activity using a smartphone application to facilitate data collection. Because wildfires threaten large populations, in an ideal case, the outcomes of PPSR-based approaches have potential to benefit large numbers of people and provide a mechanism for community members to take positive preventative action. Approaches inspired by PPSR are another outreach tool available to forest managers with the potential for positive outcomes in WUI communities, such as an increasing knowledge and salience of wildfire issues and providing a way for forest managers to work alongside the people who may oppose their actions for a common goal.

6.1.3 What is the quality of data collected by volunteers using smartphones?

Management of forest fuels in the WUI requires data about the location, type, arrangement and amount of fuels. Mobile devices can facilitate new methods of collecting forest fuel loading data in the WUI. In addition, they offer a way to engage members of the public that may not normally engage in the measurement of forests. This approach is compelling because it may enable data collection over broad areas and building of large databases of comparable and consistent data collected by a diversity of people. In this study, the quality of data collected by volunteers was similar to those collected by forest professionals for large woody debris, surface vegetation coverage, and crown closure. Non-forest professionals collected more consistent data for height to live conifer crown because they more closely followed the directions presented in the application, while forest professionals were observed to utilize differing working definitions. Forest professionals collected slope and aspect with greater accuracy, primarily due to greater familiarity with the procedure. Understory tree stem density accurately was accurately estimated by few of the participants, and other methods such as using a plot diameter measurement cord and clear definitions for inclusion of understory trees is advised.

Fire managers need to consider the required accuracy of their analysis, that digital data collection methods reinforce logical consistency of observations and that data collectors receive adequate training and feedback on the quality of data that are collected. If these recommendations are followed, data collected by volunteers can be suitable to help inform forest management decisions. Approaches using mobile devices to collect forest fuel loading data show considerable promise and warrant further investigation and development.

6.1.4 How can forest observations collected by volunteers using smartphones be integrated with multispectral remote sensing data?

This study analyzed forest fuels loading data collected by volunteers using a smartphone application and imputed these estimations over broader areas using remote sensing and topography predictor variables. Professional volunteers collected observations in high priority areas and with slightly lower measurement error, while non-professional volunteers collected measurements over a broader range of conditions and over a physically larger area. These trends suggest that the data collected by participants with and without professional forest experience can be used in a complementary manner. A framework was presented to utilize observations by both professionals and non-professionals and coordinate future volunteer efforts in an efficient manner. Following this framework, the K-MSN tools that were used to impute forest attributes can also be used to direct volunteer efforts. The use of volunteer data collection and opportunistic datasets holds potential to advance the state of forest monitoring, provided that methods are used to ensure spatial representation and attribute accuracy.

6.2 Reflecting on the research in the light of current knowledge in the field

The field of data collection using smartphones has undergone dramatic growth over the period of study. One of the most notable advancement is the development of Open Data Kit. ODK is an open source toolkit aimed for data collection using smartphones mainly in the developing world (originally designed for public health activities, it has also demonstrated utility for forest data collection; see Pratihast *et al.,* (2013)). This software could have been utilized for this project had it been available. While utilizing ODK would have reduced the development time, it would not have changed any of the research objectives or outcomes.

In a recent manuscript, Sullivan *et al.,* (2014) identified several priorities for future efforts in citizen science (using recent advance in eBird as an example) that go beyond data collection to include greater participation in community engagement, data curation, data synthesis and analysis, pattern visualization, and delivery of results to a broad community of stakeholders. Another development is in the utilization of game concepts to non-game contexts. For example, Iacovides *et al.,* (2013) found that game elements were able to help sustain participation. While these methods offer potential to shape volunteer data collection efforts, the primary questions about quality of participation remain relevant (Arnstein 1969; Cornwall 2008).

In Chapter 2, definitions and discussion of the related fields and disciplines are provided. Having gained the experience of using the application to collect data in communities, it is apparent that the work in this thesis is related to a range of fields. For example, the approach largely followed concepts and research priorities from the practice and literature base of citizen science and PPSR (Shirk *et al.* 2012). While the goals of the project were related to forest management, these activities are informed by science, and fall within the popular broad definitions of PPSR that include a diverse range of activities that can be driven by the goals of education or management of social ecological systems, provided they meet the requirement of “contributing to scientific research and/or monitoring” (in this case the data contributed to the science of remote sensing of forest fuels as well as contributing to the monitoring forest fuels to inform forest management decisions) (Shirk *et al.* 2012). These definitions can be confusing because they can be inclusive of a wide-range of activities. For example, in a review of 10 PPSR projects by Bonney, *et al.* (2009), eight of the projects involved monitoring to inform resource management, invasive species spread, or pollution. In the same review, while the majority of projects involved simple contribution of data by participants (five projects), three of the projects involved collaboration to help refine project goals and analyzing and disseminating data, and two of the projects involved deeper participation in most, or all, of the steps of the scientific process. Bonney, *et al.* (2009) identified deeper participation as a priority for future PPSR projects. Further, because of the geographic nature of the data, the work could fall under the label of VGI. Finally, many of the challenges and future objectives could be discussed within the discipline of participatory sensing which includes “data collection and interpretation” that “emphasizes the involvement of citizens and community groups in the process of sensing and documenting where they live, work, and play” (Goldman *et al.* 2009). Some projects that primarily identify as participatory sensing also self-identify with the field of citizen science (Han *et al.* 2011; D’Hondt *et al.* 2013). A major challenge is the lack of unity between fields. Future advances in this project require closer attention and clear definitions of topics and approaches within the field of participatory sensing, such as defining target audiences, considering network effects, framing motivational messaging to participants, and mobile application development and testing (these topics are discussed in the following sections).

6.3 Significance and contribution of the research

The main strength of this research was an interdisciplinary approach utilizing questionnaires, observations, smartphone data, and remote sensing and topography data. This work forms important first steps towards applying PPSR to a range of forest resource management topics.

6.3.1 Chapter 2: Review and defining the field.

Chapter 2 provides a detailed review of the integration of terms, concepts, approaches, and methods from diverse fields including citizens science, PPSR, VGI, participatory sensing, volunteerism, bioinformatics and data management. For the first time, the role of mobile devices for data collection was examined for the field of remote sensing and Earth observation. A wide array of case studies, where mobile devices were used to collect ecological data, were examined across a range of disciplines to demonstrate common challenges and opportunities. The capabilities of mobile devices were assessed and documented and their potential use for Earth observation in combination with PPSR approaches. This work was a contribution to the field of remote sensing by helping to define the potential role of mobile devices within a broader Earth observation context.

6.3.2 Chapter 3: Social and management considerations

For the first time, a smartphone application was developed for recording forest fuels conditions following a PPSR approach and tested with legitimate stakeholders in a wildfire-affected community (Kelowna, B.C.). This was a first-of-its-kind application that utilizes an innovative combination of forest rapid ocular assessment techniques with technology that provides utility for a broad range of people to rapidly collect and share observations.

The application was tested by community members from a wildfire-affected area to explore the possible outcomes for forest management and people who participate in data collection. The study was unique in applying PPSR methods to the field of forest fuels management, and demonstrated a novel attempt to find ways for forest managers to work together with people who may be in opposition to their actions toward a common goal.

6.3.3 Chapter 4: Data quality

This chapter tested the attribute accuracy of data collected using an innovative smartphone application that provided a new approach to collecting observations of forest fuels loading. This approach combined ocular rapid assessment techniques with a smartphone collection platform and PPSR inspired methods. This comparison also allowed comparison of the attribute accuracy collected by people with and without professional forestry experience. For example, for conifer crown closure, understory vegetation coverage, and large woody debris volunteers without professional experience were able to collect data with acceptable attribute accuracy that was similar to data collected by people with professional experience. For other components, such as slope and aspect, volunteers with professional forestry experience were able to collect more accurate data because they had more experience and a better understanding of the procedure. For height to live conifer crown, volunteers without professional forestry experience collected higher quality data that was more consistent because these volunteers more closely followed the instructions, while some professional volunteers were accustomed to using different definitions than others. Finally, with respect to understory conifers, few of the volunteers were able to accurately estimate stem density and other approaches are recommended.

This work demonstrates several critical concepts for building datasets collected by multiple people with a range of experience. First is consideration of the skill required for a task and ensuring that adequate training and feedback are provided. Second is ensuring consistency of procedures used to collect the data. These concepts are useful for developing and refining methods of forest fuels measurement, and also for other types of projects that use data collected by multiple people with varying levels of experience.

6.3.4 Chapter 5: Integration of smartphone data with multispectral remote sensing and topography data

The main contribution of this chapter is an innovative framework for integrating smartphone data with multispectral remote sensing data. The framework demonstrates a novel application of K-MSN tools to direct volunteer efforts. In addition, understanding was established of how data collected by people with different levels of experience can be used together to build models. Finally, the volunteered smartphone data was used to make a significant contribution to the field of remote sensing in how the RapidEye instrument can be used to detect forest fuels conditions. In particular, for the first time, this study demonstrated how the RapidEye red-edge spectral band and derived indices can relate to canopy and understory fuels.

6.4 Limitations and lessons learned

6.4.1 Limitations of chapters

In each chapter, the limitations of the specific aspect of the study are given at the end. In summary the major limitations are as follows:

Chapter 2

• The reviewed terms, concepts, definitions, and related projects are from a variety of disciplines that lack unity, and where advancements are rapidly made. Therefore, the review is indicative rather than comprehensive.

Chapter 3:

• The main limitation was the low number of participants. Therefore, the findings should be carefully interpreted, and are limited in terms of how they can be applied to larger populations. The findings can provide insight into how future efforts can be coordinated.

Chapter 4:

• The main limitation was that for some of the measurements, reference measurements were collected in a similar manner as the smartphone data (using a visual assessment). In order to fully understand the smartphone approach in this study, it should be compared with the wide range of other possible approaches in terms of attribute accuracy, time required to collect data, and experience needed.

Chapter 5:

• The remote sensing approach was tested over a small area, testing the approach over a larger area is needed to understand how well the approach can function under a broader range of conditions.

6.4.2 Identifying target populations and understanding their motivational characteristics

One of the greatest limitations identified was the need to better understand and define the motivations behind the use of the application and used this to identify target audiences. This exercise had a low turnout, which is indicative of a lack-of-understanding of the motivation of the potential users of the application. More work to consider motivations in previous projects leading to a better understanding of motivations early in the project, development of social business models, and consideration of network effects may have potentially lead to higher numbers of volunteers and more impactful findings. Given that this study was the first to use smartphones for collection of forest fuels loading information while inviting public participation, and a key objective, given the preliminary nature, was to invite broad participation and work towards identifying potential target populations and their motivational characteristics. The finding that half of the volunteers had previous working experience in forestry was a positive finding that is indicative that people with previous experience could be a future target audience. Additionally, the participation of people without previous experience collecting forest measurements who were concerned about wildfire threats and motivated to take action, but previously lacked formal methods at the community level, was also a positive finding as this group could compose another target audience. These ideas as priorities for future work are further expanded upon in section 6.5.1.

6.4.3 Recruitment framework

Another limitation is that the recruitment framework was focused to a one-time trial, which is not scalable to engaging broad geographic regions or engagement over longer time periods. For example, media coverage could not be sustained indefinitely, and other strategies would need to be employed. The usefulness of the strategies utilized here depend on how the project were implemented, for example, if it were a once-per-year effort (following the example of the North American Breading Birds Survey) yearly media attention could be useful in addition to other strategies, such as developing a social business model. If the project were sustained following an eBird example that allows year-round data collection, a more complex and refined evaluation of the target audiences' needs and motivations would need to be employed (see section 6.5.1). Public interest may also wane when a long period of time has elapsed since the last wildfire, as previous research has shown wildfire preparedness is highest immediately following a successful evacuation (Benight *et al.* 2004). More work is needed to address long-term recruitment and retention for longer-term implementations of the project.

6.4.4 Mobile development and testing

In this work, constraints were placed on the testing of the application and an observer effect was imposed. Therefore, the conclusions that can be drawn from the testing are limited. Researchers such as Kaikkonen *et al.* (2005) found that usability testing in a controlled laboratory environment identified the same issues as field testing, however the frequency that they were reported were different. Nielsen *et al.* (2006) found that in field-testing a significantly higher number of issues reported related to usability problems, interaction style, and cognitive load. More recently, researchers have suggested that the two types of testing have complimentary roles, with laboratory testing leading to field-testing (Kjeldskov and Skov 2014), and therefore further testing in a realistic context would need to follow the work in this experiment in order to draw strong conclusions.

Notably, in this study (and other similar studies including Weng *et al.* 2012; D'Hondt *et al.* 2013; King *et al.* 2014) participants collected data using devices provided by the research team. Under this model context, many of the challenges of mobile development were not realistically represented. Most importantly, mobile devices are personal, and therefore, by using a project-supplied device, people may have interacted with the application differently ranging from a lack of familiarity (i.e. using a foreign device may feel alien, unauthentic, and distracting) to major barriers learning a new system and therefore unrepresentative of how users would use the application in their normal life setting. The devices provided by the research team all had the same screen size and resolution, while actual application use would involve people with a variety of devices with different screen resolutions, processing capabilities, sensor capabilities and specifications, and sensor calibrations that would pose challenges not addressed (Zhang and Adipat 2005). Additionally, a current challenge in development is designing services that fit into the complexities of a persons life including the work, leisure, and other technologies that create a complex "digital ecosystem" and understanding this context requires testing "in-the-wild", outside of the controlled and experimental setting (Kjeldskov and Skov 2014). Therefore, to make more complete conclusions, testing using the participants own devices on the participants own time is needed to understand how the application would be used in a natural context. Additionally, these tests should also be conducted over longer time periods to overcome the "first-time observer effects" that has been measured in longer running citizen science projects (Kendall *et al.* 1996).

6.4.5 Sample size and composition

The greatest limitation in this study was the low number of participants in the study. While the amount of participants was sufficient to collect the information to map the study area and given more time could have created maps covering the broader region of Kelowna, the sample was not large enough to have a broad impact in the community in terms attitudes and understanding of wildfire issues. Approaches that could be applied to ensure greater impact on broader audiences (and identifying the target audiences) are discussed in the section 6.5.1. and 6.5.2. Additionally, the sample was too small and limited in time to fully understand how the approach could be scaled to larger extents and longer time frames.

By comparison, other studies had differing amounts of participants for different target audiences and to achieve different research goals. For example, King *et al.* (2014) developed an educational mobile application for forest areas that was used in a lab session of a university course. One hundred and thirty students used the application as part of their course work, and 50 students opted to take part in a usability study to answer nine questions as part of an online survey. Testing of the Forest Fuels application with university classes was an option in the present study (e.g. several professors offered to feature the application as part of classroom activities and early prototypes were tested and given informal feedback by approximately 30 graduate students in a field trip setting in early summer 2012 - see Appendix A), however, we opted for a smaller number of participants recruited from the broader community including, but also going beyond the university community in order to gain a wider range of experiences including a broader range of ages, people with many years working experience in forestry, and people who owned private property and were responsible for managing wildfire risks in the WUI. In another example, in an exploration of motivations of volunteers participating in a larger scale astronomy citizen science project “GalaxyZoo”, Raddick *et al.* (2010) sampled 22 people who self-selected, using email campaigns asking for volunteers for in-depth interviews, from a much larger pool of 161,961 participants, to more fully understand their motivations for sustained participation in the citizen science project. The sample size in the present study is similar to the work by Raddick *et al.* (2010), however, the sample by Raddick *et al.* (2010) represents a much larger population of volunteers. In work by Reddy *et al.* (2008) to evaluate data quality in participatory sensing projects, testing was completed by participants in several stages. In the first stage, 6 volunteers collected images of damage to sidewalks and other infrastructure over the coarse of two weeks. In the second phase, 26 participants collected data about personal environmental actions over the coarse of 61 days. In the third phase, 11 participants collected data in one session. While Reddy *et al.* (2008) used similar numbers of participants to the present study for each of the activities, testing was carried out by Reddy *et al.* (2008) over a longer time period.

In a study by D’Hondt *et al.* (2013) with very similar objectives to the present study, 13 volunteers conducted noise mapping using smartphones (supplied by the research team) following a structured sample and at locations of their choice, completed questionnaires. The acquired data were analyzed to make predictions over broader areas, and the data where compared with more traditional measures to evaluate data quality. D'Hondt *et al.* (2013, p. 682) were careful to qualify that their study did not address large-scale deployment because it would "not make sense until the issue of data quality is settled". Despite the small participation size, the group was described as ideal "for a citizen science project such as this one, consisting of motivated, community-driven citizens who are concerned with their environment but who do not typically have any technical or scientific domain knowledge" (D'Hondt *et al.* 2013, p. 687). Additionally, while the feedback gathered was too limited to be generalized to broader populations, it was "extremely useful to fine-tune future experiments" (D'Hondt *et al.* 2013, p. 682). In mobile development testing by (Kaikkonen *et al.* 2005) and (Nielsen *et al.* 2006), 40 participants and 14 participants, respectively, were assigned to two conditions (field or laboratory; 50 % of volunteers for each condition) to evaluate usability concerns for mobile interface design. Most of the seminal works in citizen science and PPSR (such as Cooper *et al.* 2007; Bonney, Ballard, *et al.* 2009; Bonney, Cooper, *et al.* 2009; Shirk *et al.* 2012; Dickinson *et al.* 2012) do not draw samples of individuals but rather discuss theory related to the activities of large groups of volunteers in projects like eBird and Project Feeder Watch (>150,000 participants in eBird in 2012 in the United States, and 2800 participant in Project Feeder Watch in 2013 in Canada alone). These massive participation projects are the result of work by large research teams over many years.

The composition of volunteers in the present study included mostly male participants (72%), generally well educated, with a mix of residential locations (urban, suburban, and rural), some of whom had been evacuated due to previous wildfires. Due to this participant composition, the findings of this study are not representative of the wider community and therefore cannot be generalized to the general population. The composition of the sample was similar to other environmental volunteerism projects (e.g. Moskell *et al.* 2010), except with a higher than usual number of males in this study. However, with careful interpretation, the sample may provide useful information and insight about volunteer groups. This is because, the volunteers exist within a broader context of the community that they live in, and therefore, the experiences they shared reflect broader contextual situations and can provide insights into future steps towards identifying and understanding the needs and motivations of target audiences, effectively recruiting and sustaining participants, addressing data quality concerns, developing models to integrate data sources, and building experience designing the project.

6.5 Directions for future research

In future work, this approach could be made available for use with a greater number of people and throughout a broader area with a wider range of conditions. The approach can be expanded to include additional interactive features within the application, including increased levels of feedback (such as maps of the data collected), social connectedness (having more in-person meetings or electronic communication such as discussion forums and social media groups), and implementation for broader objectives, for example, including monitoring ecosystem health. This project focused on the data collection aspect of a PPSR inspired project, so future work may test other types of participation in wildland fire management, for example, setting study objectives, analyzing data, weighing costs and benefits in decision making, and distributing the results to a broader audience. The issue of sustaining participation was not addressed in this one-time trial. This preliminary work points to possible strategies to target the motivations of volunteers to sustain participation (i.e. appealing to their sense of understanding, emphasizing social factors, and building the intrinsic enjoyment of the activity). The volunteers in this study, had generally grown up and lived in fire-affected regions, and made statements indicating an understanding that forest fuels loads depend on dynamic processes requiring repeated measurements over time, since they have observed changes in forest structure over their lifetimes (accumulation of fuels and insect epidemics). Information from repeated measurements is essential to forest managers' decisions over time. Other authors have shown that strategies such as adding game elements can help sustain participation (Iacovides *et al.* 2013). Further work into finding ways to sustain participation by providing ways of participation that aligns with the target audience's interests and needs is an important future research topic.

6.5.1 Defining target audiences and increasing engagement

An important future priority is to define the target audience and understand their needs and motivational characteristics in order to increase involvement in any future similar projects, raise awareness of the wildfire issues, have a broader community impact, and potentially change behavior in a sufficient number of people to have an overall beneficial impact on the community. There are standard practices established in the field of marketing for identifying the target audience, developing communication objectives, designing messages, using appropriate communication channels, measuring results, and managing further communication efforts (Kotler 2002, pp. 272). These techniques could be applied to projects that collect Earth observation data using smartphones to increase engagement. A target audience is a group within the target market to which recruitment details are directed. The target market is the group of people that the project is attempting to engage. Given the preliminary and exploratory nature of this project, the recruitment materials were distributed to a wide audience primarily following a mass marketing strategy using traditional media (television, newspaper, and radio), resulting in low levels of involvement from these methods. Directed marketing efforts were conducted on a more limited bases to forest professionals and members of neighborhood associations and outdoors clubs who made up the majority of the sample (these efforts were inspired by Moskell *et al.* 2010, who found that environmental volunteers were likely to be engaged in more than one volunteer project). Further refining these directed marketing efforts could increase the sample size and engage a broader audience.

The likely target market is defined by a combination of reduction of forest managers' budgets and subsequently a reduced ability to meet fuels treatments and public outreach goals. There is potential to use public participation to lead forest managers to share the ownership and responsibility of forest fuels management and generate creative input from other members of the community. This target market may include at least two likely target audiences including 1) the forest managers themselves and 2) people from a range of backgrounds that want to help reduce the fire risk in their community. Each of these target audience could be reached using strategies that appeal to their motivations, which were explored on a preliminary basis in this study, and future avenues that could be expanded upon are described in the following section, and which should be expanded upon in future research.

For the target audience of forest managers, who may lead and help promote the type of project within their respective communities, career factors were determined to be and important motivations for undertaking this study. Recruitment materials and roles in the project that are targeted to forest managers may appeal to the sense of furthering and promoting their role. Another strong motivation and need for forest managers is raising the profile of fuel management topics within the community to build awareness of fire hazard reduction programs and increasing engagement among citizens. During the field trial in this project, many of the people currently working in forestry expressed frustration that people in the community didn't take a more active role in reducing fire hazards on their personal property. Another challenge expressed during the field trial, is that the WUI consists of a matrix of different owners and responsibilities (including public and private, and public land includes parks, forest land, and other branches of administration) that makes it difficult to collect information and coordinate efforts. Given that budget constraints are another ever-present challenge for forest managers, the application needs to appeal to them as an economical way to engage a broader audience, share responsibility for wildfire topics, and provide information that can help coordinate efforts across the matrix of land in the WUI.

For the second target audience; participants without working experience in forest management who want to help reduce the risk of wildfire, appealing to the sense of values and citizenship may be effective motivating factors. In this project, values were one of the leading motivations for people who volunteered. At present, these people are concerned about wildfire hazards, however there is no formal avenue to take action at the community level. Additionally, this is an important target audience because they are inspired to take action, however, they lack ready access to the technical tools to make quantitative estimates. Recruiting from neighborhood associations and outdoors clubs was an effective way to reach people who were already concerned about the topic an ready to act that could be expanded upon in future work. Additionally, participants often expressed intrinsic enjoyment in using the application (for example, “I enjoyed being outside”, and “I enjoyed walking in the forest”). Several participants also mentioned that they wanted to spend more time with the application and collect data over larger areas. One potential target for the application is inviting more physically demanding data collection, as some people stated that they were looking forward to the challenge. Another motivator that could apply to a subset of the people who used the application is people who were involved with “geocaching” (defined in section 2.2.2.2) expressed strong interest in location-based games related to measuring forest fuels (this was a small proportion of the participants). These approaches could be developed, and groups involved in location-based games could form future target audiences.

Another tool to reach target audiences is the use of social business models, which utilize social media tools to connect with current and potential participants as well as have the potential to be utilized in many other parts of the project coordination and operation (Hinchcliffe and Kim 2012). Current social business models make use of services such as Facebook (Facebook.com) to distribute content, and Twitter (Twitter.com) for immediacy. Both tools can be used to reach new audiences, facilitate communication with, and between, present and prospective participants and partnering projects and organizations, coordinate efforts, provide feedback, collect metrics of progress, and provide a venue for participants to interpret, discuss, and disseminate the data and decisions related to the use of the data.

While the present study relied on more traditional electronic communication strategies (webpages, email, and telephone), many of the successful citizen science and PPSR projects make extensive use of social media. Both eBird and The Galaxy Zoo (arguably two of the largest and most influential citizen science projects) maintain an active presence on both Facebook and Twitter. At the time of writing eBird had 30,000 "likes" on Facebook (votes by users of Facebook who had responded favorably to the groups presence on Facebook), and 6,000 followers on Twitter (users of Twitter who receive a stream of updates). The Galaxy Zoo had 8,000 "likes" on Facebook and 11,000 followers on Twitter, and 650,000 posts by 9000 members over seven years on an online forum. These social business activities are obviously an important aspect of these successful projects. In addition to the public face of these projects on social media, these tools are used to coordinate a variety of activities, such as participants planning activities (such as birdwatching trips), discussing and dissemination results, and sharing their activities with networks of friends not currently involved, who may be future participants. In future work, social business models need to be built to advance the state of Earth observation using smartphones.

Finally, network effects may advance the state of Earth observation projects that use smartphones to collect data. Network effects occur when a person gains an explicit benefit by aligning their behavior with the behavior of others (Easley and Kleinberg 2010). For example, when more people use a service that requires interaction and compatibility with others, it becomes more useful, creating a positive feedback loop. An excellent example of network effects are demonstrated by the eBird project; as more data was contributed, the more useful the tools became for planning birdwatching trips and sharing lists of sightings became more high profile; the more people used it, the more useful the system became. A priority to promote network effects in this project is to increase social translucence, so that participants are aware of the actions of other participants, building engagement with other people with similar interests, and allowing collaborations and discussion (Erickson *et al.* 2000). A second step that can be taken to promote network effects is to build tools that use the collected data to provide services of value to the people involved in the project. For the target audience of the forest managers this may involve sharing maps of the fuel loading and providing measures of changes in attitudes and behaviors in the broader population. As the maps of forest fuels loading become more spatially extensive, it may inspire forest managers in other regions to become involved with promoting PPSR projects in their own communities. For the target audience of people who want to help out to reduce forest fuels hazards, a first step could involve sharing the data they helped collect (from personal observation, people often enjoy viewing maps, especially if they helped create it, and when combined with remote sensing imagery can also create a compelling visual display) (see section 6.5.2 for more details). Further visualization tools could be developed, such as showing pre, and post, fire images for similar sites (or possibly videos captured of similar sites during fires). Finally, providing recognition of efforts to collect data or taking action on their own personal property to reduce forest hazards may also have a positive network effect, with other neighborhood associations and individuals potentially seeing the positive effects and deciding to take part themselves. This could be achieved by sharing achievements on social media, which may increase visibility to a broader audience.

6.5.2 90-9-1 Principal

In a web log ("blog") post titled "Zen and the Art of Citizen Science", Caren Cooper (2014) of the Cornell Lab of Ornithology posts a critique that is relevant to this project. She describes the 1% rule-of-thumb for the Internet, which is a principal that 1% of Internet users (or fewer) are responsible for community generated content on the Internet on sites such as Youtube, Wikipedia, and online discussion forums, while 9% may edit content or post comments, and 90% simply consume content (Arthur 2006). The general trend has been observed in a wide range of Internet communities, including digital health social networks (van Mierlo 2014). Cooper (2014) proposes “the current heavy focus on app development for data entry may be misguided if it occurs without simultaneous development of tools for data access and use”. Therefore, a future area of research is sharing forest fuels loading data collected using PPSR data. In this project, one of the main limitations was the limited rate of participation, despite strong community interest indicated by the positive reception observed in almost all interactions in the community, extensive local media coverage, and enthusiasm of the participants. A focus for future efforts can be to build tools to share the results and evaluate the outcomes of consumption of these data by a broader audience. For example, research could explore whether support for fuels treatment decisions increases if members of the community viewed maps and other media that were used to make decisions knowing that other members of the community helped collect the data and had input in the decision making process. There is potential to develop compelling media for this application by combing visuals created using remote sensing imagery in combination with ground level data collected using mobile devices, and also showcasing the process of participation. In future work, these media could be presented on a webpage, and Internet questionnaires delivered to measure outcomes (Dillman 2007, chapter 9).

6.5.3 Climbing the ladder of participation

Bonney *et al.,* (2009) identified three areas where there is room for development of new citizen science projects:

1) Projects designed to test new scientific questions

2) Projects designed to engage new audiences

3) Projects designed to test new or enhanced PPSR models

The present research mainly addressed issues related to the first objective by applying PPSR to forest fuels management (although not specifically a scientific question, it is a management activity that is informed by scientific practice), and the integration of smartphone data and multispectral remote sensing data. An obvious target for new audiences to engage in forest fuels PPSR projects are people who are not aware of the present outreach efforts. To meet this goal, the practice of disseminating findings to a broad audience, mentioned in the previous section, may help. Finally, in terms of testing models of enhanced PPSR, one of the main objectives commonly called upon to lead to the advancement of PPSR is for more participation in formulating research objectives, analyzing data, and disseminating results (Bonney *et al.,* 2009; Conrad and Hilchey 2011). The work in this thesis involved participation through the collection of data, however, it solicited input on future direction of the project through the questionnaires and discussion with the participants. Using the framework by Arnstein (1969) to assess the levels of participation in the project, contributing data (following the contributory model of citizen science, i.e. scientists asking the public to collect data and providing information in return Bonney 2009) amounts to token levels of participation. If the project were to continue, and incorporate the findings of the questionnaires, it should aspire to attain higher levels of participation by including participation in the design of the application, future applications of the project, including local knowledge in the analysis and interpretation of data, disseminating results, and prioritizing future forest treatments. Increasing levels of participation would require further inclusion of strategic intent and creative involvement by the volunteers.

Participation by the public, volunteered data, and citizen contributions also brings many complicated nuances in terminology and concepts, for example contributions may be made by people with considerable expertise despite the implicate assumption that volunteers are non-experts (Brabham 2012). Companies may pay to hire employees to collect data for volunteered data bases (for example, OpenStreet map is considered VGI, however, some of the data was collected by companies with commercial interests). Further work is needed to understand how these issues would apply to a forest management project.

In the context of forest fuels management, there are several opportunities for increasing levels of participation under the objectives of setting project objectives, analyzing data, and disseminating findings (Bonney *et al.,* 2009). For forest fuels management, there may be opportunities for enhanced participation in identifying areas to study for fuels loading, analyzing the field data to identify priority areas for treatment, and disseminating findings using social and other media.

One potential limit to public participation in a forest fuels management project in British Columbia is that the data are used to prepare Community Wildfire Protection Plans (CWPP), which are required for fuels treatments on public lands and require the signature of a registered professional forester (RPF). This challenge could be met by involving RPFs throughout the project who may sign once satisfied that the data collected and analysis meet professional standards (in the case of this project, these credentials were readily in abundance). Another barrier, if the project were carried forward to engage public participation in the actual treatment of forest fuels, is the requirement for credentials such as danger tree assessment, chainsaw training, fire suppression training (if treatments are carried out during fire-season), and insurance in case of injuries or accidents. Some participants in the study suggested from experience (for example, many of the volunteers were involved in organizations doing trail maintenance for hiking and cycling trails) this challenge can be met by community groups by funding volunteers to obtain the necessary credentials and paying for insurance using member fees. One of the volunteers viewed potential use of the Forest Fuels App. to help plan fuels treatments performed by community members following a "community work party" model.

There are several further barriers to extending public participation to the full limits that require consideration and further research. For example, the cost to volunteers in terms of time and effort could be substantial, and this may be a barrier to participation for some people (Cornwall 2008; Moskell *et al.,* 2010). Crowd-sourced and volunteered efforts can represent large amounts of legitimate labour and expertise, and therefore, participants deserve consideration of workers' rights, ethical treatment, and fair compensation (Brabham 2012). In addition, technical support for a PPSR project, including server space, software development, and hardware requirements can be a considerable cost too (Wiggins 2013). Some of the participants in the present study identified these themes, for example, one participant stated "who is going to pay for it?" Finally, if all forest fuels loading data collection, analysis, interpretation, and dissemination in reports were performed by unpaid volunteers, it could cut off a source of revenue to forest consulting companies, many of whom are local businesses in wildfire-affected communities. Further investigation of these themes is important given that data collection using mobile devices by people with limited forestry experience can be motivated by reducing the costs of employing professional foresters (Pratihast *et al.,* 2013).

6.5.4 Future data collection using smartphones

Developing and testing new methods of data collection is a long standing tradition in forestry (Freese 1960). As established in this thesis, advances in mobile technology present ample opportunities to continue this activity with new methods that utilize mobile devices. In addition, software packages such as ODK, and the NatureServe Mobile Observation System streamline the task of deploying smartphone data collection approaches. Future efforts may consider the data quality issues raised in Chapter 4 of this thesis, and continue to develop and test methods of smartphone data collection.

6.5.5 Application specialization

The application could be extended to collect other ecological data, such as the health of ecosystems or the presence of invasive species. Additionally, different versions of the application could be delivered to different audiences. For example, a version for homeowners without professional forestry experience could contain information from the Partners-In-Protection FireSmart homeowner's manual (Partners-In-Protection 2013), and ask for data collection from a subset of the measurements. As part of an outreach effort, fire managers could offer to meet and discuss fuels hazards with application users. Forest managers could use campaigns such as a pre-fire-season spring cleanup where homeowners are reminded to take FireSmart measures on their personal property, and volunteers are asked to collect observations on public land. For professional users, the present form of the application may provide utility for field data collection.

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Appendices

Appendix A The Forest Fuels Application

A.1 Inspiration for design

Methods of ocular forest fuels estimation

A number of ocular rapid assessment techniques have been developed for forest fuels. For example, in the Photo Series technique (developed by Maxwell and Ward 1976) forest fuels are measured in a plot and photographed. These photographs are presented to field crews either bound in a book, or in digital form through a computer web-browser interface (Wright *et al.,* 2007). In the field, crews make a visual survey of conditions at the site, find the photograph with the closest conditions, and record the quantitative value for each fuel component from the closest matching reference image. Another technique, Photoload (Keane and Dickinson 2007b) is similar in its approach, except that synthetic fuels beds are used and photographed in a studio setting (for example, construction materials such as pipes may be used to simulate distributions of large woody debris). The Photoload method introduces a level of abstraction into the process that can help with evaluation of the components independent of the other ecosystem conditions. Sikkink and Keane (2008) reviewed a range of ocular approaches and more traditional direct measurements and found that for each method there were tradeoffs in terms of attribute accuracy, time required to complete an assessment, and training required to complete an assessment. In many cases, the ability to rapidly collect observations using ocular assessments at a wide variety of sites with sufficient accuracy is more valuable for informing fire managers than collecting more accurate data at fewer sites. Similarly, in the field of citizen science, researchers have shown that there is a balance of data quantity and data quality, where if appropriate tools are used for analysis, large datasets can lead to new insights and the formation of novel scientific hypothesis for testing (Kelling *et al.,* 2009; Hochachka *et al.,* 2012).

The concept of making rapid ocular assessments with little previous training to collect observations of sufficient accuracy to inform forest fuels management decisions was the inspiration for the Forest Fuels Application. The Forest Fuels Application provides a platform that uses mobile device technology to rapidly collect and share ocular estimates of forest fuels loading of sufficient quality and quantity to be useful to estimate forest fuels loading and be accessible to people with a wide range of experience.

PPSR in forest fuels

Several factors influenced the development of a PPSR application for forest fuels. First, in terms of outcomes for science and management, one of the greatest challenges in measuring forest fuels is collecting measurements of sufficient resolution to capture the wide range of within-stand variation, with sufficient temporal resolution to capture rapid changes in stand structure (for example due to forest succession or windfall in a storm), and covering a broad spatial extent (Keane 2001). Keane *et al.,* (2001) identified the most comprehensive forest fuels mapping effort ever completed was by Hornby (1935), where approximately 90 Civilian Conservation Corps workers traveled to forested areas and coloured in polygons on paper maps to record fuels conditions in 60 million hectares to inform fire suppression efforts. This approach was an inspiration to implement methods of forest fuels data collection on mobile devices that allow rapid collection and integration to an even larger (and rapidly growing population) of people with mobile devices.

Another motivation for implementing an application for PPSR for forest fuels were the possible outcomes for management and the individuals that participate. Previous research demonstrated that public acceptance of wildfire management activities is related to public knowledge of wildfire topics (Martin *et al.,* 2007) and trustworthy citizen-agency relations over time (Toman *et al.,* 2006b). The application was developed to provide a way for citizens to work together with fire managers, potentially increasing understanding of wildfire topics, and potentially build trustworthy citizen-agency relations by providing an opportunity to work together towards a common goal, build an understanding of the constraints of making forest management decisions, and foster a sense of shared responsibility by including public participation in the outcome of management decisions. The final motivation was to provide a tool that makes a greater amount of information about forest fuels and assessing wildfire threats accessible to a wide audience.

A.2 Collaborations and consultations

Committee

The committee was formed to include a range of expertise and interests. Dr. Nicholas Coops, research supervisor, is an expert in remote sensing and was the driving force and visionary for using smartphone data collection for Earth observation. Dr. Howard Harshaw is a social scientist who was included on the committee to help understand the social aspects of using smartphones to collect data by volunteers within the context of forest management topics. Dr. Robert Kozak is a forest scientist focused on social science, with expertise in data analysis, and was influential in the approaches used to design and analyzing the questionnaires. Dr. Mike Meitner has expertise in GIS and social applications of GIS (GIS and society); his expertise was invaluable for identifying the research objectives of comparing experts and non-experts in data collection and data informatics, data integration, and data synthesis topics.

Consultations in other departments.

• As part of the app development Ferster and Coops met with Dr. David Lowe (UBC Department of Computer Science) to discuss the potential to extract forest metrics from the imagery acquired using the mobile devices using computer vision and image analysis. Dr. Lowe discussed possible approaches and described how to build a data set for testing and methods of exploring approaches for extracting metrics, such as the "bag-of-words" and nearest neighbor approaches using histograms of the images and reference libraries. These approaches were explored and prototypes were built that featured human-in-the-loop tasks on the mobile device (e.g. setting thresholds in images and identifying features to improve classification accuracy), however, the research priorities were set to focus on the simpler rapid ocular assessment techniques and evaluating ways to apply mobile data collection within the context of forest resources management. The computer vision assessment was identified as a topic with considerable potential for future research, given that suitable constraints are placed on the images that are analyzed (i.e. removing background noise).

• Additional consultation meetings were held with Dr. Sidney Fels, Dr. Roger Lea, and Dr. Mike Blackstock from the Media and Graphics Interdisciplinary Centre (MAGIC) at UBC to present the work and discuss research areas. Dr. Fels suggested using game elements in the non-game context of forest fuels management (gamification) to provide motivation and potentially change behavior. To further explore the idea, an online course on gamification topics was completed (all lectures and assignments) at Coursera.org (an eight-week online course completed 27 August 2012) and strong consideration was given of how game elements could be incorporated into the Forest Fuels App. Other researchers have shown that game elements can help sustain participation in citizen science projects, however, previous research also indicated a limited ability to recruit new participants, which was identified as a higher priority for this project (Han *et al.* 2011; Iacovides *et al.* 2013). Had this project been carried forward on a more sustained basis, this collaboration would have been perused and game elements may have been explored to sustain participation. In several of the chapters, this topic was mentioned as a future research priority.

• Implementation meetings were also held by Ferster and Dr. Jon Corbett at UBC Okanagan Department of Community, Culture, and Global studies at UBC Okanagan. Dr. Corbett is a geographer with experience in participatory web maps related to fire in the Okanagan. A range of topics were discussed, including feedback on the application and experiment design.

Consultations beyond UBC

• An early prototype of the application and the experiment was presented at the Canadian Association of Geographers (CAG) and Canadian Remote Sensing Society (CRSS) meeting in 1-5 June 2010 in Regina, Saskatchewan. There, discussion was held with a range of people with experience working with VGI, and people working in industry designing navigational devices.

• The work was also presented at a citizen science symposium at the American Ornithology Union (AOU) annual meeting 24-29 July 2011 in Jacksonville, Florida. Feedback and discussion were presented about the application, experiment design, and notably the integration of citizen science data with remote sensing data and the complimentary roles and the role within the broader context of Earth observation. Notably, extensive discussion was held with Dr. Wesley Hochachka, an ecologist at Cornell Lab of Ornithology specializing in large scale spatial and temporal analysis, working on the successful eBird project. Contact was also made with Dr. Janis Dickinson, the head scientist for the eBird project.

Valhalla consulting

Funding for the development of the application and acquisition of the devices was provided through a National Sciences and Engineering Council (NSERC) Engage grant to Coops and Ferster with the industrial partner of Valhalla Consulting Ltd., a forest consulting company located in Coldwater, BC. The proposal covered meetings with Valhalla Consulting to discuss directions for development of the application and roles it could play in wild land fire management in British Columbia, as well as travel to the dry and fire-prone interior regions of British Columbia to test and provide feedback on an early version of the application. These steps are described in the following sections.

Application design

• A meeting was held with John Davies, R.P.F., a recognized expert in forest fuels management in British Columbia from Valhalla Consulting to discuss the potential design and the role of the application in forest fuels management in BC.

• Davies summarized and reviewed the relevant publications in British Columbia, including professional materials ("Rating Interface Wildfire Threats in British Columbia" Morrow *et al.,* 2008), and materials targeted to homeowners ("The Partners-in-Protection Firesmart Manual for Homeowners" Partners-in-Protection 2013).

• West Kelowna as a current priority area in his work and suggested that early prototypes could be tested there because it would be possible to visit sites with a range of conditions.

• Davies mentioned that he is often asked to drive to a private residence, meet with concerned citizens, and discuss a wildfire threats on private property.

• Davies suggested that a useful application would provide a way for concerned citizens to take pictures of fuels conditions, answer a few key questions, and submit a brief report by email. Then further contact could follow with discussion over phone, and Davies suggested that in a lot of cases it may save a trip to the field site.

• Davies described portable computing devices that are used by his crews (for example, the Trimble Juno) that integrate a camera, GPS, and worksheet for data entry. It was discussed how modern mobile devices, such as smartphones, could reduce the cost and provide more features for forestry crews than the present mobile devices being used.

• Davies agreed to provide a database of images and measured stand conditions near the study area to help build the visual guide for the application.

A.3 Early prototype

An early prototype was designed using web design tools including hyper text markup langue (html), cascading style sheets (css), javascript, and the JQuery library (http://jquery.com/) to deliver the interface through the web browser of a smartphone (Figure A.3.1). The prototype was developed to include all of the forest fuels components in (Morrow *et al.,* 2008) (Figure A.3.2). The strength of this approach was that it facilitated rapid design and deployment for feedback, and could be run on multiple platforms. The disadvantage was that it provided limited access to the low level functions of the device such as the camera, accelerometer, and GPS, running the application from the cache was unreliable (and therefore required network connectivity, which is not always available in the forest), and there was limited data storage potential. Data transfer was accomplished by composing an email message with a string of values that could later be parsed by a Python script (Figure A.3.3). To increase reliability, the PhoneGap (http://phonegap.com/) application was used to compile the web application as a native iOS application for field testing. This improved reliability and allowed testing where network coverage was not available, however, data storage and access to low-level device functions such as the compass and inclinometer was still limited, as was data storage. At this stage, sufficient reliability using the JQuerry web application compiled using phone gap to begin field testing and making interface refinements.

Figure A.3.1 Early prototype (a) main menu, and (b) site information, GPS, and image acquisition.

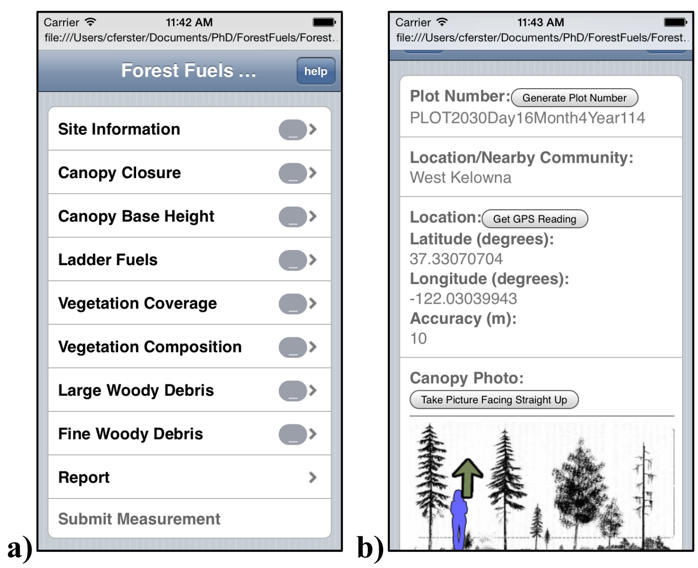


Figure A.3.2 Early prototype (a) conifer crown closure and (b) canopy base height.

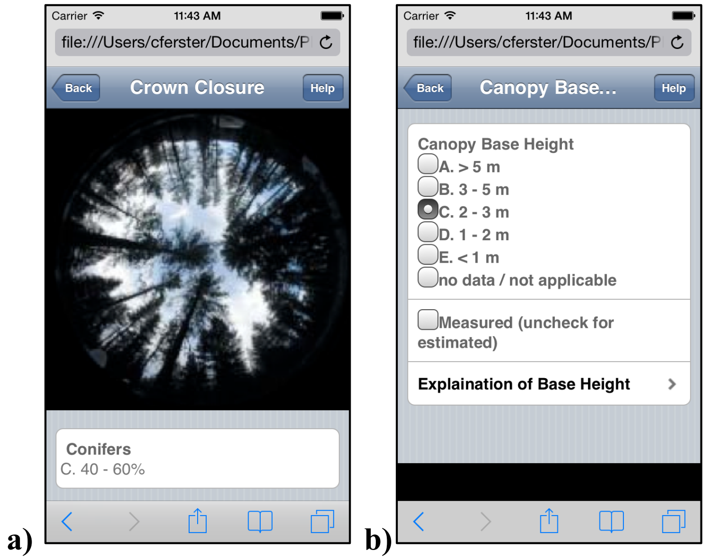
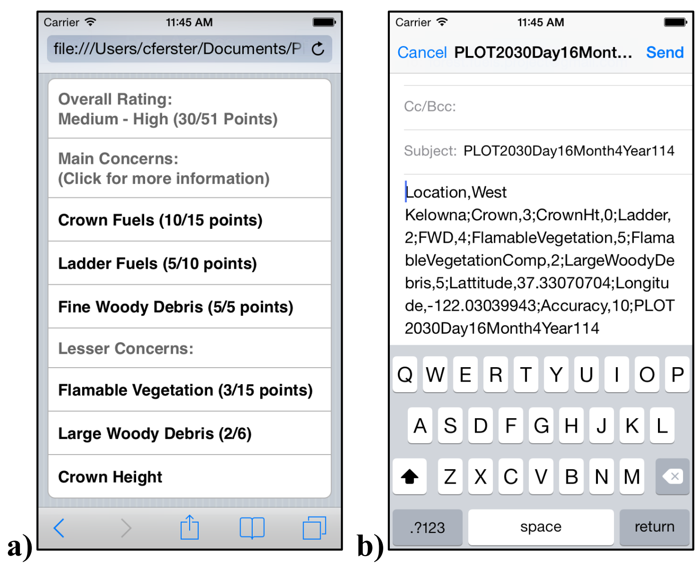


Figure A.3.3 Early prototype (a) report on fuels conditions and (b) data transfer by email.



Early testing and feedback

• A meeting was arranged on 29 March 2011 with John Davies and Andrew Hunsberger of Valhalla Consultants to test the early prototype. The meeting took place in the field in a stand that had been treated to reduce and modify forest fuels loads, and a nearby stand that had not yet been treated and had a potentially threatening fuels load (Figure A.3.4).

Figure A.3.4 Field testing the early prototype in West Kelowna, BC.

For the duration of the day, different field sites and loading conditions were visited and preliminary data was collected. Recommendations were provided for the application (Table A.3.1).

Table A.3.1 Comments from Valhalla Consulting Ltd. about early prototype.

Topic	Comment	Response
Photos	Photos: good concept with the up/down/horizontal directions. Suggest the following options: • Leave as is but add one more photo horizontally • Just have room for four horizontal photos in this section to get an idea of the general stand description, then move the up one section (and allow for more than one photo…at least two…with instructions for the assessor to move and take another photo) and the down photo to the FWD and CWD sections (and allow for more than one photo) with instructions for the assessor to take photos of the relevant woody debris for that assessment.	Modified to take four horizontal photographs (following second suggestion). Six photographs at full-resolution are large to send via email (~20 mb).
Conifer crown base height	As we discussed, given this is a measurement, perhaps this should have the instructions for measurement first and then a tab to see photos of examples.	Completed as suggested
Surface vegetation	Photo with snow is no good. Some of the pictures are tough to use because they are from a distance. As discussed, I think it would be better to have a planar view of a one sq meter plot showing different veg cover %ages. Or perhaps something similar to the crown closure diagrams that are available on the back cover of most Duksbak field books? I believe these diagrams are also available online…?	Moved to abstract surface cover diagrams (like in the back cover of Duksbak field binder).
Large woody debris	Need closer pictures. Manning Park would provide some very good photo opportunities for large woody debris photographs.	Moved to a synthetic fuel reference photo set (similar to FWD). A future goal is to acquire better LWD images.
Fine woody debris	I like the FWD photos. Perhaps, over time, photos of the percentages could be collected in the field.	Great idea. This could also apply to the other components.
Tally	It would be helpful if after the sum the total value was presented or flashed on screen as well as the rating (L, M, H, etc).	Redesigning the reporting feature.
Android/Apple	I think the system should not be restricted to Apple products. It would be excellent to use it on some of the tabs that are on the market (including iPad) as the larger viewing screen would make it easier to use.	Strongly agree. The challenge is that targeting other platforms means investing exponentially in more development time. Tablets are very well suited to the task.

A.4 Development in iOS

Following the meetings with Valhalla Consulting Ltd., the application interface was refined and implemented using the Objective C language, in the Apple Xcode environment, for iOS 6.0. The application was developed using a series of generalized views that include user interface elements such menus and buttons (for clarity, Figure A.4.1 shows an abstract an abstract representation of the views, and Figure A.4.2 shows the actual implementation in Xcode) to dynamically deliver forest fuels assessment content (Figure A.4.3). Compared to the previous implementation, the iOS native implementation included slides to introduce the topic to new users, a more robust database to store collected data and allow data collection at multiple site with the ability to review and manage information collected, tools that utilized lower level and a refined user interface.

Figure A.4.1 Views for the forest fuel application. Arrows indicate the ability to move from one view to another. Data is dynamically delivered to generalized user interface views.

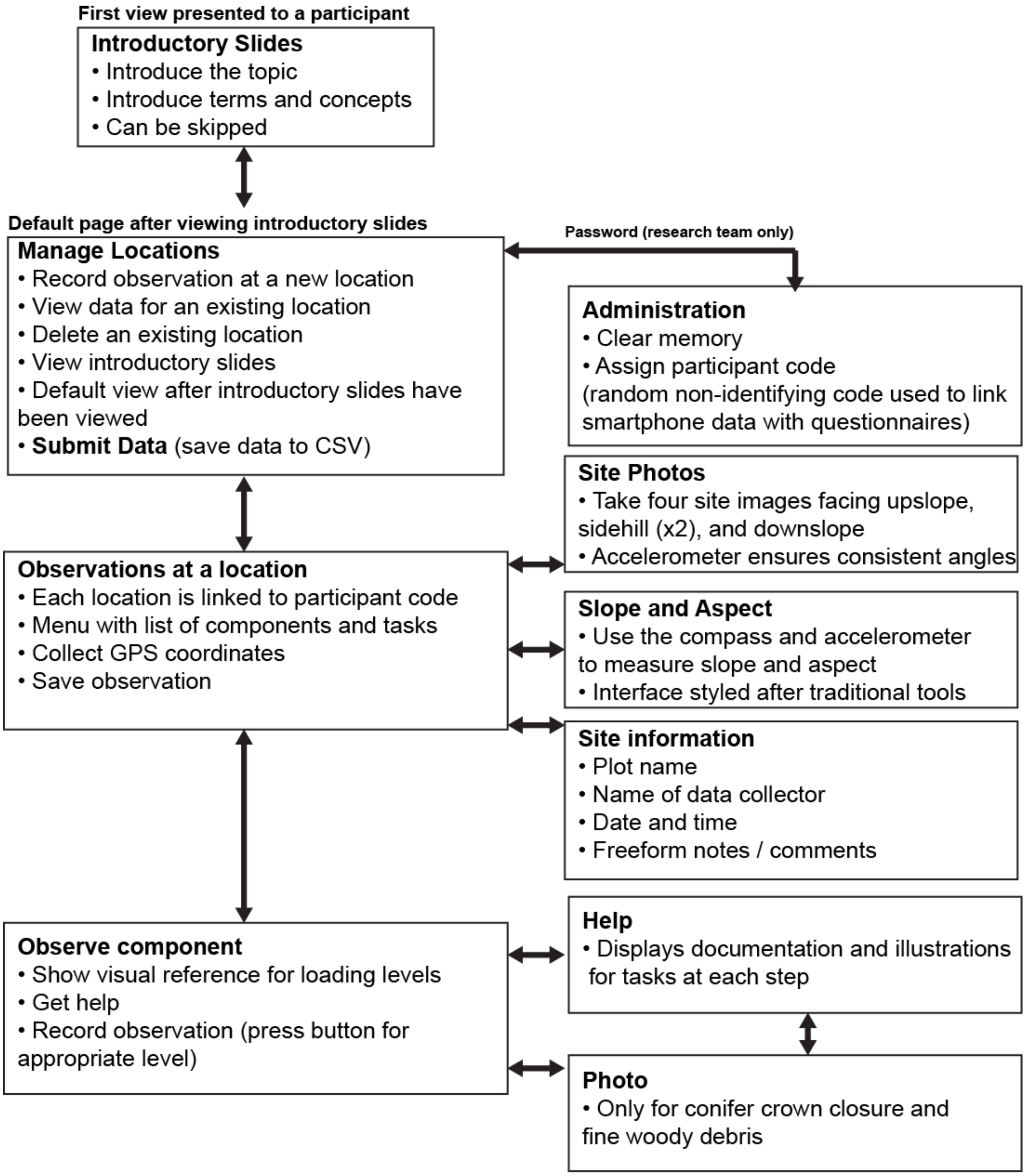


Figure A.4.2 User interface design for the forest fuels application. Data is dynamically delivered to generalized user interface views.

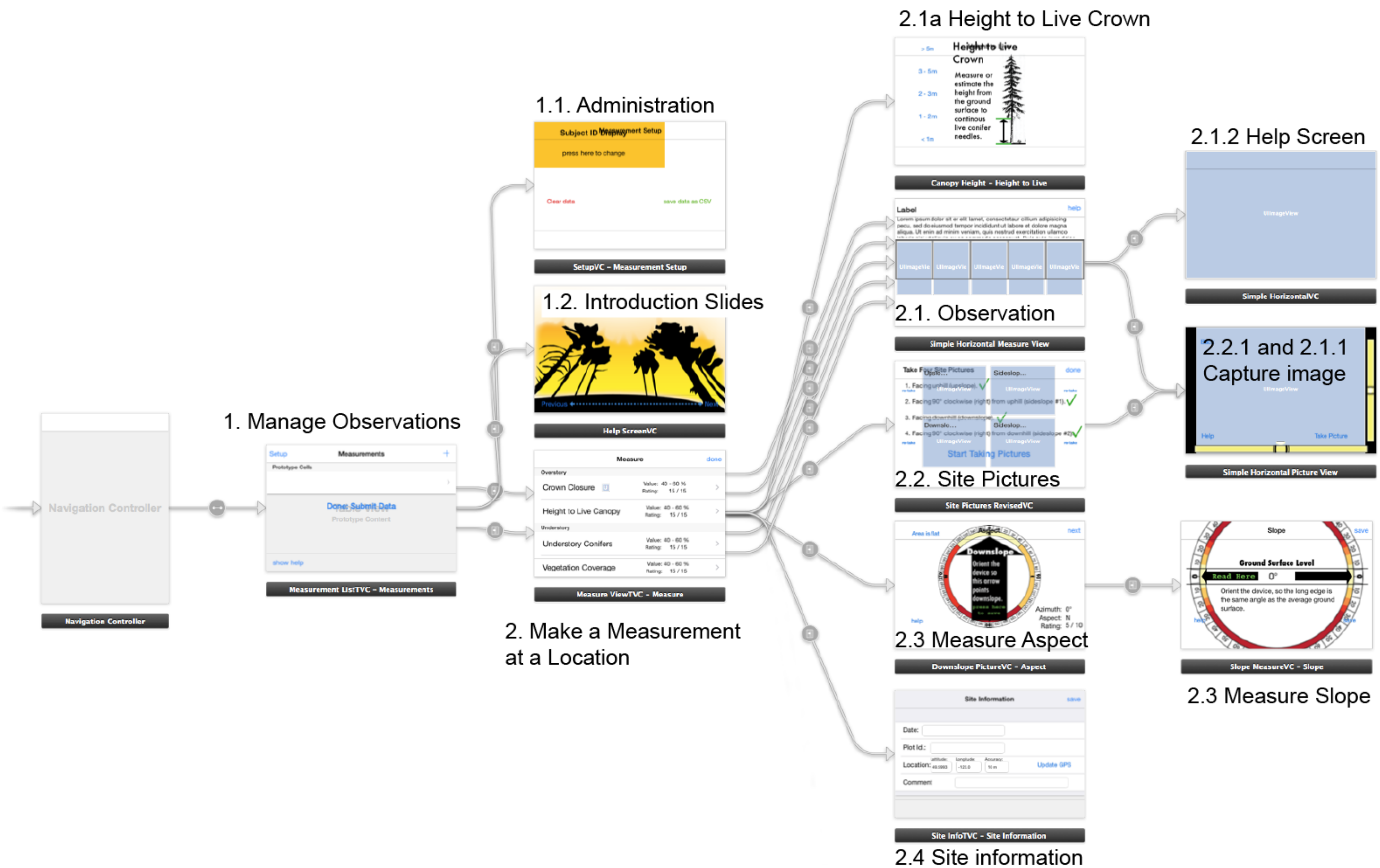
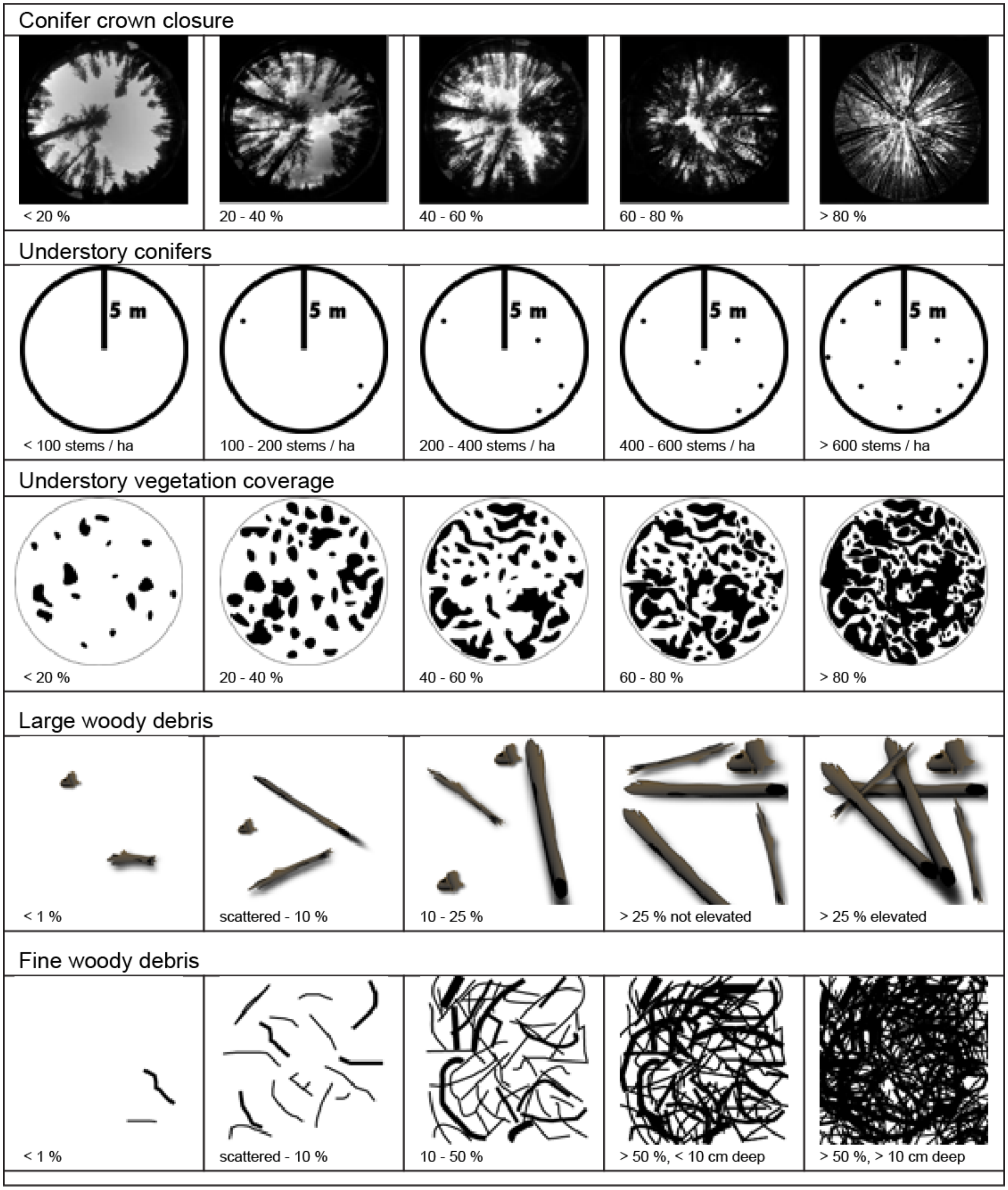


Figure A.4.3 Forest fuels loading reference images that are delivered dynamically to the generalized views.



During the forest fuels experiment, participants tested the application in conjunction with completing two questionnaires (one before and one after using the application to collect forest fuels loading data). Participants were accompanied by at least one person from the research team. Due to the non-linear links between the various views, the exact steps may not be the same for every participant, however a likely order is presented in Figure A.4.4. Screen captures of the application following this likely order is presented in Figure A.4.5 through Figure A.4.18 with descriptions of each screen in the caption.

Figure A.4.4 Tasks performed by researcher and participant during the Forest Fuels App experiment. The order of tasks is implied by the order of the menus; however, for some of the tasks, the order need not be followed exactly.

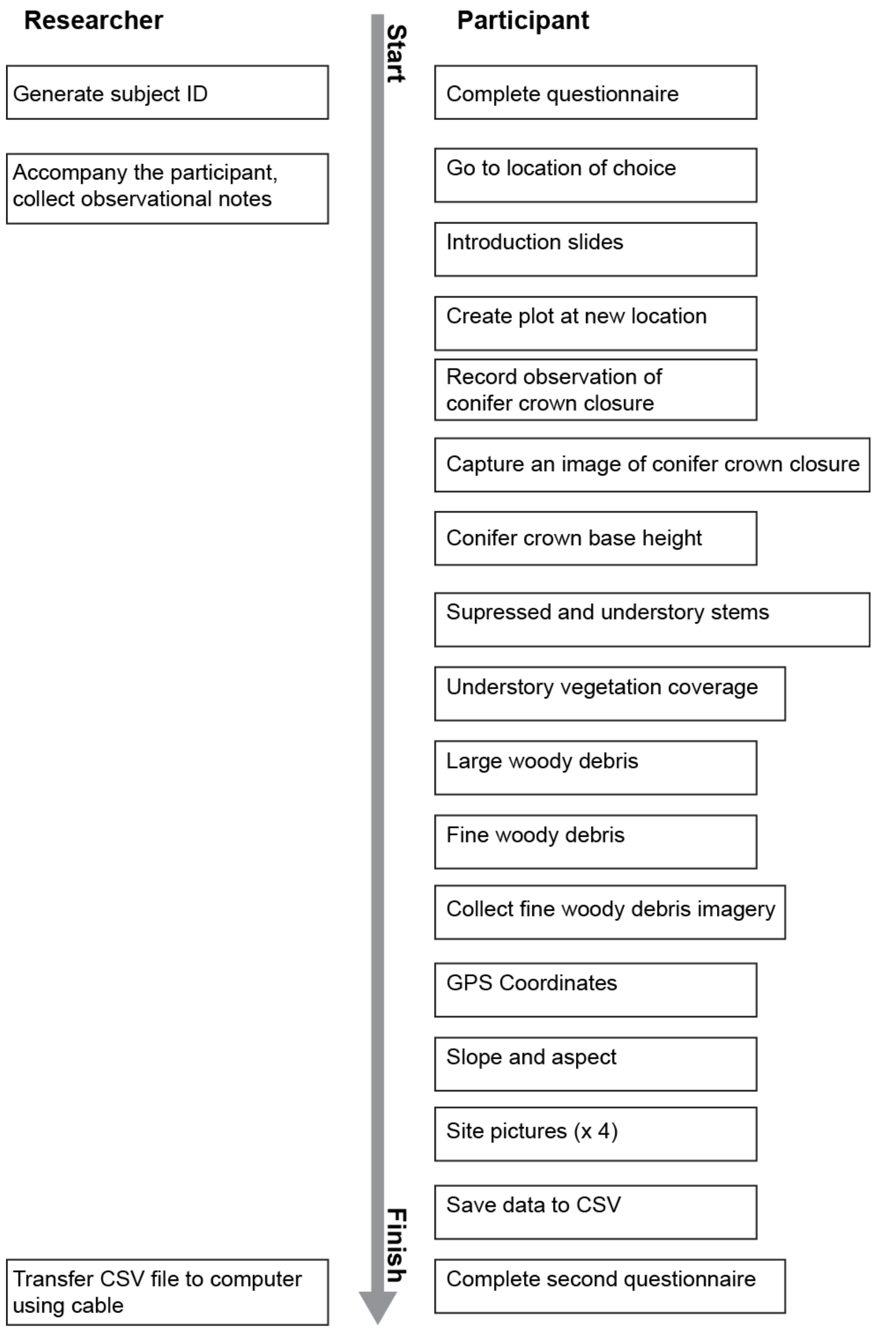


Figure A.4.5 Forest Fuels Application splash screen.

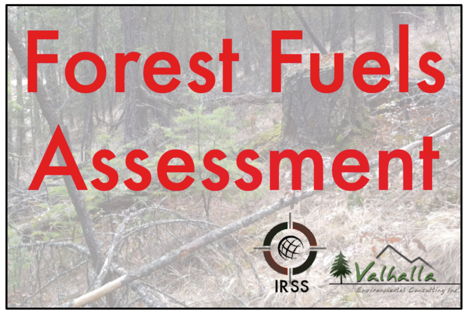
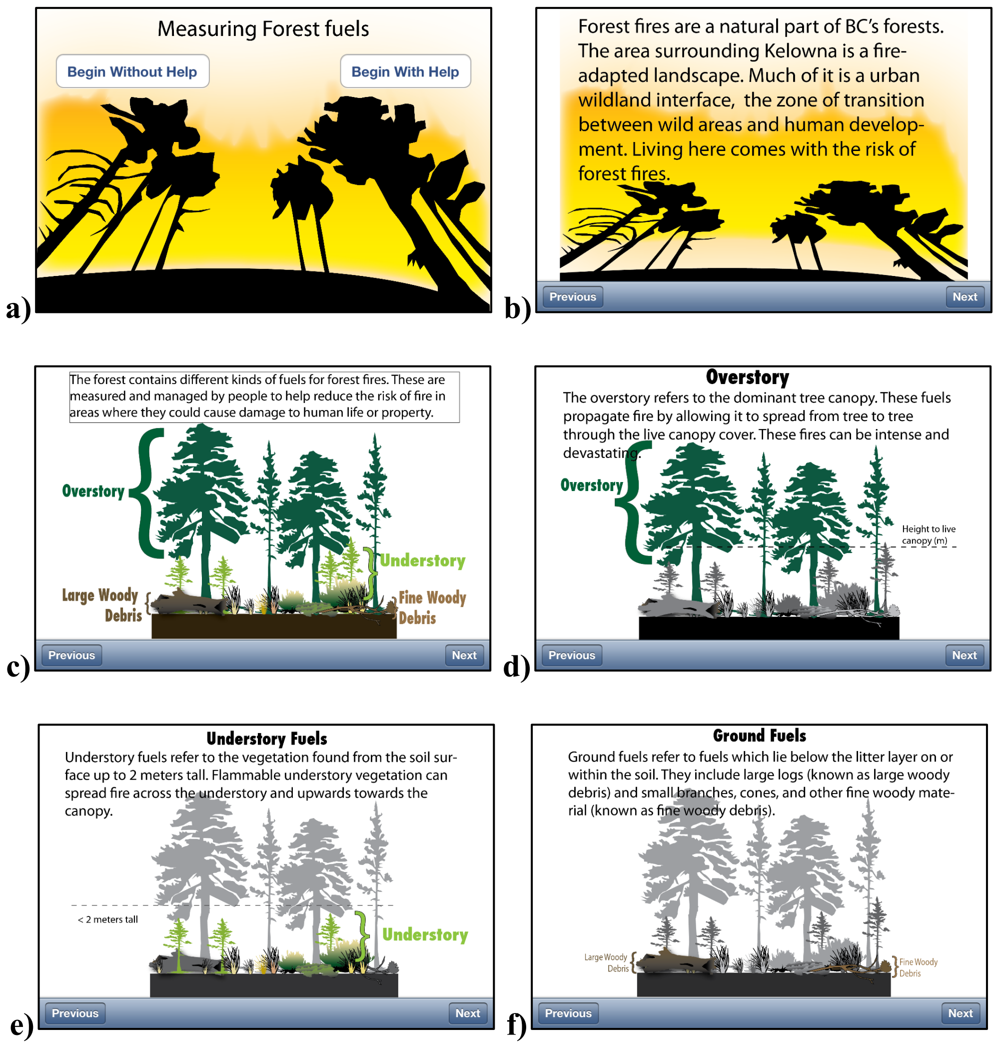
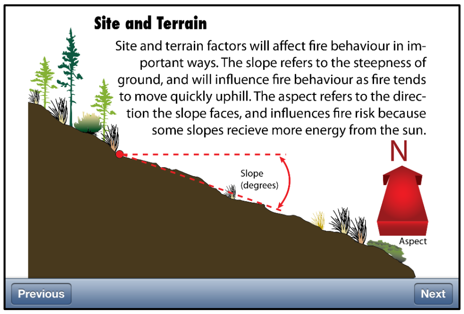


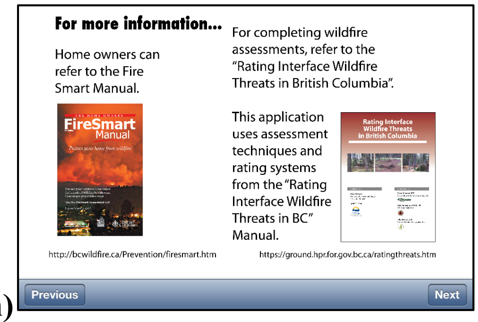
Figure A.4.6 a-i Slides to introduce the topic and provide background information to new participants.



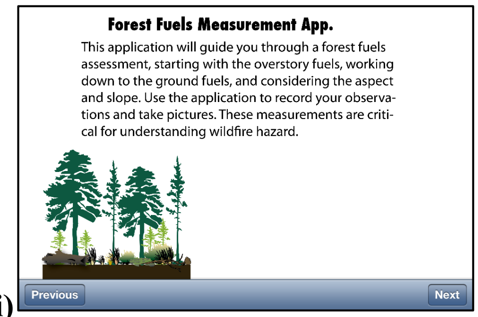
(figure continues on next page)



g)



h)



i)

Figure A.4.7 Administration view. This tool creates a subject ID to link the smartphone data to the questionnaire data, ensure that a csv file is saved for each participant, and clear the data for the next participant. The random non-personally identifying ID is based on the date and time and a randomly generated number.

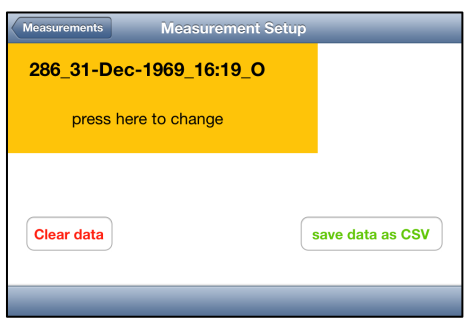


Figure A.4.8 From the location management screen a participant can add new locations (a), and view, delete, or submit data for already collected observations (b).

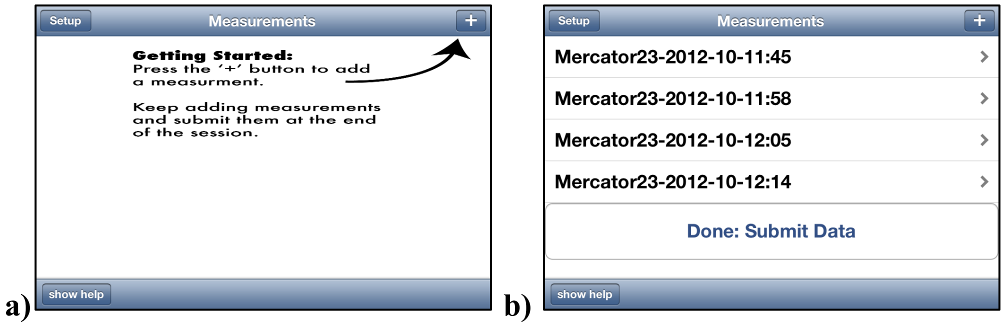


Figure A.4.9 From the make an observation screen (a), a participant can select components to make observations. As the observations are collected, colours and ratings are displayed based on the assessed hazard from Morrow *et al.* (2008) (b).

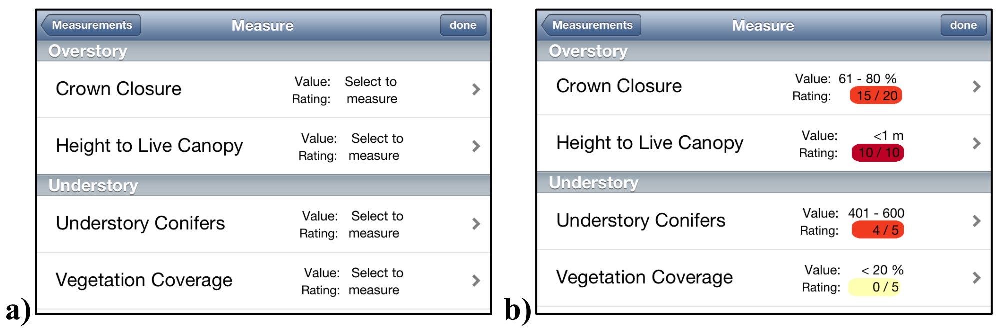


Figure A.4.10 Conifer crown observation (a), help (b), directions for image acquisition (c), and image acquisition (d). Note the accelerometer is used to ensure a flat orientation, and the interface styled after bubbles on a construction level provide feedback to the participant.

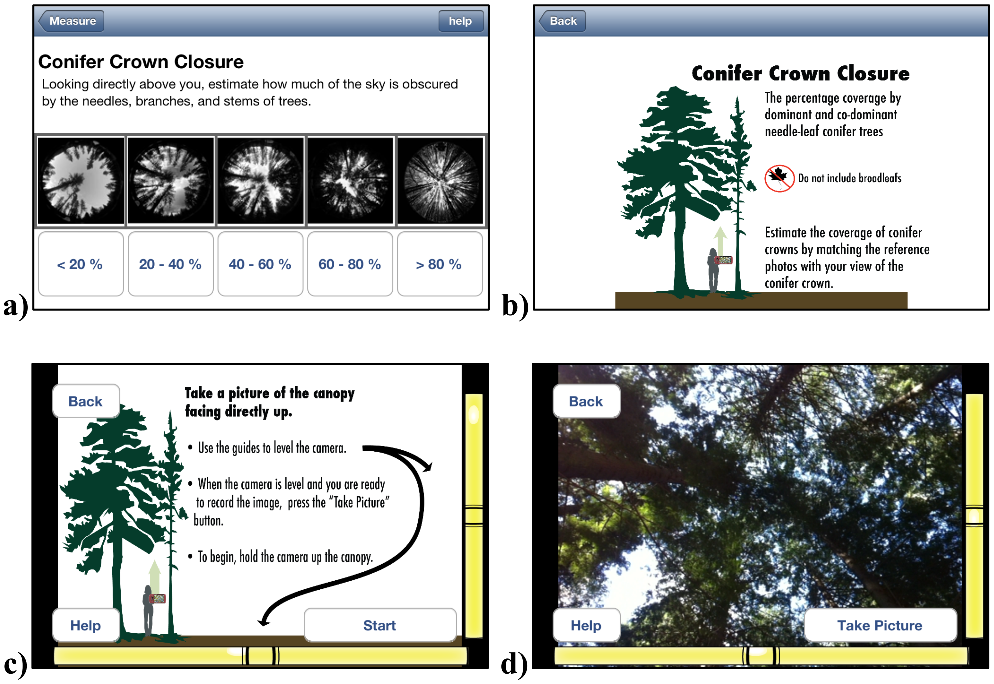


Figure A.4.11 Height to live crown observation recording.

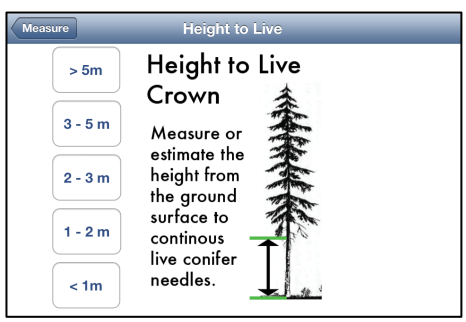


Figure A.4.12 Understory conifers observation (a), and help (b).

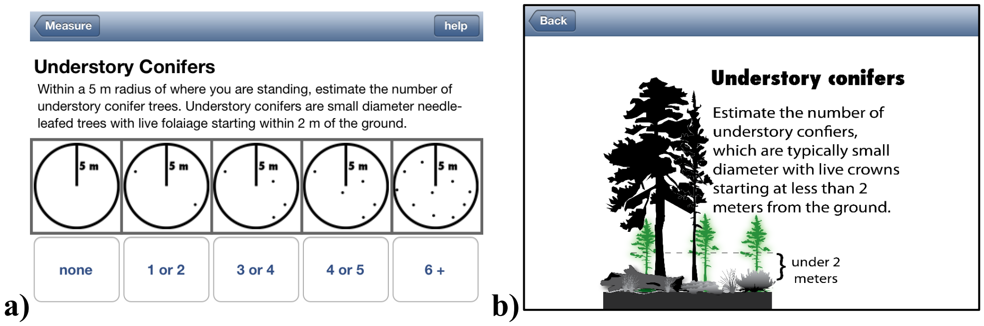


Figure A.4.13 Surface vegetation coverage observation (a), and help (b).

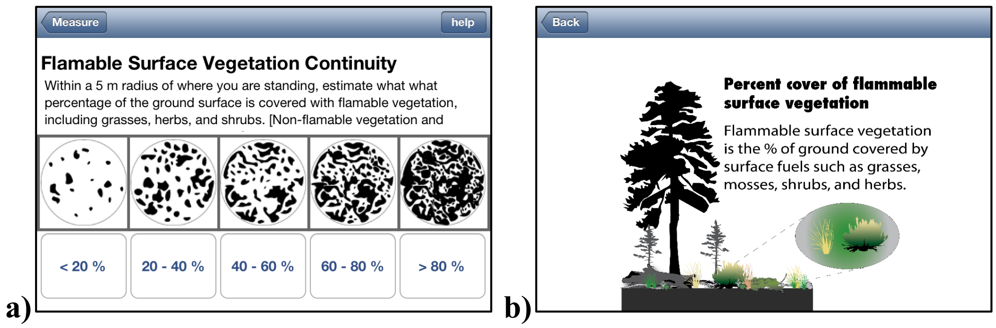


Figure A.4.14 Large woody debris observation (a) and help (b).

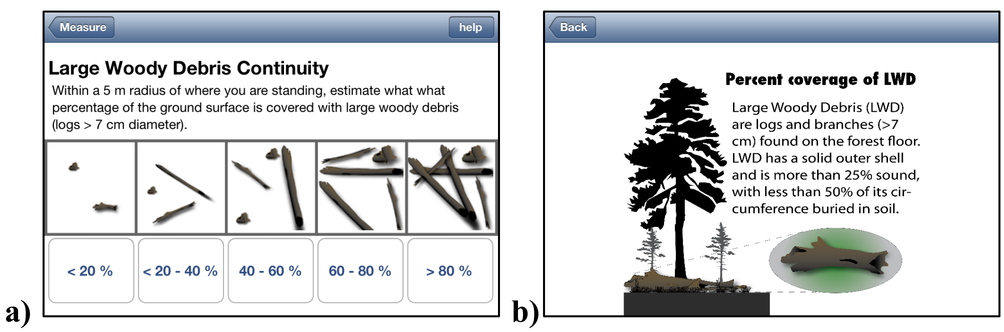


Figure A.4.15 Fine woody debris observation (a), help (b), (c) directions for image acquisition, and (d) image acquisition.

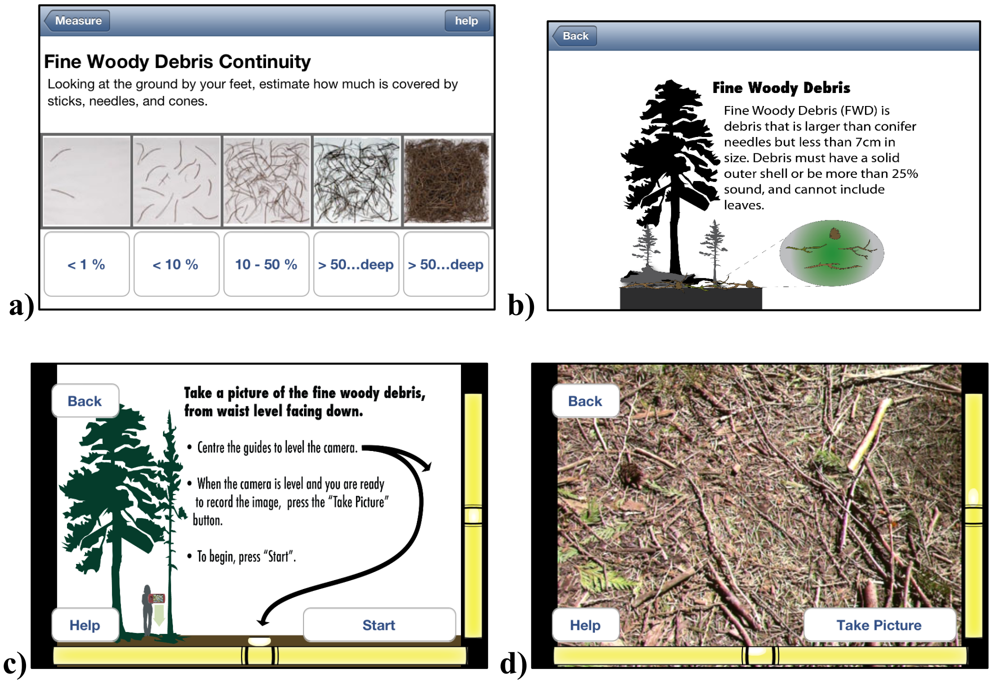


Figure A.4.16 Site information (a) capture GPS coordinates, and (b) date, plot name, location description, and free-form comment.

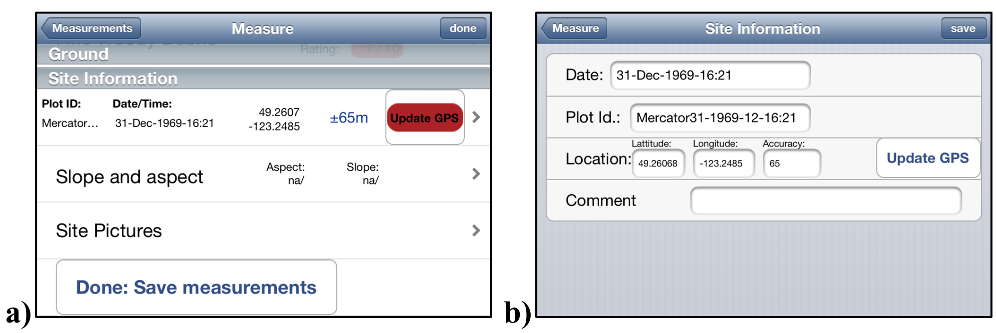


Figure A.4.17 (a) Measure aspect, (b) aspect help, (c) measure slope, and (d) slope help.

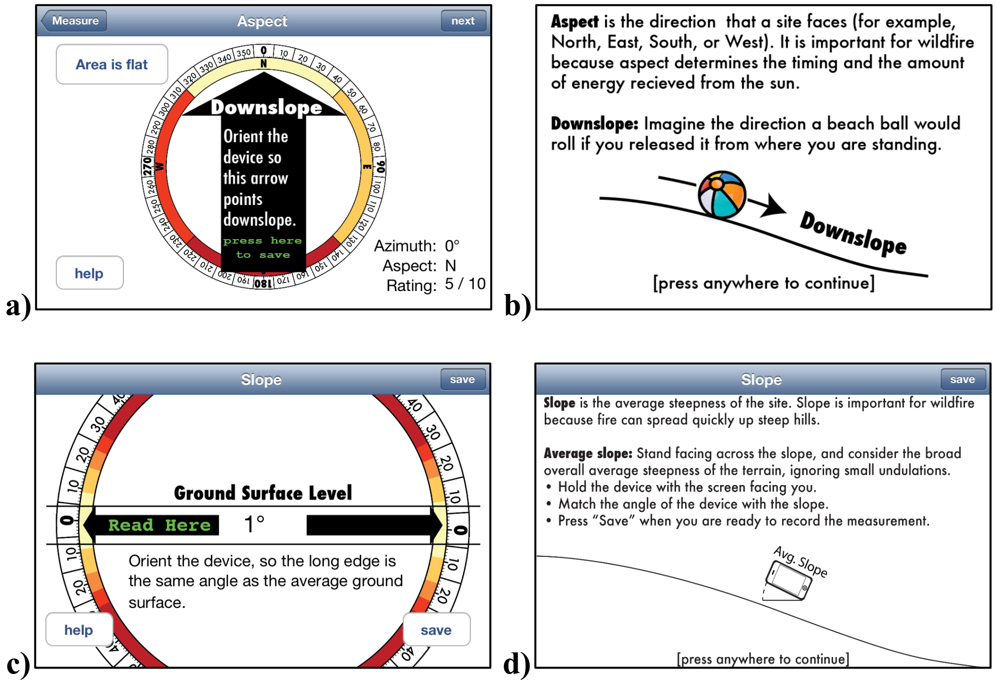
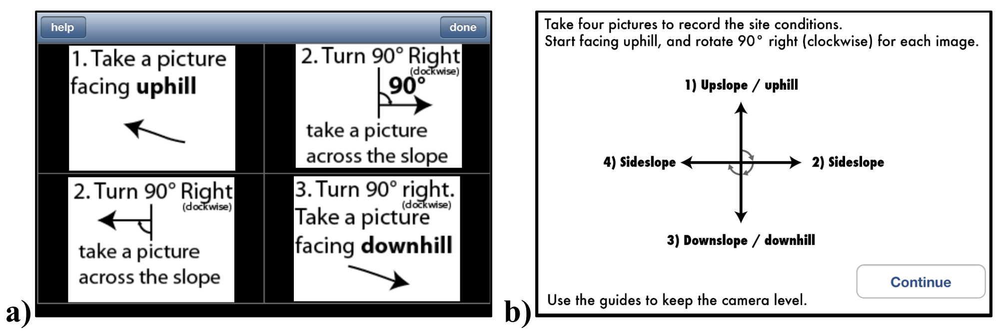


Figure A.4.18 (a) Site pictures management, and (b) help. Site picture management links to camera view with accelerometer instructions to hold the camera directly out (90° to gravity).



Data storage was implemented in iOS Core Data (Table A.4.1). Each observation collected formed one row in the database. To export the data, the participant pressed a button to generate a CSV file of all of the observations they had recorded. The generated data (Figure A.4.19 - CSV file and JPEG images) were exported by the research team by connecting the device to a computer using a cable and copying the files (Figure A.4.20).

Table A.4.1 Database fields. Due to the simple data structure, no relationships were used.

Attribute	Data Type	Description
aspect	Integer	Code for aspect category
aspectDescription	String	Text description of aspect (*e.g.,* North)
aspectPoints	Integer	Points towards overall fire rating
canopyClosure	Integer	Code for conCrownBase Category
comment	String	Free form text comment
conCrownBase	Integer	Code for conifer crown base height
conCrownBaseDescription	String	Text description for conifer crown base (*e.g.,* 5 m)
conCrownBasePoints	String	Points towards overall fire rating
conCrownClose	Integer	Integer code for conifer crown closure
conCrownCloseDescription	String	Text description of rating
conCrownClosePoints	Integer	Points towards overall fire rating
conCrownPict	String	File name of image of canopy closure
dateTime	String	Date and time of observation
downSlopePict	String	File name of downslope image
fwdCont	Integer	Integer code for fine woody debris
fwdContDescription	String	Text description of rating
fwdContPoints	Integer	Points towards overall fire rating
gpsAccuracy	Float	Device reported GPS accuracy
gpsTime	String	Date and time of GPS measurement
lattitude	Float	Lattitude from GPS
longitude	Float	Longitude from GPS
lwdCont	Integer	Integer code for large woody debris
lwdContDescription	String	Text description of rating
lwdContPoints	Integer	Points towards overall fire rating
plotID	String	Plot name (randomly generated)
sideSlopePict1	String	Filename of sideslope image
sideSlopePict2	String	Filename of sideslope image
slope	Integer	Integer code for observation
slopeAngle	Float	Slope angle in degrees
slopeDescription	String	Text description of rating
slopePoints	Integer	Points towards overall fire rating
subjectID	String	Random, non-personally-identifying subject code
supUndConf	Integer	Integer code for observation
supUndConfDescription	String	Text description of rating
supUndConfPoints	Integer	Points towards overall fire rating
surfVegCont	Integer	Integer code for observation
surfVegContDescription	String	Text description of rating
surfVegContPoints	Integer	Points towards overall fire rating

Figure A.4.19 Data generated by the application.

Site Images x 6 (JPEG format)

- Conifer crown closure
- Fine woody debris
- Upslope
- Sideslope
- Sideslope
- Downslope

CSV File x 1 (Observations)

- Participant ID
- Plot ID (randomly generated)
- Device name
- Date and time

- GPS Coordinates
- File names for images

- Conifer crown closure
- Height to live conifer crown
- Suppressed and understory conifers
- Surface vegetation coverage
- Large woody debris
- Fine woody debris

Figure A.4.20 Sample output from application. At each observation location, six images were collected and one row in the CSV file is generated.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	subjectID	plotID	fwdCont	lwdCont	surfVegCont	vegFuelComp	supUndConf	conCrownBase	conCrownClose	lattitude	longitude	gpsAccuracy	aspect	slope	terrain	slopeAngle	canopyClosure	dateTime
2	484_10-Aug-2012_11:28_S	p0	3	1	2	2	3	2	2	49.93769	-119.3931	5	-999	-999	-999	0	42.09028	10-Aug-2012-11:38
3	807_10-Aug-2012_11:23_S	p143	4	1	4	4	3	2	2	49.93796	-119.3938	5	5	1	-999	8	49.20313	10-Aug-2012-11:23
4	484_10-Aug-2012_11:28_S	p524	5	1	5	4	5	2	2	49.93726	-119.3924	5	-999	-999	-999	0	55.21701	10-Aug-2012-11:52