Use of Location-Sharing to Increase Situational Awareness and Improve Occupational Safety in Operational Forestry

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Situational awareness is imperative to maintaining safe workflow conditions on logging operations. Occupational injury and fatality risks are high for loggers, especially ground crew who work alongside highly mobile hazards like heavy machinery, or work in isolated conditions where injury response may be delayed. Situational awareness may be enhanced with location-sharing (LS) technology that allows users to send GNSS (Global Navigation Satellite System) coordinates to others, such as coworkers at a jobsite. To evaluate the potential success of LS to improve logging safety, we assessed a) device efficacy and accuracy through operational sampling and a controlled field experiment, and b) logger acceptance and adoption of LS technology through a survey of certified, Idaho loggers. First, using real-time, military-grade LS devices at three active logging operations, we were able to characterize rigging crew positions relative to three operational hazards. Ground crew spend approximately one third of the work day in potentially dangerous areas associated with machinery and equipment and about half of each day near snags. Simulated GNSS error associated with mature stands significantly impacted definitions of safe work distances, however, indicating a need for caution when using LS for proximity awareness, especially under forest canopy. Survey results indicate loggers perceive safety benefits to employing LS devices on logging operations, especially for injury response scenarios, such as alerting coworkers of an emergency and finding injured persons quickly. Loggers indicated intent to adopt safety practices involving location sharing, which is a strong indicator of action according to the Theory of Planned Behavior. Study results encourage further development of LS applications for logging safety but advise for recommendations outlining appropriate uses.

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This research could not have been completed without the support and participation of Idaho loggers. I owe thanks to Potlatch Corporation and the Idaho Department of Lands for permitting us to conduct operational sampling on their timber sales, and to the logging contractors who graciously used our transponders and allowed us to observe their daily operations. I would also like to thank the loggers who completed our survey at the Logger Education to Advance Professionalism update meetings in Lewiston, St. Maries, and Sandpoint.

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DEDICATION

I am eternally grateful for my supportive parents, David and Anita Kjellerson, and for my encouraging husband, Sean Wempe. I can always count on these people to believe in me, especially during those times when I most doubt myself. Thank you, Mom, for sharing your love of learning, and thank you, Dad, for sharing your love of the natural world, both of which have sculpted the woman I am today and have inspired my current graduate pursuits. Also, thank you, Sean, for your steadfast love, reassurance, and counsel throughout my graduate career and in all things.

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LIST OF ABBREVIATIONS

GNSS	Global Navigation Satellite System
GPS	Global Positioning System
JLP	John Lewis Pole
NIOSH	National Institute for Occupational Safety and Health
LEAP	Logger Education to Advance Professionalism
LS	Location Sharing
OSHA	Occupational Safety and Health Administration
PBC	Perceived Behavioral Control
PLD	Personal Location-Sharing Device
RF	Radio Frequency
RMSE	Root Mean Square Error
TPB	Theory of Planned Behavior
UH	Upper Hatter
WTS	Wash Trap South

CHAPTER 1: INTRODUCTION: LOCATION SHARING FOR LOGGING SAFETY

Logging continually ranks among the most dangerous professions in the United States, with workers facing high occupational fatality rates (BLS CFOI 2015; Fosbroke et al. 1997; Sygnatur 1998). According to workplace injury accounts, trees, logs, limbs, and machinery striking individuals cause the majority of workplace fatalities (Bell and Helmkamp 2003; BLS OIIFIP; Shaffer and Milburn 1999). Fatal injuries are more likely on partially-mechanized operations, which rely on ground workers rather than machines for manual tree felling and delimbing (Shaffer and Milburn 1999). While mechanization affords protection for the operators enclosed in machine cabs, exposure risk is increased for ground crew, especially for individuals at the landing, who work alongside highly mobile hazards including dragged or swung logs in addition to heavy machinery such as loaders, skidders, or log trucks (Bordas et al. 2001; Lefort et al. 2003). Hazards and safety challenges vary by crew position. Hand fallers, who use chainsaws to cut down trees, work in isolated areas to maintain minimum recommended safety distances (OSHA Regulations). Although this distance affords them protection from heavy machinery, they still risk injury from chainsaws and environmental hazards, such as falling trees and limbs (Bell 2003; Scott 2004). Emergency response may be delayed for secluded workers, though, if injury occurrence and location are not immediately recognized by coworkers.

Steep slope harvesting common throughout the Pacific Northwest of the United States typically utilizes cable systems which, similar to partially-mechanized, ground-based systems, employ both heavy machinery and ground crew. Common ground positions include choker-setters, colloquially known as hookers, who hook felled trees to the cable system, and chasers, who unhook trees at the landing. Steep slopes introduce new hazards for these workers, including rolling logs and snapped cables, as well as heavy equipment like the skyline carriage, which helps drag trees to the landing. All operations, whether ground or cable-based, share the need for vigilant situational awareness to promote safe workflow that minimizes collisions and maximizes response rates when injuries do occur.

Location sharing (LS) may provide a promising technological approach to improving logging safety by increasing situational awareness (Keefe et al. 2014). LS, at its simplest, enables users to send positioning information to others. A LS device determines its geographic coordinates with one or more satellite systems within the Global Navigation Satellite System (GNSS), including the United States' Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou, or Europe's Galileo. The device then relays its location, either locally through a radio frequency (RF) transmission or globally through satellite signals. LS may be one-way, such as with emergency response devices that report positions to a rescue center, or two-way, allowing local exchanges, such as among coworkers at a jobsite. Most LS devices are compatible with mobile devices, such as smartphones, tablets, or computers, for location mapping. Combined with real-time positioning and data transfer, LS technology could enable comprehensive visualization of a logging operation, compensating for line-of-sight limitations, especially on steep slopes or under dense canopy. Visual situational awareness could supplement audial communication achieved conventionally with two-way radios and signal horns, such as Talkie-Tooters (Rothenbuhler Engineering, Sedro Woolley, WA, USA).

The primary advantage of LS is the ability to connect individuals spatially, even in remote areas where wireless or cellular networks are unfeasible, but many LS devices feature additional capabilities with safety applications in logging. For instance, emergency situations could be communicated to coworkers through text messages or a help button, and isolated, injured workers, such as hand fallers, could be found quickly from automatic position updates transmitted at regular intervals. Additionally, virtual boundaries known as geofences could warn machine operators of worker proximity to dangerous work areas or operational hazards like heavy machinery. GNSS-based geofences recognize the presence of LS devices relative to their borders and can alert users of crossing events (Reclus and Drouard 2009). Geofence technology has already been successfully integrated into various industries, such as ranching (Anderson 2007; Butler et al. 2006; Umstatter 2011), conservation (Sheppard et al. 2015), and transportation (Reclus and Drouard 2009), to help resolve positional monitoring and restriction needs.

Two important considerations in the development of LS for logging safety are efficacy in forest conditions and acceptance by logging contractors. Experimental evidence of LS capabilities and limitations will be necessary to define appropriate and inappropriate uses of LS devices on logging operations. Successful implementation of the technology will predicate on acceptance and adoption by the logging community. If loggers do not perceive a need for safety improvements or believe LS can fill an important niche in logging safety, LS devices are unlikely to be used. Hence, evaluating logger perceptions of LS will be instrumental in guiding future studies, development, and outreach of specific logging safety applications.

Multiple factors, from atmospheric conditions to environmental features, influence the path and potency of satellite waves, and, subsequently, GNSS positioning accuracy. Free electrons in the ionosphere significantly attenuate signals (Parkinson and Enge 1996), and waves entering the troposphere face refraction and delay by particulates like water vapor and aerosols (Solheim et al. 1999; Businger et al. 1996). Positioning accuracy also relies upon the sensitivity of satellite equipment, such as the internal clock (Parkinson and Enge 1996), and upon the adequate presence of in-range satellites in predictable positions. On the surface, land and canopy features can block satellite signals, leading to a loss-of-lock, in which GNSS units lose connection with one satellite constellation and must locate a new arrangement (Liu and Brantigan 1995). Furthermore, the presence of multiple, reflective surfaces can lead to multipath errors, in which signals reflect off obstructions, travel indirect paths to the GNSS receiver, and arrive staggered (Larson et al. 2008).

The potential safety implications of positioning error should be evaluated, especially for fine-resolution applications, such as hazard proximity awareness with geofences. Characterization of ground workers' situational relationships with hazards and the estimated effects of canopy-induced, positioning error can help inform geofence best practices, such as geofence radii and types of hazards appropriate for delineation. In chapter two of this thesis, we quantified worker-hazard positional relationships based on GNSS-RF data collected at three active cable logging operations. We defined worker safety status dichotomously (safe or unsafe), based, respectively, on presence outside or inside programmed geofences around three operational hazards: the log loader (heavy machinery), skyline carriage (mobile, overhead equipment), and snag (dead, standing tree). Through a separate, controlled field experiment, we estimated GNSS positioning error for our LS devices in clearcut and mature canopy conditions. We then simulated canopy-induced error effects on operational positioning data to assess their impact on worker safety status. Results indicate canopy-induced error significantly affects worker GNSS positioning relative to a geofence.

Idaho loggers have previously suggested potential benefits to utilizing positioning technologies on logging operations, such as knowing relative locations of rigging crew and hand fallers, but they have also voiced several concerns, including cost, potential for distraction, increased production pressure, encouragement of risk behavior, device failure, technology dependence, and privacy violation (Newman et al.). Before developing LS applications further, it is imperative to assess acceptance, determining what LS features are most valued by loggers and evaluating intent to adopt LS practices.

Future actions can be better understood through predictive, psychological theories, such as the Theory of Planned Behavior (TPB), which stresses the role of intention, attitude, subjective norms, and perceived behavioral control in behavior actualization (Ajzen 1991). Intention, the theory argues, indicates how much effort an individual is willing to contribute to completion of an action; the stronger the intention, the more likely an individual is to act. Intention is influenced by three factors: 1) an individual's favorable or unfavorable beliefs about a behavior, referred to as attitude; 2) subjective norms, representing the social pressure to behave a certain way; and 3) perceived behavioral control, or the perceived ability to enact a behavior. In occupational health applications, studies have utilized the TPB model to explain a variety of self-protective behaviors in the workplace (DeJoy

1996), such as structural firefighter behavior intentions after receiving NIOSH health and safety messages on occupational hazards (Welbourne and Booth-Butterfield 2005). It has also been employed as a framework for questionnaires, guiding surveys on safe lifting (Johnson and Hall 2004), self-protective behaviors by farmers (Colément and Van den Broucke 2008), hearing protection use by miners (Quick et al. 2008), and safety violations by aircraft maintenance workers (Fogarty and Shaw 2010).

In chapter three of this thesis, we surveyed Idaho loggers at three certification update meetings, concurrent with a presentation on LS for logging safety. Seventeen close-ended questions covered topics on LS device types and features, concerns associated with real-time LS, likelihood of benefits and disadvantages, and adoption of LS for logging safety. We based a portion of the survey on TPB variables to better understand adoption of LS safety behaviors. TPB-based questions addressed a) attitudes toward potential outcomes of using LS; b) the expected behavior of others, representing normative pressure; c) perceived influence in whether LS is used, to measure perceived behavioral control; and d) likelihood of using LS, as a measure of intent. We also statistically analyzed loggers' perceived importance to improving workplace safety generally as well as the influence of age, smartphone use, attitudes, norms, and control on intent. Results indicate overall support of LS and likely adoption of LS safety practices by Idaho loggers.

Taken together, results from the two studies presented are useful for 1) better characterizing appropriate and inappropriate uses of LS technology in logging safety as inferred from LS device accuracy in forested conditions, and 2) informing development of safety recommendations to inform loggers about best practices to reduce fatal and near-fatal traumatic injury incidence rates using LS technology. In addition to the research presented in the thesis, the author conducted field studies to evaluate the use of multiple base station correction and trilateration based on Received Signal Strength Indication (RSSI) as methods to improve positioning accuracy with GNSS-RF LS devices. The author also contributed to other refereed journal articles not published in this thesis (Zimbelman et al. 2017; Keefe et al., in prep.; Newman et al.) as a result of graduate research sponsored on CDC/NIOSH Cooperative Agreement 5 U01 OH010841. In conjunction with the thesis, these research products form the basis of helping to improve and advance use of LS for occupational safety applications in operational forestry. The research will also help to inform future applications LS technology to improve occupational safety in wildland firefighting and other high-risk occupations in natural resources.

CHAPTER 2: CHARACTERIZING RIGGING CREW PROXIMITY TO HAZARDS ON CABLE LOGGING OPERATIONS USING GNSS-RF: EFFECT OF GNSS POSITIONING ERROR ON WORKING SAFETY STATUS

Wempe, A.M.; Keefe, R.K. Characterizing rigging crew proximity to hazards on cable logging operations using GNSS-RF: Effect of GNSS positioning error on worker safety status. *Forests* **2017**, *8*, 357, doi: 10.3390/f8100357.

ABSTRACT: Logging continues to rank among the most lethal occupations in the United States. Though the hazards associated with fatalities are well-documented and safe distances from hazards is a common theme in safety education, positional relationships between workers and hazards have not been quantified previously. Using GNSS-RF (Global Navigation Satellite System-Radio Frequency) transponders that allow real-time monitoring of personnel, we collected positioning data for rigging crew workers and three common cable logging hazards: a log loader, skyline carriage, and snag. We summarized distances between all ground workers and each hazard on three active operations and estimated the proportion of time crew occupied higher-risk areas, as represented by geofences. We then assessed the extent to which positioning error associated with different stand conditions affected perceived worker safety status by applying error sampled in a separate, controlled field experiment to the operational data. Root mean squared error was estimated at 11.08 m in mature stands and 3.37 m in clearcuts. Simulated error expected for mature stands altered safety status in six of nine treatment combinations, whereas error expected for clearcuts affected only one. Our results show that canopy-associated GNSS error affects real-time geofence safety applications when using single-constellation American Global Positioning System transponders.

2.1. INTRODUCTION

Ground workers on cable logging operations work in close proximity to multiple, moving hazards, including highly active heavy equipment, raw materials, and other objects that are swung, dragged, dropped, and dislodged on steep slopes. Proximity to these hazards creates potentially injurious situations for cable logging workers (Bell and Helmkamp 2003; Bordas et al. 2001; Lefort et al. 2003; Shaffer and Milburn 1999). Unlike mechanized, ground-based operations in which employees are generally working within enclosed machine cabs, cable operations rely on ground crews who work unprotected alongside equipment and other hazards in a dynamic environment. Hand fallers and members of the rigging crew face increased risk of injury from hazards such as falling limbs or falling live (green) and dead trees, as well as rolling logs and rocks on steep slopes (Bell and Helmkamp 2003; Shaffer and Milburn 1999; Sygnatur 1998). Although United States Occupational Safety and Health Administration (OSHA) and state-level regulations require felling of standing dead trees (snags) within active logging areas (OSHA Regulations, 1910.266(h)(1)(vi)), snags may still be present on the periphery of units and during initial work periods prior to felling.

The dangerous nature of logging work is reflected in the industry's high fatal injury rates, as published annually by the Bureau of Labor Statistics (BLS). The BLS' 2015 Census of Fatal Occupational Injuries reported 132.7 logger deaths for every 100,000 full-time employees, which was the highest rate of any profession in the United States in 2015 (BLS CFOI 2015). The rate increased 20% from 2014, when logging also ranked as the most fatal occupation (BLS CFOI 2014). Lefort et al., who characterized logger injuries in the late 1980s and early 1990s, noted that mechanization of the logging industry had reduced the total number of workplace injuries, but had triggered an increase in injury severity (Lefort et al. 2003). They attributed this trend to the changing nature of exposure; ground crew are now working closer to the landing where they face impacts from moving logs and machinery. In 2015, the BLS identified trees, logs, or limbs as the primary source of fatal injury in 41 of 80 total occupational deaths in the logging industry, while 14 deaths were attributed to machinery (BLS OIIFIP). Consistent with reports by the Bureau of Labor Statistics, an analysis of Worker's Compensation claims in West Virginia indicated objects, primarily trees, snags, or logs, striking crew members accounted for 47% of injuries, more than any other cause (Bell and Helmkamp 2003). Similarly, according to claims records from eight southern states in 1997, falling trees or limbs and moving logs caused the most injuries (28%), followed closely by equipment, including skidders, feller-bunchers, dozers, and loaders (23%) (Shaffer and Milburn 1999).

GNSS-RF (Global Navigation Satellite System-Radio Frequency) transponders have the potential to reduce the incidence of injuries and fatalities on logging operations by improving situational awareness (Keefe et al. 2014). GNSS-RF units determine their coordinates from one or more navigation satellite systems, including the United States' Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou, or Europe's Galileo. They then transmit those coordinates to other units either globally using satellite signals or locally using radio frequency transmissions. Used in conjunction with mobile devices such as smartphones, handheld tablets, or onboard computers, GNSS-RF technology can provide a real-time, comprehensive visualization of all the interacting components of logging operations, supplementing voice communications used conventionally on two-way radios and signal horns such as Talkie-Tooters (Rothenbuhler Engineering, Sedro Woolley, WA, USA). For example, with knowledge of ground crew positions in relation to potential hazards, machine operators could make more informed decisions based on the known locations of workers displayed on maps on mobile devices and, in some cases, supplement situational awareness with visual or audial alerts indicating worker presence in hazardous work zones delineated by geofences (Keefe et al. 2014; Grayson et al. 2016; Zimbelman et al. 2017).

GNSS has been utilized widely in forestry for decades. GNSS is integrated into Geographic Information Systems (GIS) to map ownerships and delineate stand boundaries, forest road locations, and other features on timber sales (Bettinger and Wing 2004). Mobile positioning devices have been installed on harvesting machines to track movement over the course of harvest operations and assess soil impacts and performance (Carter et al. 1999; Taylor et al. 2001). GNSS is increasingly being used in place of traditional, observational methods to characterize productive cycle-times of forest machines (Becker et al. 2017; McDonald and Fulton 2005; Strandgard and Mitchell 2015). Harvesters have also been fitted with GNSS devices to collect tree positioning data (Kaartinen et al. 2015; Hauglin et al. 2017). Development of GNSS paired with RF for real-time positioning is emerging quickly in forestry and has a variety of potential uses including operational and wildland fire logistics, real-time optimization, and safety (Keefe et al. 2014; Grayson et al. 2016; Zimbelman et al. 2017; Becker et al. 2017).

Situational awareness can be augmented further by combining GNSS-RF positioning with virtual boundaries known as geofences, which delineate hazardous areas, silvicultural treatments, or work zones on timber sales (Keefe et al. 2014; Grayson et al. 2016). Geofences provide a means by which to monitor the real-time locations of people, equipment, or other resources relative to spatial boundaries and can be programmed to alert users of crossing events (Reclus and Drouard 2009). They have been successfully integrated into various industries to help resolve positional monitoring and restriction needs (Reclus and Drouard 2009; Anderson 2007; Butler et al. 2006; Marsh 1999; Sheppard et al. 2015; Umstatter 2011) and have potential applications in logging to alert machine operators about ground worker proximity (Keefe et al. 2014; Grayson et al. 2016; Zimbelman et al. 2017).

To improve logging safety, geofence boundaries need to account for dynamic positional relationships between workers and hazards. As ground workers move throughout cable corridors, spatial proximity of people to one more pieces of equipment, snags, skyline rigging, and harvested resources are in constant flux. OSHA, which establishes guidelines and regulations for safe practices on logging operations in the United States, does not provide explicit safe distance recommendations for most logging equipment. Rather, it relies upon workers to interpret safe proximity in situational context. OSHA regulation 1910.266(f)(2)(vii) states that a “machine shall be operated at such a distance from employees and other machines such that operation will not create a hazard for an employee” (OSHA Regulations). Oregon OSHA Division 7 (2009), as well as common industrial safety awareness campaigns, advise workers to stay “in the clear,” which generally is translated as a distance equivalent to the length of a tree or log being transported to the landing (Oregon OSHA). If loggers frequently occupy areas less than one tree length from a hazard, a geofence associated with that hazard may need to be smaller than the recommended safety distance in order for operators to discern between normal activity and higher risk situations, or early warning signals may need to be deployed. Knowledge of positional relationships will also help define GNSS accuracy needs. If ground crew generally work within five to ten meters of a hazard, positioning errors greater than five meters may be detrimental to safety; whereas lower accuracies may still be useful for improving general awareness if workers already avoid proximity to hazardous areas. The use of mobile geofences, which can move with hazards, introduces additional considerations, such as geofence alert accuracies associated with the geometry of multiple moving components (Zimbelman et al. 2017).

Although the sources of occupational injuries and fatalities are well-documented for logging and use of geofences for logging safety applications has been studied in designed experiments, spatial analysis of the actual positional relationships between workers and some common hazards on active operations has not been quantified or summarized previously. In fact, despite the widespread attention to spatial proximity in safety training as well as state and federal regulations in forestry, there has been virtually no prior analysis of actual positional movements among ground workers of the sort that is now possible using GNSS-RF technology. In this paper, we characterized the real-time positions of ground crew workers and three common situational hazards during active cable operations using coordinates collected by Raveon Atlas PT GNSS-RF devices (Raveon Technologies Corp, San Diego, CA, USA), which feature a VHF data modem combined with a 12-channel GNSS receiver that receives position information from a single constellation, the American NAVSTAR GPS system. It is important to note that the devices do not receive positional information from GLONASS, BeiDou, or Galileo, as some other current GNSS-RF devices do. We summarized safe worker–hazard distances by calculating the amount of time, in one second increments, that workers occupied zones outside (“safe”) and inside (“unsafe”) circular geofence assigned to each hazard. Because forest overstory is known to impact GNSS accuracy (Deckert and Bolstad 1996; Liu and Brantigan 1995; Rempel and Rodgers 1997), we also conducted a designed experiment on the University of Idaho Experimental Forest to quantify canopy impacts on receiver accuracy in both mature and recently clearcut stands. These conditions correspond to the early stages of harvesting operations (canopy intact), transitioning to later stages (canopy removed) that result during typical clearcut operations in the northwestern United States. We then used simulation to re-analyze our operational data and evaluate the extent to which canopy-induced error, as determined in the earlier designed experiment, affected the GNSS-characterized safety status of ground workers.

Our specific objectives were to determine whether the proportion of unsafe time, defined as time spent inside one or more hazard geofences, differed by (1) hazard type (loader, carriage, snag), (2) timber sale, or (3) GNSS environment (observed GNSS data versus simulated GNSS data).

2.2. METHODS

2.2.1. Controlled Experiment

2.2.1.1. Data Collection

To estimate the impact of GNSS error on operational positioning data collected at logging operations, we first calculated Atlas PT error in a controlled field experiment on the University of Idaho Experimental Forest (UIEF) in Princeton, Idaho (USA). The UIEF encompasses canopy features and slopes representative of north Idaho mixed-conifer forests, ranging in age from recent clearcuts to mature stands approximately 90 years old. Eight stands were selected for sampling in the Flat Creek and East Hatter units of the UIEF, all located at mid-elevation (approximately 915 meters) on the north slope of Moscow Mountain in the Palouse Range, in the vicinity of 46.8413° latitude, −116.7734° longitude. Four stands were clearcut harvested within five years prior to the experiment, which took place in October and November of 2016. The other four stands were over-mature, with most trees approximately eighty to ninety years old, having regenerated after railroad logging in the early 20th century. Based upon plot inventories completed in each stand following sampling, tree heights ranged from 3.2 to 40.3 meters (m) in mature sites (mean of 18.2 m), and diameters at breast height (DBH) ranged from 13 to 89 centimeters (cm) (mean of 31 cm). Stands were comprised of ponderosa pine (*Pinus ponderosa*), grand fir (*Abies grandis*), western larch (*Larix occidentalis*), western white pine *(Pinus monticola*), Douglas-fir (*Pseudotsuga menziesii*), and western red cedar (*Thuja plicata*). Table 2.1 shows stand characteristics measured at time of sampling (azimuth, slope) and during inventory (height, DBH), as well as sampling conditions, including satellite availability and constellation. The number of in-view satellites was recorded every second by each of four Atlas PT transponders during sampling and then averaged across all devices. A differential GPS (DGPS) GNSS receiver, the Arrow 100 made by EOS Positioning Systems (Terrebonne, QC, Canada), collected position dilution of precision (PDOP) values at each Atlas PT location. Low PDOP values (less than four) indicate lower GNSS positioning error and are a function of satellite constellation orientation.

Table 2.1. Controlled experiment: University of Idaho Experimental Forest stand characteristics and sampling conditions.

Stand	Cover	Mean Height (m)	Mean DBH (cm)	Azimith (°)	Slope (%)	Date	Mean Satellites	Mean PDOP
260	Mature	23.52	33	95	37	10/12/16	7	1.6
58	Clearcut	NA	NA	352	18	10/17/16	8	1.3
531	Clearcut	NA	NA	165	35	10/19/16	8	1.4
290	Mature	14.6	25	35	5	10/19/16	7	1.5
345	Clearcut	NA	NA	130	8	10/24/16	10	1.3
139	Mature	16.7	31	347	43	10/24/16	6	1.6
524	Mature	17.3	31	27	14	11/10/16	6	1.7
262	Clearcut	NA	NA	205	2	11/17/16	8	1.2

At each stand, we collected GNSS positioning data using four Atlas PT transponder units. We sampled for thirty minutes at a transmission frequency of one second, allowing for a potential of 1,800 total observations per unit per site (actual signal transmission efficiency ranged from 0.739 to 0.997). Each unit was fastened to a wooden post using plastic zip ties, such that the base of the radio antenna was positioned at a height of one meter above the ground. The Atlas PTs were arranged in a triangular plot as shown in Figure 2.1, with a centrally located unit (“A”) positioned 25 m in slope-distance from unit “B”, 50 m from “C”, and 75 m from “D.” The orientation (azimuth) of unit B from A was selected randomly prior to sampling, and orientations for C and D were measured using a Suunto azimuth compass at 120° (±0.5°) from unit B’s orientation.

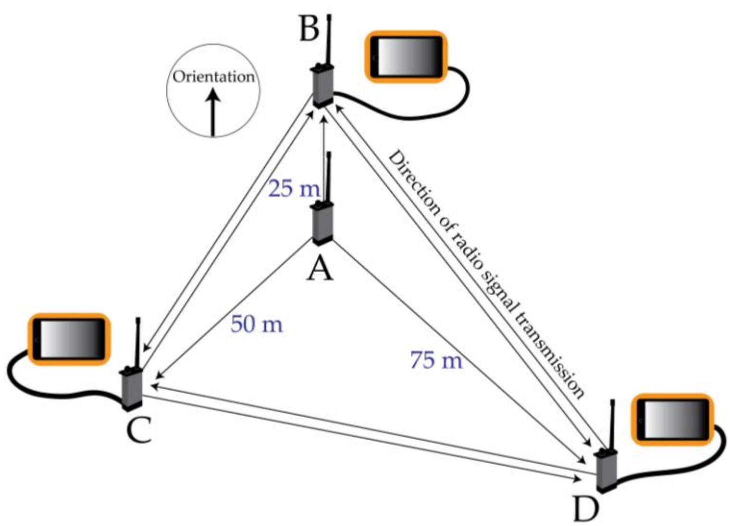

Figure 2.1. Design of the controlled experiment.

During sampling, each Atlas PT transmitted its location coordinates to each other unit once per second via radio frequency. Units B, C, and D were connected to Dell Venue Pro 8 5855 (Dell Inc., Round Rock, TX, USA) tablets equipped with Raveon RavTrack PC real-time tracking software (Version 6.5, 2015, Raveon Technologies Corp, San Diego, CA, USA) and Microsoft Access™

(Version 16.0, 2016, Microsoft, Redmond, WA, USA). Tablets automatically logged transmissions to an MS Access database for subsequent analysis. The same Atlas PT and tablet were used for each position (A, B, C, D) at every stand.

2.2.1.2. Estimation of Error

To determine the positioning error associated with Atlas PTs, we compared the recorded (observed) coordinates to reference coordinates determined using the Arrow 100. The Atlas PTs receive single frequency (L1) signals from the United States GPS system and are capable of static horizontal accuracies of less than 2.5 m 50% of the time and less than 5 m 90% of the time. The Arrow 100 (also single frequency) is a multi-constellation receiver utilizing GLONASS and BeiDou in addition to GPS. Differential correction with a Satellite Based Augmentation System (SBAS), which is the Wide Area Augmentation System (WAAS) in the United States, enables it to achieve accuracies less than 60 cm. After the four Atlas PTs were situated in the arrangement described above, the Arrow 100 was placed at each Atlas PT position where it recorded coordinates and position dilution of precision (PDOP) values (Table 2.1). After sampling, we projected all data to the Universal Transverse Mercator (UTM) projection, which has units in meters, using ArcGIS 10.3 software (version 10.3.1, 2015, Esri, Redlands, CA, USA). We then calculated the horizontal error for each observation (each one-second interval transmission) as the hypotenuse distance between the two sets of UTM easting (denoted UTM_e) and UTM northing (denoted UTM_n) points (actual—observed), as shown in Equation (1). Observed coordinates were retrieved from unit B's transmission log of all four Atlas PT positions over the sample period.

$$Error = e = \sqrt{(act.UTM_e - obs.UTM_e)^2 + (act.UTM_n - obs.UTM_n)^2} \qquad (1)$$

We determined if this error varied by stand, cover, or individual transponder unit using an Analysis of Variance (ANOVA), and then we identified significant sources of variation among stands and transponders using a Bonferroni multiple comparison test.

Error was summarized for each unit and each stand as the root mean square error (RMSE), which is a measure of the difference between predicted (based on the Arrow 100) and observed (based on the Atlas PT) values.

$$RMSE = \sqrt{\frac{\sum e^2}{n}}, \qquad (2)$$

where *e* represents error as calculated in Equation (1), and *n* represents the sample size (number of one-second transmissions). All calculations and statistical analyses for the study were completed using R open source statistical computing software (Version 3.3.1, 2016, The R Foundation, Vienna, Austria) and are presented in the Results section (R Core Team).

2.2.2. Operational Sampling

2.2.2.1. Data Collection

GNSS positioning data were collected using Atlas PT units at three active cable logging operations in north Idaho (Figure 2.2) on slopes ranging from 40–65%. All logging activities were conducted by professional, certified logging contractors on regular, operational timber sales at three ownerships: Idaho Department of Lands state endowment land (John Lewis Pole, or JLP), Potlatch Corp (Wash Trap South, or WTS) and the University of Idaho Experimental Forest (Upper Hatter, or UH). All operations were rigged for uphill yarding using motorized carriages. The state and industrial operations had swing yarders (Linkbelt 90 and Skagit GT-4, respectively) and the contractor working on the UIEF had a custom excaliner constructed on a John Deere carrier. Ground crew were responsible for setting chokers (the hooker, in regional terminology) and unhooking chokers when logs reached the landing (the chaser). The WTS and UH timber sales were clearcut operations, while the state JLP timber sale was a cedar pole harvest. Under Idaho law, cedar poles are required to be removed prior to other harvesting on cable operations when more than ten poles per acre are present.

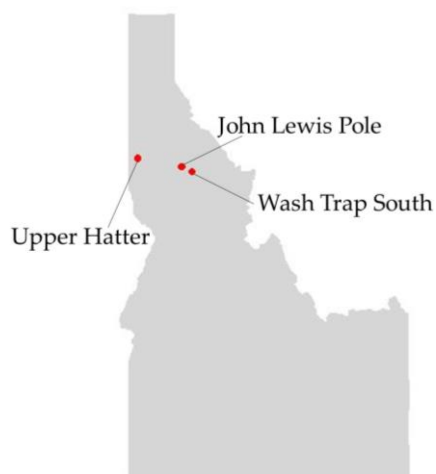

Figure 2.2. Idaho state map, with logging operation sites shown in red.

Excluding road (corridor) repositioning and equipment repairs, at least ten hours of positioning data were collected during regular operations at each harvest over the course of three days per site, with sampling occurring between mid-August and December 2016. Worker Atlas PT units were placed in radio pouches for protection and then distributed to ground crew, who wore the radio pouches on their belts. Machine-mounted units were attached to the external, metal grating covering cab windows, where the unit antennas (GPS and radio) were unobstructed. Skyline carriage units were secured to the carriage top using zip ties, such that antennas were exposed to the sky. At each site, an Atlas PT placed uphill on the yarder cab was connected to a Dell tablet for data collection and real-time visualization of unit positions with Raveon RavTrack software using the same methods as in the controlled field experiment. In addition to collecting fluid GNSS coordinates of mobile hazards with the Atlas PT units, we also identified a snag or danger tree within the harvest unit and recorded its location with a Garmin 64 handheld GPS (Garmin Ltd., Olathe, KS, USA). Thus, our raw data comprised of GNSS positioning for two to three ground workers and three types of operational hazards: machinery (the loader), equipment (the carriage), and a stationary, environmental hazard (the snag) (Figure 2.3). After sampling, coordinates from the Atlas PTs and Garmin were converted to UTM for all analyses.

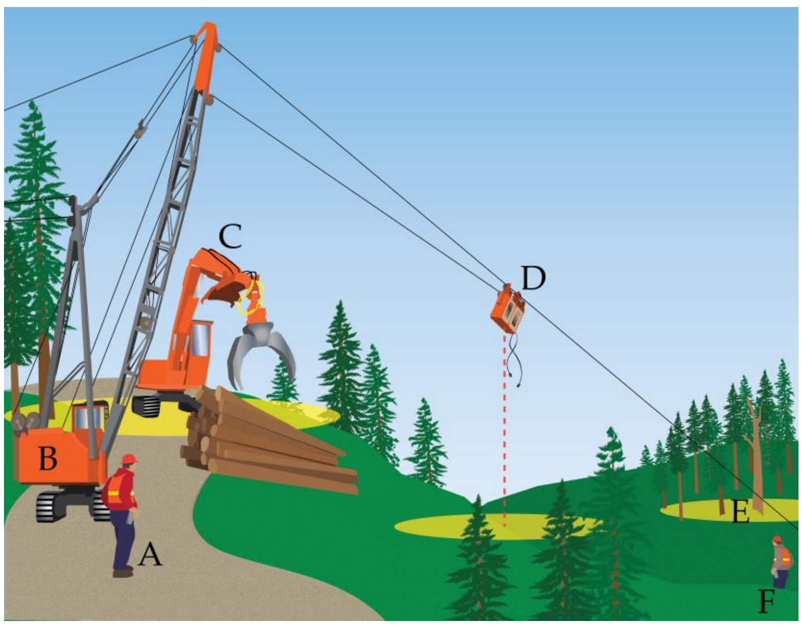

Figure 2.3. Typical cable logging operation with (A) chaser, (B) yarder, (C) loader, (D) carriage, (E) snag, and (F) hooker (note: images are not drawn to scale). Yellow ellipses highlight areas with increased risk of injury associated with the three types of hazards shown. Of the three hazards, snag GNSS coordinates were fixed (static), while loader and carriage locations were dynamic.

2.2.2.2. Summarizing Worker Proximity to Hazards

We defined worker safety in terms of worker position relative to circular geofences surrounding each of the three hazards. Conceptually, the area inside each geofence was assumed to represent a work area with higher risk of fatal or non-fatal traumatic injury due to the potential for being struck by the hazard. While work inside these areas is necessary on partially-mechanized operations, the presence of ground workers within geofenced areas require increased situational awareness and caution on the part of both ground workers and operators to avoid injuries. Areas beyond geofence borders encompass safe work areas, where the risk of injury from striking hazards is generally lower. Thus, at any given time, a worker was positioned either inside or outside the hazard geofences of up to three hazards and was classified as either safe or unsafe relative to each. Similarly, at any time, a given hazard such as the skyline carriage might have as many as three rigging crew workers in close proximity.

Using the statistical programming environment R, we created geofences centered at each hazard's coordinates, as recorded by the associated Atlas PT (or Garmin, in the case of the snag). The carriage geofence was assigned a radius of 30 m, approximating one tree length (Oregon OSHA), to encompass the risk of being struck by both the carriage itself, swinging choker cables, or logs being yarded by the carriage. The loader geofence also had a radius of 30 m (one tree length). The snag's geofence radius of 60 m represented two tree lengths, which is the standard recommended safe working distance from danger trees published by OSHA (OSHA Regulations, 1910.266(h)(1)(vi)).

For each one second time stamp in the operational data, we calculated the distance of all ground crew from each of the three hazards. For the purposes of spatial analysis, and in order to summarize six to seven entities moving dynamically in time and space, we grouped proximities in five meter increments from 0–350 m. We then summed the frequency at which workers occupied each proximity zone at each of the three timber sales, as well as the proportion of time spent in safe and unsafe zones, internal and external to the geofence associated with each hazard. To simplify analysis, ground workers were analyzed as a group rather than individually. Rigging crew workers in the region regularly alternate roles, switching among, for example, hooking and chasing, and thus summarizing across all work tasks allowed workers to retain the same Atlas PT units without stopping to switch. Also, for the purposes of analysis, the locations of the workers and hazards reported by Atlas PT GNSS positioning were considered observed coordinates with an expected degree of error comparable to the error evaluated previously in the controlled experiment.

We used the Marascuillo Procedure for comparing multiple proportions to test the null hypotheses that the proportion of observed worker presence in unsafe areas did not differ by (1) timber sale or (2) hazard type. The Marascuillo Procedure compares the test statistic (Equation (3)) to a critical value (Equation (4)) calculated for each pair of proportions in a way that accounts for degrees of freedom when comparing multiple proportions simultaneously.

$$value = \left|p_i - p_j\right| \tag{3}$$

$$critical\ range = r_{ij} = \sqrt{X^2_{1-\alpha,k-1}}\sqrt{\frac{p_i(1-p_i)}{n_i} + \frac{p_j(1-p_j)}{n_j}}, \tag{4}$$

where $X^2{}_{1-\alpha,k-1}$ is the Chi-square distribution with a confidence interval of $1 - \alpha$ (α is the significance level) and degrees of freedom equal to $1 - k$, (k equals the number of populations). p_i represents the proportion for sample i, p_j represents the proportion for sample j, and n represents the sample size. If the value from Equation (3) is greater than the critical range, then the two compared proportions are significantly different.

2.2.3. *Simulation of GNSS Error*

A simulation script was written in the R language in order to assess the effect of horizontal positioning error on the safety status of individuals. For each one second time stamp in the operational data, a one second observation was selected at random from one of the four mature or clearcut plots in the controlled experiment described previously. We applied an error adjustment to the operational data based upon the UTM easting and UTM northing differences, as well as azimuth (in degrees) from the actual (Arrow 100) and observed (Atlas PT) coordinates. Thus, we assumed for the purposes of analysis that each worker location in the operational data was uncorrected, and then shifted each coordinate individually by a distance and direction corresponding to either mature canopy or clearcut error accuracy from the controlled experiment. To simplify analysis, we assumed that hazard locations were true coordinates; thus, they were not adjusted during simulation. 500 iterations of the simulation script were processed. After resampling and application of error adjustments to worker positions, inter-point distances from each of the three jobsite hazards were again summarized in zones of five-meter increments, and the proportions of safe and unsafe status were determined. Since adjustments to the operational data were sampled from individual GNSS errors recorded on multiple different sites and dates, simulated data do not represent the true location of each worker at a given time. Rather, we used simulation to provide an indication of the degree of impact to be expected from positioning error in relation to a fixed point (the geofence) in each GNSS environment (observed, mature, or clearcut).

We determined whether GNSS positioning error would impact definitions of workers as safe or unsafe based on proportions of time spent inside geofenced hazard zones. Using the Marascuillo Procedure, we tested the null hypothesis that unsafe proportions were equal for observed, mature, and clearcut data for each hazard at each site, where observed data represented worker positions as recorded by the Atlas PTs, mature data represented simulated worker positions accounting for GNSS error associated with canopy, and clearcut data represented simulated worker positions accounting for GNSS error under un-obstructed conditions. The Marascuillo Procedure was performed for each iteration, and the mean value was compared to the mean critical range to determine if proportions differed significantly.

2.3. RESULTS

2.3.1. Controlled Experiment: Estimating Atlas PT Positioning Error

Plot-level Root Mean Squared Error (RMSE) calculated for all four Atlas PT units within each stand (Equation (2)) ranged from 2.64 m to 4.09 m in clearcuts, with the best accuracy achieved in Stand 531. By contrast, RMSE ranged from 8.56 m to 14.34 m in mature stands, with the lowest accuracy occurring in Stand 524 (see Table 2.2 for RMSE by stand and unit). The RMSE of all mature stands combined was 11.08 m, while the overall RMSE of clearcuts was 3.37 m. With the exception of one unit (B in Stand 58), RMSE values in clearcut conditions are under the five-meter accuracy expected for Atlas PTs 90% of the time. However, none of the devices in mature stands achieved this level of accuracy.

Table 2.2. Root mean square error (RMSE) of Atlas PT GNSS horizontal positioning error, in meters, at each unit position (A, B, C, and D) and across all units (last column).

Cover	**Stand**	**Unit RMSE (m)**				
		A	**B**	**C**	**D**	**All Units**
MATURE	260	13.07	8.29	12.52	4.79	10.34
	290	11.68	6.91	7.48	7.28	8.56
	139	11.23	7.68	12.78	7.90	10.14
	524	18.17	11.16	11.59	15.30	14.34
CLEARCUT	58	4.33	5.36	2.98	1.46	3.81
	531	2.42	1.67	3.16	3.01	2.64
	345	1.38	1.49	3.09	3.66	2.67
	262	3.96	3.69	4.52	4.07	4.09

Actual error calculated for each second of sampling (Equation (1)) varied significantly by stand (F-statistic = 4735, p-value $< 2 \times 10^{-16}$), cover (F-statistic = 25,390, p-value $< 2 \times 10^{-16}$), and individual transponder unit (F-statistic = 337.3, p-value $< 2 \times 10^{-16}$). The Bonferroni multiple comparison test comparing all stands indicated that only two stands did not differ significantly from one another (clearcut units 345 and 531, with $p = 1.00$). Multiple comparison indicated that all transponder units differed significantly from one other (p-values less than 2×10^{-16}) except for units B and D ($p = 0.089$). Figure 2.4 illustrates actual error variation across stands of different cover types.

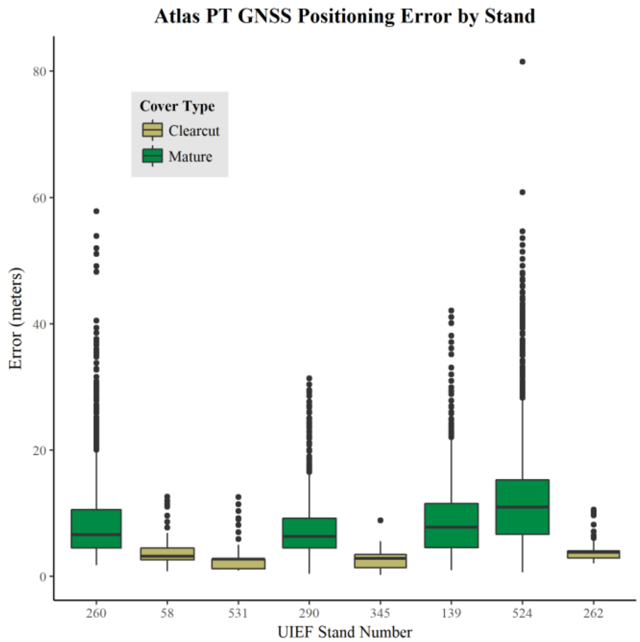

Figure 2.4. Boxplot comparing Atlas PT actual GNSS error in the controlled experiment across eight stands: four mature (green) and four clearcut (tan).

Figure 2.5 illustrates the distribution of Atlas PT GNSS positions collected over each thirty-minute sampling period compared to the single coordinates recorded by the EOS Arrow 100 at each Atlas PT location. The largest actual error observed for an Atlas PT in a mature stand was 81.5 m, and the largest error observed in a clearcut stand was 12.6 m.

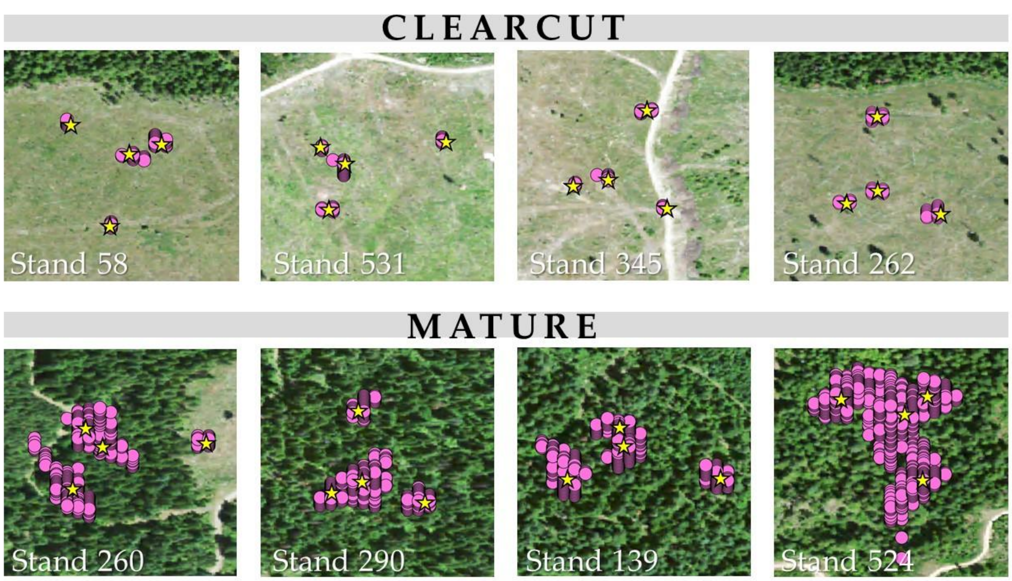

Figure 2.5. Visual comparison of Atlas PT coordinates (purple dots) and Arrow 100 coordinates (yellow stars) in clearcut versus mature stands of the controlled experiment. Scale is 1:1500.

2.3.2. Operational Sampling: Summarizing Worker Positional Relationships to Hazards

Figure 2.6 illustrates the distribution of worker–hazard distances for each of the three hazards at each harvesting operation. Bars show frequency of ground worker presence within distance zones in increments of five meters, ranging from 0 to 350 m from the specified hazard. John Lewis Pole plots represent three ground workers (the chaser, bucker, and hooker), while Wash Trap South and Upper Hatter encompass positioning data of two workers (the chaser and hooker). Each of three days is overlaid for a given site and hazard, except for the John Lewis Pole carriage, which included two days of sampling, and Upper Hatter loader, which included one day. Distances are based on GNSS coordinates collected every one second (s); thus, a frequency of 6000 corresponds to 6000 s (100 minutes) spent inside a given proximity interval. The proportion of time in which ground crew occupied zones defined as unsafe due to increased risk of injury or fatality is summarized in Table 2.3. Unsafe zones were defined as distances between 0–30 m for the loader and carriage and 0–60 m for the snag. Observed (Obs.) values are based upon GNSS positions collected by Atlas PTs during sampling and subsequent calculations of distances from hazards in R. Mature (Mat.) and clearcut (Clear.) values represent mean proportions for the GNSS environment simulated with and without mature forest overstory across 500 iterations. Proportions cover three sampling days at each of three sites: John Lewis Pole (JLP), Wash Trap South (WTS), and Upper Hatter (UH). Sample sizes are indicated in parentheses below each set of proportions. Differences in sample sizes reflect missing GNSS coordinates for a hazard, either due to positioning or transmission error, or because the equipment designated as a hazard was not in operation for a portion of the sampling period. Proportions shown in Table 2.3 were used in the Marascuillo Procedure analysis.

Across all days and all sites, ground workers spent a combined 18.5 hours (h) within thirty meters of the loader geofence (34.6% of their time), 21.4 h within thirty meters of the carriage (38.7% of time), and 32.3 h within sixty meters of the snag (46.7% of time). It is important to note that our results represent collective ground worker positioning data, pooling the chaser and hooker (as well as a bucker for John Lewis Pole). Chasers generally work close to the landing while hookers work varying distances along the cable corridor, so proximity to landing hazards such as the loader would be expected to differ for the two workers.

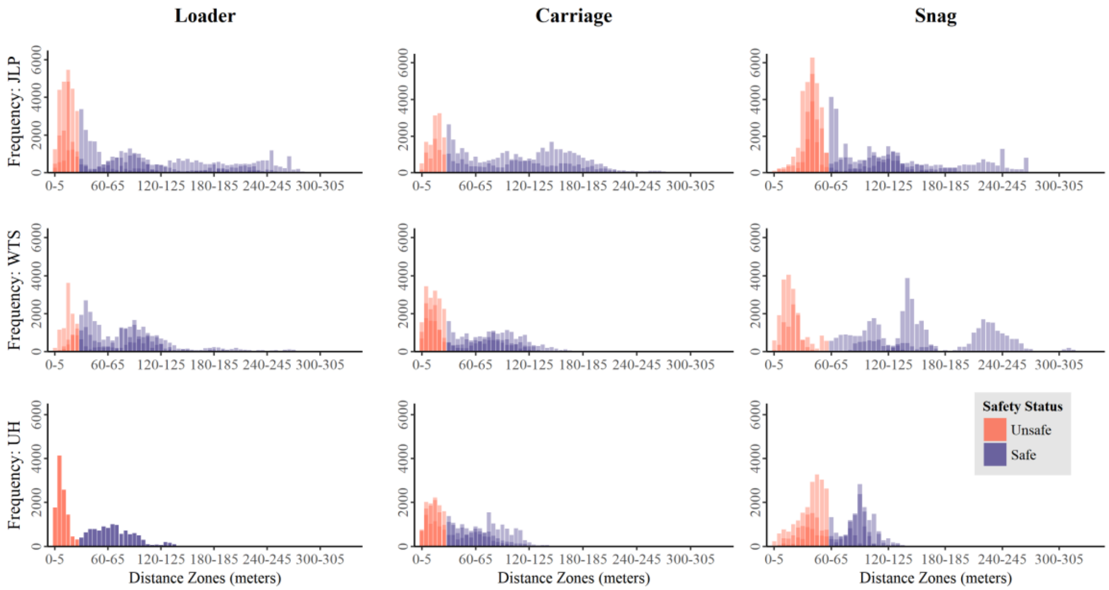

Figure 2.6. Distribution of ground worker distances from each of three hazards (loader, carriage, and snag) across three logging operations (John Lewis Pole, Wash Trap South, and Upper Hatter). Vertical bars are in 5 m increments. Red bars indicate location inside of the hazard's geofence (Safe); blue bars indicate location outside of the geofence (Unsafe). Shades of color represent different sampling dates.

Table 2.3. Proportion of instances (1-second intervals) when ground workers occupied unsafe zones associated with each hazard based on observed, mature, and clearcut data, with sample size, n, shown in parentheses.

	Loader			Carriage			Snag		
Site	**Obs.**	**Mat.**	**Clear.**	**Obs.**	**Mat.**	**Clear.**	**Obs.**	**Mat.**	**Clear.**
JLP	0.404	0.382	0.406	0.252	0.238	0.257	0.503	0.497	0.512
	(n = 100886)			(n = 72251)			(n = 110495)		
WTS	0.226	0.220	0.225	0.477	0.449	0.477	0.363	0.361	0.362
	(n = 66872)			(n = 70430)			(n = 76926)		
UH	0.492	0.487	0.491	0.449	0.423	0.449	0.528	0.498	0.523
	(n = 21742)			(n = 56490)			(n = 61826)		

Results from the Marascuillo Procedure comparing proportions among hazards and sites are shown in Table 2.4. For each pair of comparisons, the table shows the value (Equation (3)) representing the Marascuillo test statistic and the critical range (Equation (4)). If the value exceeds the critical range ("yes"), the difference in the two compared proportions is significant. The Marascuillo Procedure compared thirty-six total proportions, but only the eighteen tests of interest in our study are shown. They include comparing (1) each hazard across all three sites: loader (Test 3, 4, and 12), carriage (6, 7, and 14), and snag (8, 9, and 15) and (2) each site for all three hazard types: John Lewis Pole (1, 2, and 5), Wash Trap South (10, 11, and 13), and Upper Hatter (16, 17, and 18). All 18 hazard and site comparisons of interest were significant, indicating that the proportion of worker presence inside geofence boundaries varied by hazard type and site.

Table 2.4. Results of the Marascuillo Procedure, comparing unsafe proportions across hazards and sites (alpha = 0.05).

Test	Compared Proportions	Value (Test Statistic)	Critical Range	Value > Critical Range?
1	JLP_L-JLP_C	0.152	0.009	yes
2	JLP_L-JLP_S	0.099	0.008	yes
3	JLP_L-WTS_L	0.178	0.009	yes
4	JLP_L-UH_L	0.088	0.015	yes
5	JLP_C-JLP_S	0.251	0.009	yes
6	JLP_C-WTS_C	0.225	0.01	yes
7	JLP_C-UH_C	0.197	0.01	yes
8	JLP_S-WTS_S	0.14	0.009	yes
9	JLP_S-UH_S	0.025	0.01	yes
10	WTS_L-WTS_C	0.251	0.01	yes
11	WTS_L-WTS_S	0.137	0.009	yes
12	WTS_L-UH_L	0.266	0.015	yes
13	WTS_C-WTS_S	0.114	0.01	yes
14	WTS_C-UH_C	0.028	0.011	yes
15	WTS_S-UH_S	0.165	0.01	yes
16	UH_L-UH_C	0.043	0.016	yes
17	UH_L-UH_S	0.036	0.016	yes
18	UH_C-UH_S	0.079	0.011	yes

Results of the Marascuillo Procedure comparing unsafe proportions between observed, operational data and simulated canopy and clearcut error effects are shown in Table 2.5. The table summarizes the results for nine separate tests, each with three comparisons in which observed (Obs), mature (Mat), and clearcut (Clear) proportions (Table 2.3) were compared for a single hazard at each timber harvest. Observed proportions differed significantly from mature proportions for six of nine hazards: JLP Loader, JLP Carriage, JLP Snag, WTS Carriage, UH Carriage, and UH Snag, but differed significantly for only one clearcut proportion (JLP Snag). Mature and clearcut proportions differed significantly from each other for six of nine hazards: JLP Loader, JLP Carriage, JLP Snag, WTS Carriage, UH Carriage, and UH Snag.

Table 2.5. Results of the Marascuillo Procedure, comparing unsafe proportions of observed, mature, and clearcut data (alpha = 0.05).

Test	**Compared Proportions**	**Mean Value (Test Statistic)**	**Mean Critical Range**	**Value > Critical Range?**
	Obs-Mat	0.022	0.005	yes
JLP Loader	Obs-Clear	0.002	0.005	no
	Mat-Clear	0.024	0.005	yes
	Obs-Mat	0.014	0.006	yes
JLP Carriage	Obslear	0.005	0.006	no
	Mat-Clear	0.019	0.006	yes
	Obs-Mat	0.007	0.005	yes
JLP Snag	Obs-Clear	0.009	0.005	yes
	Mat-Clear	0.016	0.005	yes
	Obs-Mat	0.006	0.006	no
WTS Loader	Obs-Clear	0.001	0.006	no
	Mat-Clear	0.005	0.006	no
	Obs-Mat	0.027	0.007	yes
WTS Carriage	Obs-Clear	0.000	0.007	no
	Mat-Clear	0.027	0.007	yes
	Obs-Mat	0.002	0.006	no
WTS Snag	Obs-Clear	0.000	0.006	no
	Mat-Clear	0.002	0.006	no
	Obs-Mat	0.005	0.012	no
UH Loader	Obs-Clear	0.001	0.012	no
	Mat-Clear	0.004	0.012	no
	Obs-Mat	0.026	0.007	yes
UH Carriage	Obs-Clear	0.001	0.007	no
	Mat-Clear	0.027	0.007	yes
	Obs-Mat	0.030	0.007	yes
UH Snag	Obs-Clear	0.005	0.007	no
	Mat-Clear	0.024	0.007	yes

2.4. DISCUSSION

Our results showed clearly that the nature of positional relationships was complex and varied both between sites and between hazard types in each treatment comparison tested. Distinct, multi-modal patterns of worker proximity to hazards were evident, and the locations of peak distances where workers tended to spend more time varied by day. Although we did not formally test differences among the three days sampled at each site, it was evident graphically when overlaying the distributions of proximity (Figure 2.6) that distinct patterns of spatial proximity exist and change over time. These trends likely correspond to, for example, hookers gradually working further from the loader as they set chokers and yard materials to the landing from further down the hill, or gradually working either closer to or further away from snag hazards adjacent to harvest units.

A more nuanced analysis of individual worker positions relative to multiple hazards, such as studying hooker or chaser movements separately, could help to better quantify the spatial and temporal nature of positional relationships during normal work. However, we felt that our analysis reflected the reality of cable logging, in which multiple hazards are present simultaneously for any given worker, often in different directions. For example, a member of the rigging crew setting chokers near the bottom of the hill may be at risk of impact with rolling logs inadvertently bumped by the loader at the log deck. At the same time, he or she may also be at risk of being hit by a rotating log attached to a choker as the carriage begins to laterally yard logs toward the skyline if he or she is not sufficiently ‘in the clear’ at a safe distance from the carriage (and log). Simultaneously, a snag on the perimeter of the corridor could fall if dislodged by the log being yarded or a cable under tension. Although we focused on three possible hazards, the reality of cable logging is that multiple, other concerns are also present, including the processor swinging logs, pinch points caused as swing yarders, loaders, and processors rotate adjacent to the cut slope of the logging road, possible chain shot from the processor, and loose boulders in the corridor that may become dislodged.

Results of our controlled experiment on the UI Experimental Forest showed that the positioning accuracy of the GNSS-RF transponders used in our study was greatly affected by canopy. RMSE for the Atlas PT GNSS receivers in clearcuts was 3.37 m; whereas in mature, 90-year old mixed conifer stands, the RMSE was 11.08 m. The error observed in our study represents a function of variables affecting positioning accuracy, including Atlas PT receiver quality, the satellite geometry for the specific times and dates of sampling (see Table 2.1 for PDOP values), and multipath effects unique to the individual environments of each site. Improved GNSS receivers may demonstrate higher accuracies, even in mature stands. GNSS error associated with forest canopy has been well-documented though (Deckert and Bolstad 1996; Liu and Brantigan 1995; Rempel and Rodgers 1997), so the observed variation in positioning accuracy by cover type is consistent with past studies.

When simulation was used to evaluate the relative importance of variable GNSS accuracy on worker safety status during active logging, results clearly showed that canopy-induced error did significantly affect safety status, as defined using geofences. It is important to note that simulated canopy and clearcut error impacts on worker safety status were based on resampling from positioning data obtained at different locations, dates, and times than the operational sampling, so our results serve as an approximate estimation of canopy effects; actual error observed at active logging operations may differ due to topography or other factors. Further, error estimates based on static positioning in the controlled experiment were likely more conservative than error associated with dynamic positioning during active logging operations (Parkinson and Enge 1994; Wang et al. 2016). A further caveat we wish to highlight is that the statistical method used in our analysis to evaluate differences among sites and hazards, the Marascuillo Procedure, does not formally account for potential correlation that exists between adjacent location sample points in time and space. To the extent possible, we addressed this issue through the use of an analytical script that involved randomized resampling from our experimental data. For subsequent analysis, development of an analytical method that incorporates hierarchical modeling, including both fixed and random effects, into the procedure may help address impacts of possible correlated data structures associated with real-time GNSS.

Applications of real-time positioning for logging safety need to account for the reality that both mature and clearcut conditions, and associated impacts on GNSS accuracy, occur over the course of most conventional harvesting operations in the northwestern U.S. When a harvest unit has been felled in its entirety and the rigging crew is working in the open, more accurate positioning is possible. However, higher errors should be expected for GNSS-RF applications related to manual fallers or feller-bunchers, or in partial harvesting operations, such as the John Lewis Pole cedar pole harvest. Lower accuracies attributed to canopy cover may also be compounded by terrain effects, which can reduce satellite fix rates in forested areas, particularly in valleys (Deckert and Bolstad 1996; Liu and Brantigan 1995; D'Eon et al. 2002). For example, GNSS accuracies of devices associated with the rigging crew could vary between hookers working downhill and chasers working on ridgelines.

If sub-meter accuracy is desired under canopies, similar to precision forestry applications that require accurate marking of skid trails or individual trees (Blum et al. 2015), ground based augmentation systems (GBAS) may be necessary. GBAS determine the degree of error and transmit corrections to rover units which can then re-calculate their positions accordingly (Kaartinen et al. 2015). Haughlin et al. recently achieved 0.94-m accuracy on a harvester using RTK (real-time kinematic) correction, compared to 7 m with GNSS alone (Haughlin et al. 2017). It is also important to note that the Atlas PT transponders used in this study relied on only the United States' NAVSTAR GPS constellation for position determination. Many current GNSS devices, including even consumer-grade handheld units for recreational use, are multi-constellation devices that determine position using not only GPS, but also the Russian Global Navigation Satellite System (GLONASS), European (Galileo), or Chinese (BeiDou) navigational satellite systems. It is likely that newer GNSS-RF transponders capable of multi-constellation positioning will have higher accuracy in forested, mountainous locations where the number of trackable satellites may be diminished. However, use of multi-constellation sensors will not eliminate the multipath error endemic to highly reflective environments such as forests (Parkinson and Enge 1994). Similarly, although GBAS can greatly reduce GNSS positioning errors under canopies, differential correction cannot account for multipath effects. Even DGPS receivers will demonstrate higher errors in mature stands than in clearcuts.

According to our distance-based definitions of safe and hazardous work areas, the rigging crews we evaluated spent, on average, over one-third of their work day in unsafe conditions associated with the loader and carriage and nearly half of the day near snags. Geofences programmed at standard recommended safe working distances may not be able to distinguish between routine risk levels and imminent risks of injury. Machine and equipment geofences at one tree length could alert operators of initial entrance of ground workers into their workspaces to prompt additional safety precautions, such as visual confirmation of worker positions. Indication of higher risk situations, however, may require smaller geofences or a multi-stage warning system of concentric geofences.

The simulated proportions of time spent in unsafe zones based on expected mature stand error varied significantly from observed proportions for six of nine tests; thus, using the technology evaluated in our study, accuracy errors associated with GNSS-RF devices under the canopy do impact GNSS-based definitions of safety on logging operations, even when using basic, dichotomous definitions based on presence inside or outside a geofence. Devices with greater accuracy capabilities, at least through multi-constellation GNSS processing, and preferably RTK or other improved localization, are recommended for fine-resolution applications such as worker positioning around the landing. Proportions of safe and unsafe time differed significantly between observed and clearcut data in only one test, indicating that the higher accuracies achievable in clearcut conditions enable greater reliability in geofence alerts.

Use of GNSS-RF technology for safety applications on logging operations should be proportional to accuracy limitations. Given the large GNSS error observed under mature forest canopy in our designed experiment, single-constellation GNSS-RF radios such as the Raveon Atlas PT should only be deployed for very coarse monitoring of worker locations to improve general situational awareness and communication in forested environments; no operator decisions should be made based on observed, transmitted locations indicating the proximity of workers to jobsite hazards. That said, our operational sampling results offer a glimpse into the novel sorts of analyses that are becoming possible with real-time, networked positioning solutions in operational forestry. There is tremendous potential for improving both the safety and efficiency of logging through analysis of the high-resolution spatial and temporal data that results from deployment of GNSS-RF and similar location-based services in production forestry.

Future research on GNSS-RF use for logging safety may wish to consider both vertical and horizontal positioning to better account for overhead hazards, such as the carriage, and to better specify inter-element distances on steep slopes. Future studies may also address how current positioning devices and systems can be adapted specifically for forestry applications, such as improvements to the user interface that allow loggers to utilize the technology easily and effectively with little distraction to normal work flow. This could entail display and sound settings or possible integration with other forms of data acquisition. For instance, Light Detecting and Ranging (LiDAR) information collected on snag locations could be synchronized with GNSS data to note worker proximity to snags or other environmental hazards (Wing et al. 2015).

2.5. CONCLUSIONS

Atlas PT GNSS-RF positioning accuracy using only the NAVSTAR GPS system was more than three times greater in clearcut harvest units than under mature forest canopies. Error associated with mature overstory significantly affected worker safety status based on proximity to situational hazards. Ground workers spend approximately one-third of the work day within high-risk areas adjacent to mobile hazards such as the loader and carriage. Multi-constellation GNSS processing technology or other methods to improve localization accuracy are needed to provide the level of positioning detail necessary to avoid injuries with these fast-moving, dynamic hazards. In clearcut conditions, where errors are generally under four meters, differential correction or other improved localization may be less critical but still recommended, especially for positioning at the landing and along the chute below the yarder.

CHAPTER 3: INTENT TO ADOPT LOCATION SHARING FOR LOGGING SAFETY APPLICATIONS BASED ON THE THEORY OF PLANNED BEHAVIOR: RESULTS OF A SUBSEQUENT SURVEY OF IDAHO LOGGERS

Submitted to *Safety*

ABSTRACT**:** Logging entails work in remote areas with multiple, situational hazards, and consistently ranks among the most fatal occupations in the United States. Location-sharing (LS) devices that enable users to communicate geographic positions to others have been suggested as a technological approach to increasing workplace safety on logging operations. LS can connect individuals in isolated environments to improve situational awareness, which is critical for both injury prevention and response. Successful implementation of LS technology into operational practices will depend on its acceptance by the logging community. This study evaluated logger perceptions concerning the role of LS devices in logging safety through a survey administered at three logger training programs. The primary goal of the survey was to gauge logger adoption of LS safety practices based on intent, as outlined by the Theory of Planned Behavior. We also assessed the perceived need for safety improvements and logger appraisal of the ability of LS devices to accomplish safety goals while avoiding undesirable outcomes. Survey results indicate overall support of LS technology for logging safety and logger intent to adopt specific LS-based practices, including using automatic LS for hand fallers, using personal location-sharing devices (PLDs) on all ground workers and heavy equipment, and using PLDs for general situational awareness. Results support further development of LS safety applications and are valuable for designing recommendations on appropriate uses of LS devices in logging safety.

3.1. INTRODUCTION

Location-sharing (LS) devices enable individuals to send geographic positioning information to others. Using the Global Navigation Satellite System (GNSS), devices can triangulate user locations anywhere on Earth, including in remote environments. Known coordinates can then be shared via cellular infrastructure, satellites, or radio frequency (RF) transmissions. Communication may be one-way or two-way. For example, SPOT receivers (SPOT LLC, Covington, LA, USA) designed for emergency situations, allow users to send a one-way text message to members of a contact list, or to signal an alert with coordinate specifications to the GEOS Rescue Coordination center. Alternatively, radio-based devices from manufacturers like Garmin (Garmin Ltd, Olathe, KS, USA), Raveon (Raveon Technologies Corp, San Diego, CA, USA), or TrellisWare (TrellisWare Technologies Inc, San Diego, CA, USA) enable local exchanges between two or more devices. Smartphone-based RF receivers, such as Beartooth (Beartooth Radio Inc, Bozeman, MT, USA) and goTenna (goTenna, New York, NY, USA), also enable two-way LS, using a Bluetooth-connected smartphone as the user interface for LS and communication outside of cellular networks.

LS abilities and features vary. For example, some devices may incorporate help alerts, either to emergency response services (SPOT, Garmin inReach) or to other, local users (goTenna, Raveon Atlas PT). Automatic position updates (Raveon Atlas PT, TrellisWare Ghost, inReach, SPOT) share an individual’s location at regular intervals, and devices with programmable virtual boundaries, known as geofences, can notify users when someone has moved into a pre-defined area (Atlas PT). Many devices also have messaging capabilities, either through text, voice, images, or videos. The radius of communication for LS depends on the signal type and device receiver quality. Devices with satellite-based signal transmission (SPOT, Garmin inReach) can send positioning data anywhere on the globe; whereas, RF-based communications are limited to local networks, with distances of one to ten miles typical for consumer devices and ranges greater than twenty miles possible with professional-grade units (Raveon, TrellisWare). Some LS devices increase RF range with mesh networking, in which each device can serve as an intermediate relay node, similar to conventional radio repeaters, for data delivery (e.g. Beartooth, goTenna, Ghost).

Since LS through GNSS-RF is possible in remote areas where cellular communication is not feasible, LS technology could be used on logging operations to improve occupational workplace safety (Keefe et al. 2014). Devices with automatic updates and geofencing could augment situational awareness of worker positions relative to hazardous areas or equipment for injury prevention. Automatic updates could also expedite injury response, enabling users to notice when isolated workers may be injured and then find them quickly. Help alerts may be used to notify coworkers or off-site response services of an injury. Commercially-available LS technology targeted toward the cable logging industry has recently been introduced in New Zealand (Logsafe GPS Monitoring, Blockhouse Bay, Auckland, New Zealand), and other commercial solutions are emerging. In these systems, yarder operators can check ground worker positions and receive alerts when those workers have moved into dangerous work spaces.

Logging regularly ranks among the most dangerous professions in the United States, by both the Bureau of Labor Statistics (BLS) and the National Institute for Occupational Safety and Health (NIOSH) National Traumatic Occupational Fatalities Surveillance System (Fosbroke et al 1997; Sygnatur 1998). According to the BLS Census of Fatal Occupational Injuries annual report, loggers faced the highest civilian fatality rate of any occupation in 2015, with 132.7 deaths per 100,000 full-time employees (BLS CFOI 2015), a 20% increase from the previous year, when loggers also had the highest rate (BLS CFOI 2014). Many logging fatalities have occurred in the Pacific Northwest region of the United States, which include the states of Idaho (3 total deaths from 2011-2015), Oregon (33 deaths from 2011-2015), and Washington (20 deaths from 2011-2015) (BLS OIIFIP). In 2014, one third of US logger fatalities occurred in these three states (BLS CFOI 2014; BLS OIIFIP). Incident details cataloguing the primary causes of injury have been reported by the BLS as well as studies analyzing Worker's Compensation claims (Bell and Helmkamp 2003; Shaffer and Milburn 1999). Records consistently report that loggers are fatally injured when struck by other objects, primarily trees, logs, and limbs, followed by machinery (Bell and Helmkamp 2003; BLS OIIFIP; Shaffer and Milburn 1999). Such fatal injuries are more likely on partially-mechanized operations, which rely on ground workers rather than machines for manual tree felling and delimbing (Shaffer and Milburn 1999). While mechanization increases protection from limbs and logs for machine operators enclosed in a cab, exposure risk is increased for ground crew who work alongside these machines, especially for individuals at the landing who may come into contact with moving logs as well as loaders, skidders, and log trucks (Bordas et al. 2001; Lefort et al. 2003; Shaffer and Milburn 1999). Fatal injury risks are also high for hand fallers, who use chainsaws to cut down trees on terrain generally too steep for machinery. Fallers work in relatively isolated conditions but still face mechanical and environmental hazards, such as chainsaws and falling trees or limbs (Bell and Helmkamp 2003; Scott 2004). Due to the distance between fallers and other co-workers, injury occurrence and location may not be immediately known.

Situational awareness on logging operations is imperative for preventing injuries as well as responding quickly when they do occur. The ultimate success of LS for logging safety will depend on loggers' perceived value of the technology and willingness to adopt safe work practices incorporating LS devices. In a mixed-methods study Newman et al. (forthcoming) evaluated Idaho loggers' perceptions of logging safety risks and potential applications for LS. Interviewed loggers suggested LS would be most beneficial for machine operators to know ground worker positioning, such as for hookers and hand fallers, and ensure these out-of-sight individuals are safely in-the-clear. They also recognized value to finding injured coworkers quickly. Idaho loggers broached several potential drawbacks, however, including cost, distraction, production pressure, high learning curves, and risk behavior. They expressed concerns about GNSS devices becoming mandatory and not always necessary, such as for mechanized operations and smaller crews. They were wary of being monitored and developing a dependence on the technology, which could prove hazardous in the case of technological failure. They also suggested that devices may simply not get used even if available.

Idaho logger concerns about LS are consistent with previous studies of logger attitudes about safe work procedures. For instance, production pressure and its perceived correlation to safety is a recurring theme in logging literature (Bordas et al. 2001, Egan et al. 1997, Egan 1998, Montorselli et al. 2010, Newman et al.). Alabama loggers interviewed by Bordas et al. (2001) believed safety training negatively impacted productivity, although Montorselli et al. (2010) compared logging crews in the Italian Alps and found evidence to challenge commonly held perceptions about the inverse relationship between safe practices and productivity. Loggers seem to differentiate between safety practices and safety regulation, however. Effective February 1995, the Occupational Safety and Health Administration (OSHA) implemented a comprehensive, national safety standard regulating logging activities. In 1997, Egan et al. reported that nearly 60% of surveyed West Virginia loggers perceived government regulation as an extreme barrier to production and in a subsequent survey by Egan in 1998, over half of West Virginia loggers felt government safety standards are not good for logging and could put them out of business. Similarly, Idaho loggers identified mandatory use as a concern about LS for logging safety (Newman et al.). Idaho loggers also cited cost as a barrier, which has been expressed as one of the primary obstacles to adopting safer mechanized cut-to-length technology by Italian logging contractors (Ferrari et al. 2012), as well as the primary reason for low usage of portable timber bridge technology by loggers in the eastern United States (Shiau et al. 2002). Ease of use was recognized as the most important factor in deciding to use portable timber bridges for temporary stream crossings, consistent with the desire for easy-to-learn technology by Idaho loggers (Newman et al.). Additionally, Idaho loggers pointed out the possibility of LS creating a sense of security that could lead to increased risk behavior, a pattern demonstrated by Klen (1997) in a survey of Finnish loggers. Forty-five percent (45%) of participants reported a change in work behavior with the use of personal protective equipment, relaying that they became more careless, faster, and bolder.

Despite these issues, however, studies have indicated a high perceived value of safety and safety training programs among loggers. For instance, New England loggers in focus groups and surveys placed a high priority on learning safety concepts in training programs and reported adopting techniques learned in training (Egan 2005). Further, during assessment of a Virginia training program, 82% of interviewed loggers described at least one new safety practice implemented following training (Wightman and Shaffer 2000). Safety practices primarily involved use of personal protective equipment, with only 7% of interviewees adopting new safety devices; thus, evaluation of the relative impact of perceived obstacles and benefits on logger attitudes may aid understanding of logger adoption of technologically-based safety practices.

Building upon logger perspectives described in the Newman et al. study, the goal of our research was to refine our understanding of the perceived role of LS technology in logging safety. Through a survey administered at three Idaho logger certification renewal programs (Logger Education to Advance Professionalism (LEAP)), we (a) identified specific LS device types and features beneficial for improving workplace safety, (b) assessed concerns and their risk of occurrence, and (c) gauged a new component of LS and logging safety: the likelihood Idaho loggers will adopt specific LS safety practices (Figure 3.1).

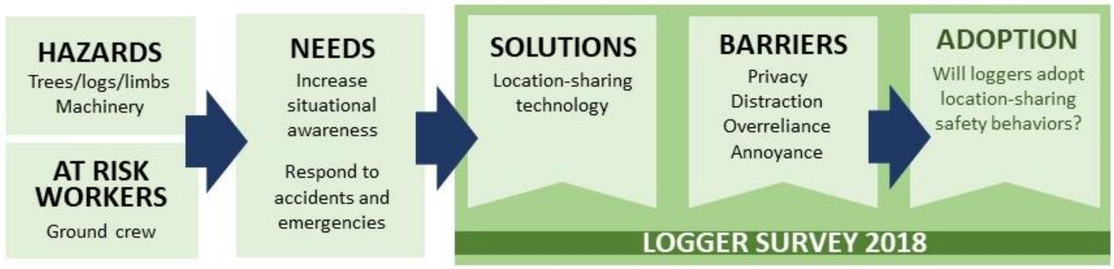

Figure 3.1. Concept model showing our study's contribution to understanding the role and reception of LS technology on logging operations.

To better understand the factors that may contribute to logger adoption of LS technology, we employed the Theory of Planned Behavior (TPB), a psychological theory that emphasizes the role of intention in human behavior. According to the TPB, and its predecessor the Theory of Reasoned Behavior, intent drives individuals to exert more effort into completion of an action, increasing the likelihood a behavior will occur (Ajzen 1991). Surveys employing the TPB typically phrase intention as *I will*, *I expect*, or *I intend* (Francis et al. 2004; Yzer 2012). Intention is influenced by three factors: attitude, subjective norms, and perceived behavioral control (PBC). Attitude encompasses beliefs concerning a behavior (Ajzen 1991). TPB studies evaluate attitude by identifying potential behavioral outcomes, such as likelihood of occurrence, and assessing outcome value or desirability (Francis et al. 2004; Montaño and Kasprzyk 2015; Perloff 2010). Value may be instrumental, based on qualities like usefulness, or experiential, such as pleasantness (Yzer 2012). The second factor, subjective norms, accounts for the social pressure an individual feels to behave a certain way (Ajzen 1991). Normative pressure in the TPB can be either injunctive, in which an individual is motivated by what important others think should be done, or it can be descriptive, in which the actual behaviors of others influences an individual (Francis et al. 2004; Perloff 2010; Yzer 2012). The last factor, control, was originally defined by Ajzen (1991) as either self-efficacy or PBC, which he deemed as interchangeable concepts. Consequent analyses and discussions have distinguished between the internal factors that determine self-efficacy (i.e. difficulty) and the external forces of PBC (i.e. how much the behavior is up to the individual) (Armitage and Conner 2001; Francis et al. 2004).

The TPB has been used widely to understand and explain variance in behavior (Armitage and Conner 2001) including health-related behaviors (Adamos and Nathanail 2016; Blue et al. 2001; Montaño and Kaspryk 2015; Welbourne and Booth-Butterfield 2005). It has also been employed as a framework for questionnaires addressing occupational health behaviors, guiding surveys on safe lifting

(Johnson and Hall 2004), farmers' self-protective behaviors (Colément and Van den Broucke 2008), miners' use of hearing protection (Quick et al. 2008), and safety violations by aircraft maintenance workers (Fogarty and Shaw 2010). We included TPB-based questions in our survey to gain a more nuanced understanding of the interactions between perceived value of LS technology, desire to implement practices, and level of influence in company decision-making processes. For example, if loggers consistently indicate that they support LS but lack influence in the decision to adopt changes, then implementation of LS-based safety practices is less likely to be successful.

Use of LS to improve logging safety predicates on loggers' perceived need for safety improvements and willingness to adopt LS technology. Thus, the primary purpose of this study was to understand how and if LS might be successfully incorporated into logging operations to guide future recommendations and associated outreach communicating appropriate use of LS to loggers. Our specific objectives were to 1) evaluate Idaho loggers' perceived importance of developing new methods to improve workplace safety and likelihood of adopting LS safety methods, and 2) determine if intent to use LS varies by age, phone use, or the TPB attributes of attitude, norms, and PBC.

3.2. METHODS

3.2.1. Survey Population and Administration

This study and associated materials were reviewed and approved by the University of Idaho Institutional Review Board (project 18-037). Through a paper survey, we assessed logger perspectives on the most important roles for LS technology on logging operations and evaluated logger intent to adopt specific LS safety practices. LS safety applications are still an emerging concept in forest operations, so previous exposure to this technology was expected to be minimal or nonexistent in the general population of Idaho loggers. To ensure quality responses, we required participants to have appropriate and relevant background information for answering specific questions on LS devices, capabilities, and applications. Thus, we defined our population as all professionally certified loggers in the Idaho Logger Education to Advance Professionalism (LEAP) program and surveyed a convenience sample that included all certified loggers attending the "Location Sharing for Logging Safety" presentation at the 2018 LEAP update meetings. The LEAP update, administered by University of Idaho Extension, is an annual, one-day workshop offering in-depth coverage of forestry concepts for loggers and logging contractors. Participation in the update meeting satisfies training requirements necessary to maintain Pro-Logger accreditation in the state (UI Extension 2018). In 2018, the update was offered at three Idaho locations: Lewiston (March 20), Coeur d'Alene (March 21), and Sandpoint (March 22). Pro-Logger accreditation is a voluntary program administered by Idaho's Associated Logging Contractors (ALC) for professional timber harvesters, including logging contractors, loggers, forest owners, and forest products companies (ALC Pro-Logger). It indicates the continuing completion of advanced professional and safety training.

At the beginning of the LEAP presentation on LS, we distributed the survey to all attendees, along with a consent letter, LS informational handout, and raffle ticket. We explained the survey's purpose and procedure and informed attendees of the opportunity to be win a scale model log truck through a ruffle drawing at the conclusion of the presentation. Completion of the survey was integrated into the presentation, such that the presenter indicated when to answer specific questions and provided relevant content and background explanation. Immediately following the LEAP presentation, we announced the winner of the log truck and then collected all questionnaires, including both blank and completed copies.

In designing the LEAP presentation, the authors carefully considered the possibility of social desirability bias in survey response and thus attempted to present material in a factual, neutral manner. Due to potential negative biases arising from unease or hostility toward safety regulation (Egan 1997; Egan 1998), we avoided language in the LEAP presentation and survey that would imply necessity, so we could assess logger adoption as a voluntary action.

3.2.2. The Instrument

The logger survey encompassed seventeen close-ended questions. Questionnaire design and formatting were influenced by survey best practices outlined in Dillman et al. (2009), and TPB attribute measurement and scaling were based on guidelines suggested by Francis et al. (2004) and Montaño and Kasprzyk (2015).

The first four questions were presented in a forced-choice format with three answer options: "yes," "no," and "unsure." These questions addressed previous use, belief that various types of LS devices and features would improve workplace safety, and concern about worker privacy associated with LS reach. The topic of reach, or who receives positioning information (Figure 3.2), was included based on worker monitoring concerns voiced by Idaho loggers in the Newman et al. interview. The survey asked participants to indicate privacy concerns about real-time locations being shared with "coworkers at the jobsite" and "supervisors or others at a remote office or shop," in order to better define the circumstances under which shared positioning would be acceptable to loggers. Due to the availability of lower-cost LS receivers using smartphones as a communication conduit (goTenna, Beartooth), we asked loggers if they own a smartphone ("yes" or "no"), and, if so, how often they carry the phone with them while working on logging operations ("always," "often," "rarely," or "never"). Since adoption of safety practices predicates on a perceived need for safety improvements, we asked workers about the importance of finding new ways to improve safety on logging operations, from "very unimportant" to "very important" (5-point scale). Other questions in the first half of the survey addressed concern about carrying an extra device (3-point, unipolar scale) and priorities for the focus of LS technology, including “contacting off-site emergency response,” “finding injured workers quickly,” “alerting coworkers when someone needs helps,” and “preventing accidents on the jobsite” (ranking).

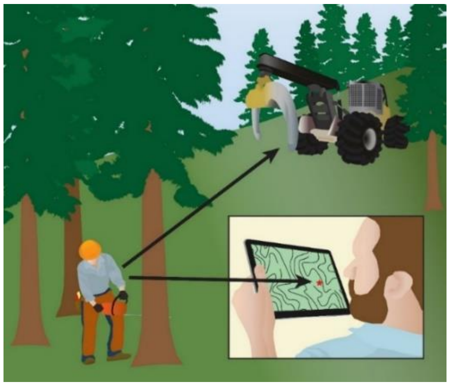

Figure 3.2. Illustration of *reach*: a LS device carried by the hand faller could transmit the worker’s location to other coworkers at the jobsite, such as the skidder operator in the top right corner, or to off-site employees, such as the supervisor shown in the bottom right.

The next five survey questions were framed according to the attributes of the TPB, with the purpose of assessing the likelihood that informed loggers would adopt safety practices involving use of LS devices (Figure 3.3). Since the analytic power of the TPB is generally higher the more detailed the behavior being assessed (Perloff 2010), we defined three, specific LS practices (behaviors) in our survey that corresponded to draft recommendations being considered for use of LS in logging safety: 1) “using personal, location-sharing devices (PLDs) with local, automatic location sharing for hand fallers,” 2) “using PLDs on all ground workers and heavy equipment,” 3) “using GPS-based PLDs and geofences for general situational awareness.”

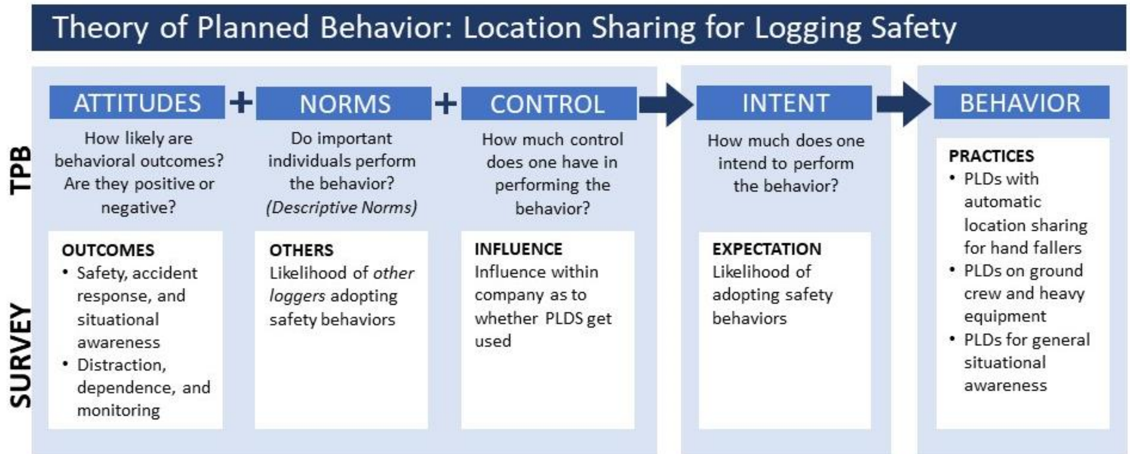

Figure 3.3. Attributes of the Theory of Planned Behavior and associated survey questions (Francis et al. 2004; Montaño and Kasprzyk 2015).

We used indirect measures of instrumental attitude in our survey, asking participants to first select outcome likelihood (“very unlikely,” “somewhat unlikely,” “unsure,” “somewhat likely,” “very likely”) then outcome value (“very bad,” “somewhat bad,” “neutral,” “somewhat good,” “very good”) (see Table 3.1 for scales of each attribute). Outcomes were based on logger interviews identifying potential advantages and disadvantages of LS on logging operations (Newman et al.). They included 1) “improving overall workplace safety,” 2) “developing a dependence on the technology,” 3) “finding injured coworkers faster,” 4) “causing distraction from other work activities,” 5) “knowing when coworkers might need help,” 6) “causing workers to feel like they are being watched or monitored,” and 7) “knowing when coworkers are in safe or unsafe areas.” In order to reduce respondent burden, the three behaviors (LS safety practices) were consolidated into an all-encompassing behavior of “using PLDS on logging operations” for measures of attitude. Referencing a single behavior allowed us to limit the number of question permutations and avoid requiring participants to discern between unfamiliar behaviors with nearly homogenous outcomes. We assessed perceived descriptive norms directly by asking survey participants to indicate the likelihood, from “very unlikely” to “very likely” (5-point Likert scale) that each of the three behaviors would be performed by other loggers. Since we evaluated occupational behaviors in which individual actions and decisions are interconnected with the actions and decisions of others, including co-workers, employees, and supervisors, our survey measured PBC instead of self-efficacy, with one question addressing degree of influence in whether PLDs get used (“a lot,” “some,” or “none”). We measured intention as the perceived likelihood (5-point Likert scale) of using PLDs in each of the ways indicated by the behaviors.

Table 3.1. Summary of TPB attributes’ measurement and scale.

Attribute	**Measure**	**Scale**
Intent	Direct	5-point, bipolar: unlikely--likely
Attitude (Instrumental)	Indirect	
Potential Outcome		5-point, bipolar: unlikely--likely
Value of Outcome		5-point, bipolar: bad--good
Perceived Norms (Descriptive)	Direct	5-point, bipolar: unlikely--likely
Perceived Behavioral Control	Direct	3-point, unipolar: none--a lot

Although TPB questionnaires typically employ 7-point scales, 5-point scales are occasionally used as well (Francis et al. 2004). To reduce cognitive burden without sacrificing survey content, we used 5-point scales for bipolar measures (attitude, norms, intent) and a 3-point scale for the unipolar question on control. High cognitive burden was anticipated for this survey due to the inevitable complexity involved with requiring participants to evaluate technology applications with limited processing time between introduction to the concepts and assessment.

The last four questions of the survey covered demographic and employment information, including age, years of logging experience, job title (hand faller, chaser/hooker, equipment operator, truck driver, owner, or other), and operation type (mechanized ground-based logging, partially mechanized ground-based logging, cable logging, or other). Multiple selections could be designated for job title and operation type.

3.2.3. Data Analysis

Surveys from the three LEAP update locations were pooled for data summaries and statistical analyses. Analysis of Variance (ANOVA) was used to determine if geographic biases existed for a subset of survey questions, including LS privacy concerns, smartphones at work, importance of new safety solutions, intent to adopt LS, and age. All tests were insignificant, indicating no response variation across location, except for one question: intent to use PLDs on all ground workers and heavy equipment (p-value = .0009). We believe this result was an artifact of the data and assumed for the purposes of subsequent analysis that there were no within-group differences for the three locations.

We report responses to each survey question as percentages in the Results section. The only question not represented in final results was the ranking of LS uses, as only 152 (about 54%) of respondents answered the question uniformly. Additionally, we calculated Cronbach's alpha, a measure of internal consistency, for select sets of survey questions. The higher the Cronbach's alpha value, the more likely compared questions measure the same underlying concept.

We completed statistical analysis for several specific questions using R open source statistical computing software (Version 1.0.44, 2016, The R Foundation, Vienna, Austria) (R Core). First, we analyzed the question on the importance of finding new ways to improve safety on logging operations. Responses were recoded numerically as 1, 2, 3, 4, and 5 for "very unimportant," "somewhat unimportant," "neutral," "somewhat important," and "very important," respectively. We compared median response scores using the Wilcoxon Sign-Rank Test (*wilcox.test* function) and the non-parametric Sign Test (*SignTest* function). We applied both tests because Wilcoxon Sign-Rank assumes medians are symmetrically distributed, an assumption only loosely met with our data set; whereas the comparable but less powerful Sign Test does not require a symmetrical distribution. With both methods we tested the null hypothesis that the median response was less than or equal to 3 ("neutral"), or that loggers do not place a high importance on new logging safety solutions.

To determine the likelihood loggers will adopt the three LS safety practices, we again used Wilcoxon Sign-Rank and Sign procedures, testing the null hypothesis that the median intent score is less than or equal to 3, where 1 corresponds to "very unlikely," 2 is "somewhat unlikely," 3 is "unsure," 4 is "somewhat likely," and 5 is "very likely." Additionally, we used two-way ordinal regression with Cumulative Link Models (*clm* and *Anova* functions in R) to determine (a) if intent varies by age or the frequency which loggers carry smartphones on logging operations, and (b) if there is an interaction effect between the two independent variables. We assumed older loggers would be less experienced and comfortable with technology generally and thus would be less likely to adopt technologically-based safety practices in the workplace. We also assumed individuals who more frequently carry a smartphone at work would be more accustomed to regular technology use and thus more likely to adopt LS. Age and frequency were recoded numerically in the data set, with 1, 2, 3, 4, and 5 representing age categories of "less than 20 years," "20-29 years," "30-39 years," "40-40 years," and "50 or more years," respectively, and frequency values of "never," "rarely," "often," and "always" corresponding to 1, 2, 3, and 4, respectively. The sample size (n) for smartphone carriers was 201, which included responses for only those individuals that indicated "yes" to a previous question on smartphone ownership (202 out of 279 total responses). Individuals who did not own smartphones were treated as *NA* in R and omitted from the model.

Regression analysis is frequently employed in TPB studies to assess if attitude, norms, or PBC correlate with intent (Adamos and Nathanail 2016; Colément and Van den Broucke 2008; Hankins et al. 2000; Welbourne and Booth-Butterfield 2005). Since our data set did not meet all the assumptions of linear or multiple regression, we used non-parametric ordinal regression, which is appropriate for ordered, categorical data, such as Likert scaled survey responses. For each behavior, we tested the null hypothesis that there was not a significant correlation between attitude, norms, or PBC with intent. The only assumption of ordinal regression is data demonstrate proportional odds, meaning the relationship (slope) between each pair of terms is the same. To avoid assumption violations for modeling of the second behavior (PLDs on workers and heavy equipment), we applied scale effects for the PBC term. Scale effects did not ameliorate violations for the third behavior (PLDs for general situational awareness); consequently, results for this particular model include assumption violations for the PBC variable.

Measures of outcome likelihood ("very unlikely," "somewhat unlikely," "unsure," "somewhat likely," and "very likely") and value ("very bad," "somewhat bad," "neutral," "somewhat good," and "very good") were recoded bipolarly as -2, -1, 0, 1, and 2, respectively. This scoring system is recommended by Ajzen (1991) and is typical for TPB studies (Montaño and Kaspryzk 2015). To express attitude as a single value across multiple possible outcomes, we calculated a total score by multiplying each outcome likelihood with each corresponding value and then summing across all seven outcomes. Scores for a single outcome could range from -4 to 4, and total scores for an individual survey participant could range from -28 to 28. Positive numbers represent situations in which desirable outcomes are likely to result from LS use or undesirable outcomes are avoided.

Conversely, negative numbers signify undesirable outcomes are likely or good outcomes are not. The higher the total score, the stronger the positive attitude toward LS safety behaviors.

Measures of PBC (“none,” “some,” “a lot”) were designated as 1, 2, and 3, respectively. Norm responses were numbered 1, 2, 3, 4, and 5 for “very unlikely,” “somewhat unlikely,” “unsure,” “somewhat likely,” and “very likely,” respectively. Since the survey measured attitude and PBC of a single, inclusive behavior (using PLDs on logging operations), all behaviors had one total attitude score and one PBC score. Each of the three behaviors had a separate norm and intent score.

3.3. RESULTS

3.3.1. Completed Sample

We distributed 331 surveys across the three LEAP update meetings (Lewison: 117, St. Maries: 83, Sandpoint: 131), and received 296 completed questionnaires (Lewiston: 96, St. Maries: 80, Sandpoint: 120) for an overall response rate of 89%. Sixteen surveys (Lewiston: 4, St. Maries: 6, Sandpoint: 6) were completed by non-loggers, including foresters and millworkers, as stated by participants in the job title question. We removed these 16 from analysis, so our final sample comprised of 280 surveys. According to the Bureau of Labor Statistics’ Quarterly Census of Employment and Wages, Idaho employed an average of 1,290 loggers (North American Industry Classification System code 113310) in 2016 (BLS QCEW 2016), and in June 2018 the current number of certified logging professionals in the state was 424 (ALC 2018). Thus, our completed sample represented approximately 66% of all Pro-Loggers and about 22% of all Idaho loggers.

3.3.2. Summary of Survey Results

Logger questionnaire responses are shown in Tables 3.2-3.4 as percentages for each answer category. Sample size (n) for individual questions is also presented. Sample size varied due to questions being left blank by respondents and to systematic exclusion of responses with more than one option selected or uninterpretable answers.

Demographic and employment results are summarized in Table 3.2. Our sample was comprised predominately of loggers fifty or more years old (55.4%) with over twenty years of logging experience (74.4%). Specific logger occupations varied, but the majority of respondents selected more than one job, including that of owner (39.4%), followed closely by loggers employed solely as equipment operators (30.3%). Most surveyed loggers work on ground systems, including mechanized, partially mechanized, or a combination of both (63.1%); whereas only about one quarter work on cable systems (26.4%).

Table 3.2. Survey responses for demographic and employment characteristic, with sample size (n) indicated in parentheses.

	Response Percentage (%)
Job Title *(n=277)*	
Hand faller only	1.8
Chaser/hooker only	0.4
Equipment operator only	30.3
Truck driver only	1.1
Owner only	13.0
Multiple jobs, including owner	39.4
Multiple jobs, not including owner	10.5
Other	3.6
Operation Type *(n=276)*	
Mechanized ground only	33.0
Partially mechanized ground only	16.3
Cable only	7.2
Fully and partially mechanized	13.8
Ground and cable	19.2
Other	10.5
Age *(n=278)*	
20-29 years	7.9
30-39 years	20.5
40-49 years	16.2
50 or more years	55.4
Logging Experience *(n=278)*	
9 or less years	7.9
10-19 years	17.6
20-29 years	21.9
30-39 years	25.9
40 or more years	26.6

Based on questions about LS devices with three answer options (“yes,” “no,” “unsure”), the majority of sampled loggers did not have previous experience using LS devices but did believe that such technology could improve safety on active logging operations (Table 3.3, Sections A-C). Two-way radios with LS had the most support (78.8% indicated “yes”), followed by devices that share locations through smartphones (72.1%). Specific device features identified by loggers as having the potential to improve workplace safety included alerts when workers enter dangerous areas (76.9%); automatic updates of user positions to coworkers at the jobsite (72.7%); messaging through text, voice, or video (72.2%); and SOS or Help buttons to contact coworkers at the jobsite (83.3%), supervisors at the office (62.4%), or emergency services (79.0%). Questions concerning emergency response as a type of device and as a feature demonstrated low internal consistency (Cronbach’s alpha of 0.37). The only feature not deemed useful for improving safety was the ability to send automatic position updates to supervisors at the office, for which only 33.9% of respondents selected “yes.” More loggers reported privacy concerns when positions are seen by supervisors or others at a remote office or shop (32.6%) than for coworkers at the jobsite (18.8%); although the majority of loggers expressed no concern related to worker privacy and use of real-time LS on logging operations (Table 3.3, Section D). Cronbach's alpha values for survey questions on automatic position updates and privacy concerns were 0.06 for LS with coworkers and 0.25 for LS with supervisors.

Table 3.3. Survey response percentages for No/Unsure/Yes questions, with sample size (n) indicated in parentheses. Answer categories chosen by 50% or more of survey participants are highlighted in grey.

	Response Percentage (%)		
	No	*Unsure*	*Yes*
A. Previous use of LS devices			
Emergency receivers *(n=271)*	91.5	1.8	6.6
Two-way radios with LS *(n=270)*	79.3	1.1	19.6
Smartphone receivers *(n=271)*	87.8	1.1	11.1
B. Improvement to safety by device			
Emergency receivers *(n=263)*	16.0	20.5	63.5
Two-way radios with LS *(n=269)*	8.6	12.6	78.8
Smartphone receivers *(n=272)*	14.0	14.0	72.1
C. Improvement to safety by feature			
Dangerous area alerts *(n=277)*	11.9	11.2	76.9
Automatic updates to coworkers *(n=275)*	13.1	14.2	72.7
Automatic updates to supervisors *(n=271)*	47.2	18.8	33.9
Help button to coworkers *(n=275)*	7.3	9.5	83.3
Help button to supervisors *(n=274)*	24.1	13.5	62.4
Help button to emergency services *(n=276)*	8.3	12.7	79.0
Messaging *(n=273)*	12.8	15.0	72.2
D. Privacy concerns associated with real-time LS			
Coworkers *(n=276)*	72.5	8.7	18.8
Supervisors *(n=273)*	56.0	11.4	32.6

Seventy-four percent (72.4%) of loggers own a smartphone (n=279), and 96.4% of those loggers report carrying their phone with them while working on logging operations (n=201), with 52.7% "always" carrying their phone, 30.3% "often" carrying it, and only 13.5% "rarely" with it. Loggers overwhelmingly agreed that finding new ways to improve safety on logging operations is important (67.8% chose "very important" and 19.2% chose "somewhat important"), with only 1.8% of respondents marking it as unimportant (0.7% selected "very unimportant" and 1.1% selected "somewhat unimportant") (n=276). When asked to indicate degree of concern related to carrying an extra device, such as a radio or smartphone, while working on logging operations, most respondents felt either "not at all concerned" (56.0%) or only "somewhat concerned" (34.7%), and only 9.4% of respondents indicated they were "very concerned" about carrying an extra item (n=277).

Over half of participants thought each of the seven potential outcomes of using PLDs on logging operations were likely (Table 3.4, Section C). The greatest consensus for any one outcome was for finding injured coworkers faster, which 54.9% of loggers deemed "very likely" to occur and 66.8% valued as "very good" (Table 3.4, Section D). Other "very good" outcomes included: improving overall workplace safety (44.7%), knowing when coworkers might need help (56.6%), and knowing when workers are in safe or unsafe areas (42.0%). Positive outcome responses had high internal consistency, with Cronbach's alphas of 0.86 (for likelihood) and 0.85 (for value). Loggers were mostly "unsure" about the other three outcomes: developing a dependence on the technology (39.1%), causing distraction from other work activities (32.0%), and causing workers to feel like they are being watched or monitored (38.5%), although about 20-30% considered these "somewhat bad." Some indicated benefits to technology dependence (21.1% "somewhat good") and workers feeling monitored (15.2% "somewhat good"). The mean total attitude score, accounting for both likelihood and value of all outcomes, was 6 on a scale of -28 to 28, with a standard deviation of 8 (n=248). This score represents an overall (weakly) positive attitude toward using PLDs on logging operations.

Table 3.4. Survey responses for TPB-based questions, with sample size (n) indicated in parentheses. Answer categories chosen by 50% or more of survey participants are highlighted in grey.

	Response Percentage (%)				
	Very Unlikely	*Somewhat Unlikely*	*Unsure*	*Somewhat Likely*	*Very Unlikely*
A. **Intent** - Likelihood of adopting LS (self)					
Automatic LS of hand fallers *(n=270)*	10.7	14.8	18.9	27.0	28.5
PLDS on workers & equipment *(n=274)*	10.2	14.6	23.7	32.1	19.3
PLDS for situational awareness *(n=273)*	10.3	13.9	28.9	29.7	17.2
B. **Norms** - Likelihood of others adopting LS					
Automatic LS of hand fallers *(n=273)*	4.0	10.3	28.9	38.8	17.9
PLDS on workers & equipment *(n=273)*	2.6	15.4	38.1	34.8	9.2
PLDS for situational awareness *(n=272)*	4.4	14.0	40.1	34.2	7.4
C. **Attitude** - Likelihood of PLD use outcomes					
Improving overall safety *(n=276)*	4.0	11.2	15.6	39.9	29.3
Developing technology dependence *(n=273)*	6.2	12.1	27.8	33.0	20.9
Finding injured coworkers faster *(n=273)*	4.8	4.4	8.4	27.5	54.9
Causing distraction *(n=275)*	2.5	13.5	23.6	41.5	18.9
Knowing when coworkers need help *(n=272)*	4.0	2.6	10.7	41.2	41.5
Causing workers to feel monitored *(n=276)*	6.2	13.0	19.9	34.1	26.8
Knowing if workers are in safe areas *(n=277)*	2.9	8.7	16.6	43.0	28.9
	Very Bad	*Somewhat Bad*	*Neutral*	*Somewhat Good*	*Very Good*
D. **Attitude** - Value of PLD use outcomes					
Improving overall safety *(n=273)*	0.7	0.4	17.9	36.3	44.7
Developing technology dependence *(n=274)*	8.0	23.4	39.1	21.2	8.4
Finding injured coworkers faster *(n=274)*	1.5	0.0	8.8	23.0	66.8
Causing distraction *(n=275)*	18.2	31.3	32.0	11.6	6.9
Knowing when coworkers need help *(n=272)*	0.7	0.4	11.4	30.9	56.6
Causing workers to feel monitored *(n=270)*	14.4	27.0	38.5	15.2	4.8
Knowing if workers are in safe areas *(n=269)*	1.5	1.5	17.5	37.5	42.0
	None	*Some*	*A Lot*		
E. **Control** - Influence in PLD use *(n=273)*	17.2	35.2	47.6		

Surveyed loggers indicated high PBC, with 47.6% reporting having "a lot" of influence in whether PLDs get used within the company or organization, and only 17.2% stating no influence (Table 3.4, Section E). Loggers varied in their estimation of intent among other loggers (a measure of descriptive norms), but generally were either “unsure” about others’ actions or predicted they were “somewhat likely” to adopt each of the three safety practices (Table 3.4, Section B).

Overall, loggers indicated an intent to use LS on their logging operations, with high internal consistency among the three behaviors (Cronbach’s alpha of 0.84). Fifty-six percent (55.5%) of respondents reported they were likely (“somewhat likely” or “very likely”) to use PLDs with local, automatic location sharing for hand fallers, and 51.4% were likely to use PLDs on all ground workers and heavy equipment; whereas only about one quarter of participants reported they were unlikely to use these safety practices (Table 3.4, Section A). Intent was lowest for using GPS-based PLDs and geofences for general situational awareness (41.6% likely to use), while using PLDs with local, automatic LS for hand fallers had the most support, with 28.5% of loggers selecting “very likely.” Figure 3.4 shows survey responses for the likelihood of using each of the three safety practices.

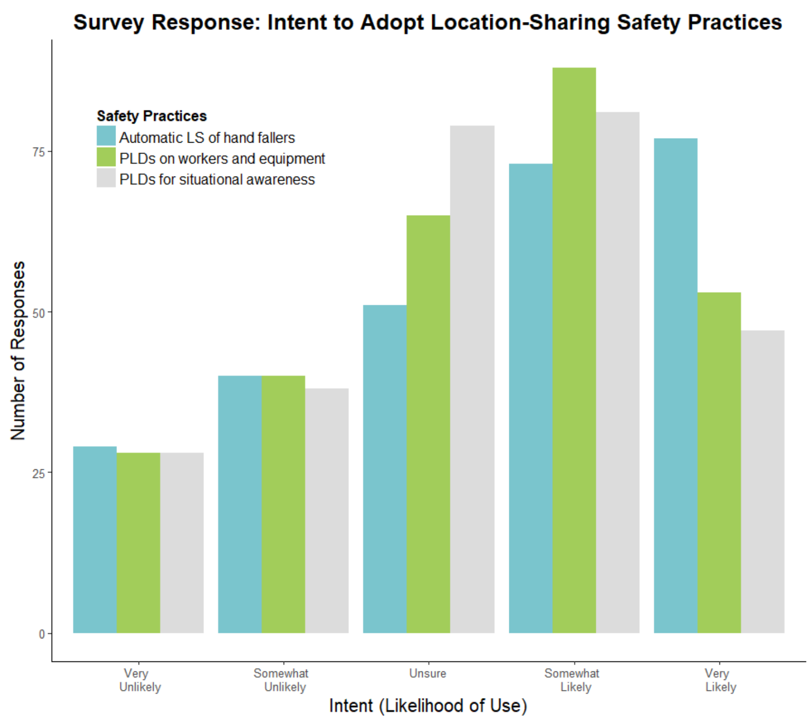

Figure 3.4. Logger intent to adopt LS safety practices: number of survey responses for different levels of likelihood.

3.3.3. Hypotheses

P-values for Sign and Wilcox Sign-Rank tests are presented in Table 3.5, along with Sign Test medians and Wilcoxon Sign-Rank Test pseudo-medians. According to both tests, we rejected the null hypothesis that loggers do not perceive an importance to finding new safety solutions, as the median response score of 5 (“very important”) was significantly greater than 3 (“neutral”). Analysis also indicated that all three LS safety behaviors were significantly likely to be used by participants, rejecting the null hypothesis that median scores were less than or equal to 3 (“unsure”).

Table 3.5. Results of Sign Tests (black text) and Wilcoxon Sign-Rank Tests (grey text) (alpha = 0.05).

Survey Question	**Null Hypothesis**	**Median**	**P-value**
Importance of finding new ways to improve safety	median ≤ 3 ("neutral")	5 5.0	< 0.001 < 0.001
Likelihood of using automatic LS for hand fallers	median ≤ 3 ("unsure")	4 3.5	< 0.001 < 0.001
Likelihood of using PLDs on workers/equipment	median ≤ 3 ("unsure")	4 3.5	< 0.001 < 0.001
Likelihood of using PLDs for situational awareness	median ≤ 3 ("unsure")	3 3.5	< 0.001 .0001

Ordinal regression results are shown in Tables 3.6 and 3.7, with p-values and Chi-Squared (X^2) test statistics for each independent variable. We failed to reject the null hypothesis that intent varies by age; however, results indicate intent does vary by the frequency at which loggers carry their smartphones during work activities, such that individuals who have their smartphone with them more often on logging operations are more likely to adopt the LS safety practices (Table 3.6). Age and phone use did not have significant interaction effects.

Table 3.6. Results of ordinal regression (alpha = 0.05) for intent versus age and smartphone frequency with interactions effects (Age:Phone).

	P-value **(X^2 test statistic)**		
Behavior	*Age*	*Phone*	*Age:Phone*
Automatic LS for hand fallers	.2077 (4.552)	< 0.001 (250.204)	.7915 (5.470)
PLDs on workers and heavy equipment	.6271 (1.744)	< 0.001 (261.657)	.7389 (6.010)
PLDs for general situational awareness	.6578 (1.607)	< 0.001 (254.152)	.9674 (2.919)

Results of ordinal regression evaluating the effect of attitude, descriptive norms, and PBC on intent to perform safety behaviors show that intent varies significantly by total attitude score and norms for all three behaviors and varies by control for two behaviors (Table 3.7). Thus, for the survey sample, TPB attributes are correlated with logger likelihood of using PLDs. One model (PLDs for general situational awareness) had assumption violations for the PBC term, so results of this model should be interpreted with caution.

Table 3.7. Results of ordinal regression (alpha = 0.05) for intent versus Attitude, Control, and Norms of three behaviors.

	P-value **(X^2 test statistic)**		
Behavior	*Attitude*	*Norms*	*Control*
Automatic LS for hand fallers	< 0.001 (75.253)	< 0.001 (55.839)	0.0358 (6.657)
PLDs on workers and heavy equipment	< 0.001 (75.143)	< 0.001 (53.225)	0.9851 (0.030)
PLDs for general situational awareness	< 0.001 (76.003)	< 0.001 (74.293)	0.0453 (6.187)

3.4. DISCUSSION

Fatal injuries continue to plague the logging industry, and according to our survey results, a significant number of participants (67.8%) believe that developing new safety solutions is "very important." LS technology may be able to help improve situational awareness on logging operations, both before and in the critical moments after an injury incident. In the former case, interventions such as GNSS-based warning alerts may help reduce injury occurrence. In the latter, LS technology may serve two roles: 1) identifying injury occurrence through smart detection (e.g. advanced person-down alerts), even when injured individuals are unable to actively communicate the need for help, and 2) expediting coworkers' search for injured individuals. Thus, LS may help enhance workplace safety and reduce the frequency or severity of occupational injuries in three distinct and important ways. Understanding logger perceptions of LS applications will be essential for focusing future studies of potential LS devices and directing outreach that recommends LS to loggers.

Idaho loggers are mostly inexperienced with LS technology in the workplace but generally agree on the potential for LS devices to improve occupational safety in logging operations, particularly those devices that allow injured individuals to notify coworkers of emergencies. More surveyed loggers thought a help button that could send distress calls to coworkers would improve safety than any other LS feature. Over three-fourths of loggers also indicated a benefit to help buttons contacting emergency services, although emergency search and rescue receivers were not as valued as other types of devices, such as two-way radios with LS capabilities or receivers that interface with smartphones. Low internal consistency between questions relating to emergency response (Cronbach's alpha of 0.37) could suggest a possible measurement error or imply loggers value LS devices that offer two-way communication in addition to the ability to contact off-site emergency services. Although loggers supported devices featuring automatic LS among coworkers, they did not perceive a value in sharing real-time positions with supervisors. These views seem to be independent of reported privacy concerns (Cronbach's alpha of 0.06 for coworkers and 0.25 for supervisors). Loggers generally did not express unease about sharing real-time locations, though response differed by device reach, with more privacy concern for supervisors receiving positioning data (32.6% of loggers) than for coworkers (18.8%). Survey results suggest LS devices and features that focus on connecting coworkers at the jobsite and initiating emergency response, with capabilities such as automatic position updates, help buttons, and messaging, may be most effective at improving workplace safety on logging operations.

Recreational-grade, smartphone-based receivers may offer an affordable and accessible LS solution for loggers, addressing previously cited concerns about cost and difficulty learning a new technology (Newman et al.). These small antennae synchronize with smartphones via Bluetooth. Geographic positions determined by the phone's internal GNSS receiver can be shared with other in-range devices through a RF signal. Seventy-two percent (72.4%) of loggers in this study already own a smartphone and thus are more likely to be comfortable using the phone's interface for new safety applications. Additionally, of those who own smartphones, just over half report always carrying the phone at logging operations, and nearly one third often have their phone with them. Consequently, using a small, lightweight RF receiver along with a smartphone for LS would likely pose less of a burden or annoyance to loggers. Smartphone-based options might be especially appealing to hand fallers, who already carry various equipment and gear throughout the work day. Recreational devices may not include as many capabilities as military-grade, purpose-built tactical radio units but still allow users to share locations and messages, if not quite in real time. Some also have the help button feature, which was strongly supported by loggers as a means to improve safety.

The majority of surveyed loggers predicted that each of the proposed outcomes to using LS technology were likely, with the highest consensus for finding coworkers faster (54.9% selected "very likely"). Loggers also valued this benefit most, with 66.8% of participants classifying it as a "very good" result. Internal consistency among all presumed positive outcomes was high, with Cronbach's alpha of 0.86 for likelihood and 0.85 for value, suggesting all four items measured the same underlying concept of improving occupational safety.

Loggers consistently agreed in the value of safety improvements but were more unsure about the outcomes we expected to be negative based on formerly expressed opinions (Newman et al.). Participants assigned these three items (dependence on the technology, distraction, and feeling monitored) more variable levels of desirability. For instance, 21.2% of loggers thought technology dependence was "somewhat good," compared to 23.4% who considered this outcome "somewhat bad." This trend could indicate that loggers do not prioritize concerns uniformly. Whereas some may perceive technological dependence as a drawback, others may consider it an advantage compensating for human error. Future education and promotion of LS technology should thus emphasize potential device limitations and sources of error, such as reduced GNSS-RF accuracy attributed to canopy and topographical features (Wempe and Keefe 2017; Zimbelman and Keefe 2018), or patterns of movement among interacting workers (Zimbelman et al. 2017). Evaluation of workers feeling monitored may also vary by individual, based on beliefs about expectation of privacy at work. The effects of nonresponse error on the results is unknown but likely minimal due to a high response rate (89%).

Our completed sample represented few individuals (less than 2%) employed solely as ground workers, such hand fallers or chasers and hookers. These loggers, who face high injury risks and would be most likely to carry LS devices directly on their person throughout the work day, may have underrepresented opinions in this study. The advantage of surveying a large number of company owners (52.4% of participants), however, is gaining the perspective of those most likely to purchase devices and introduce LS-based safety practices to logging operations. For instance, nearly half of surveyed loggers feel they have a lot of influence in whether PLDs would get used. Our sample also comprised of few individuals with less than nine years of logging experience (7.9%), a bracket which includes those workers most likely to be injured on logging operations (individuals with less than one year of logging experience) (Shaffer and Milburn 1999).

In order for LS to be successfully implemented into logging safety procedures, demonstrated proficiency of LS devices must be paired with loggers' perceived value of the technology and willingness to incorporate LS into daily operations, despite barriers. The key results from this study were (a) surveyed Idaho loggers with advanced training on industry and safety concepts did recognize the safety benefits of LS, and (b) approximately half of loggers indicated they are likely to use LS safety practices (median intent scores were significantly greater than neutral values). Internal consistency was high among the three safety practices (Cronbach's alpha of 0.84), so loggers may not have differentiated between the fine details of each one. However, more loggers selected "very likely" to use automatic LS for hand fallers (28.5%) than using PLDs on workers and heavy equipment (19.3%) or using PLDs for general situational awareness (17.2%). These results are consistent with previous interviews in which Idaho loggers suggested LS primarily for hand faller positioning (Newman et al.). About 40% of respondents likely work with hand fallers based on those who reported operation type as partially mechanized ground based, cable, or both; whereas one third of participants work on mechanized ground-based operations, which do not typically employ ground workers. The prevalence of mechanized loggers could account for the higher predictions of other loggers adopting LS safety practices, as more participants selected "somewhat likely" for others than for themselves. Logger intent did not vary by age but was related to the reported frequency of carrying a smartphone at logging operations. Those accustomed to regular smartphone use may be more experienced and comfortable with learning new, digital devices and thus may be more amenable to using LS technology.

Intent correlated with attitudes and descriptive norms for all behaviors, and with PBC for two of three behaviors, indicating that the TPB is an appropriate framework for modeling influences on logger intent to adopt technologically-based health behaviors. Since descriptive rather than injunctive norms were measured in our survey, we cannot postulate on the exact nature of the relationship between intent and norms, whether loggers experience peer pressure to adopt safety practices or whether they believe their opinions are representative of the larger logging community. Results simply suggest that loggers are behavioral indicators for each other. However, Morris and Venkatesh (2000) demonstrated the initial importance of subjective norms in motivating technology adoption and sustained use of software systems among older workers. They suggested older individuals may feel less confident in their ability to make judgements about technology; although, eventually their motivations align with younger workers who are more motivated by attitude, particularly instrumental (usefulness) beliefs. Future outreach pertaining to LS should consider the role of subjective norms in initial introduction of technologically-based safety practices to a workforce predominated by older loggers (over half of our sample were fifty years or more), as well as the importance of instrumental attitudes, which correlated with intent in our survey. During the LEAP presentation, we addressed both instrumental attitudes, informing participants of the potential uses of LS, as well as descriptive norms, describing previous interview results of logger-suggested applications for LS. Although we did not reference perceived decision-making authority in the LEAP presentation, we did briefly mention differing cost points among LS devices, which may factor into loggers' intent to adopt LS safety practices as another type of control: perceived difficulty. We did not explicitly explore the role of difficulty in the survey, but the relationship between intent and barriers to difficulty, such as cost, could be explored in a future study.

Finally, we defined our safety practices as occupational health behaviors and thus analyzed use of LS in the context of the TPB; however, behaviors associated with LS could also be expressed as a form of technological adoption. Using a lens such as the Technology Acceptance Model (TAM), which relates acceptance and use of technology to perceived usefulness and ease-of-use of information systems (Davis 1989), may provide additional insight into logger adoption of LS. In a comparison of the TAM and TPB, Mathieson (1991) found the TAM affords a slight empirical advantage buts affords less specific opinion information than the TPB.

3.5. CONCLUSIONS

Idaho loggers surveyed at three logger training programs conveyed overall positive perceptions in favor of using LS to improve workplace safety on logging operations. They particularly valued the ability to alert coworkers of emergency situations and to respond quickly, such as finding an isolated, injured coworker. Loggers are likely to adopt LS safety practices, especially for real-time positioning of hand fallers. Survey results encourage further evaluation and development of LS-based safety applications to reduce fatal and near-fatal injuries in logging, as well as formalization of recommendations on appropriate and inappropriate uses.

CHAPTER 4: CONCLUSIONS

The goal of introducing LS practices to logging operations is to improve occupational safety by reducing the frequency and severity of workplace injuries and fatalities. The primary benefit of LS technology is providing loggers with increased situational awareness in dynamic environments, especially those in which ground workers and heavy equipment work in close proximity on difficult terrain or in adverse weather and reduced visibility conditions (Keefe et al. 2014). LS technology may help to improve logging safety in three ways: 1) it may aid in the prevention of injuries with interactive hazard warnings based on hazard proximity; 2) it may help alert coworkers or emergency response units of jobsite injury occurrence, especially incidents involving solitary workers in remote areas; and 3) it may facilitate faster or more efficient injury response. For example, LS could equip operators with increased spatial awareness using real-time, position mapping or geofences that trigger sound alerts when workers approach unsafe work distances. LS can also form the basis for detection and location of emergency situations, making coworkers aware of injuries with person-down alerts that are triggered when motion stops or when a combination of sensor measurements occur in tandem. For instance, lack of movement for a pre-determined period of time coupled with low decibel sound levels associated with an idling or stopped chainsaw, could activate a warning for loggers to check on a potentially injured coworker. When an injury has occurred, LS can provide the current location of an injured individual to accelerate coworker response and minimize the wait for medical attention.

The research presented in the preceding chapters and related publications demonstrates how GNSS-RF transponders can be used to characterize complex, spatial inter-relationships on logging operations in novel ways that have not previously been reported in the literature. Through real-time positioning, we quantified worker-hazard distances, both spatially and temporally, and defined worker safety based upon proximity to multiple, simultaneous hazards that are common on cable logging operations. Our results showed that ground crew spend approximately one third of the work day in hazardous conditions associated with equipment and approximately half of their day near snags. Due to the regularity at which loggers occupy high-risk areas, hazard geofences programmed at recommended safe working distances, about one tree length for heavy equipment and two tree lengths for snags, may not be able to identify imminent injury risks. Furthermore, reduced positioning accuracy attributed to canopy (Deckert and Bolstad 1996; Blum et al. 2015; Liu and Brantigan 1995; Rempel and Rodgers 1997) may inhibit adequate distinction of hazard proximity. We established that Raveon Atlas PT GNSS error associated with mature forest significantly affects worker placement inside or outside of hazard geofences and corresponding designation of safety status. The potential safety consequences of status misclassification due to GNSS error will depend on the type of error. A false positive, in which a transponder incorrectly locates a worker inside a geofence, is unlikely to endanger workers but could potentially distract an operator needlessly. A false negative, however, could expose ground crew to greater risk if operators maneuver machinery and materials assuming workers are safely in-the-clear. Figure 4.1 illustrates how GNSS error of five and ten meters would create circles of position uncertainty, with radii equal to the error correction. Circles crossing the geofence indicate potential misclassifications of worker safety status, with false positives shown in blue, and false negatives depicted in red. Due to demonstrated canopy effects on GNSS-derived safe work distances, geofences are not recommended for informing equipment operator decisions about whether ground crew are safely in-the-clear but could be used to help notify operators of worker movement into and out of their workspaces. Also, LS for hazard proximity awareness should supplement, rather than replace, other forms of safety practices. For instance, loggers should not abandon current precautions, including observational or audial confirmation of workers in-the-clear.

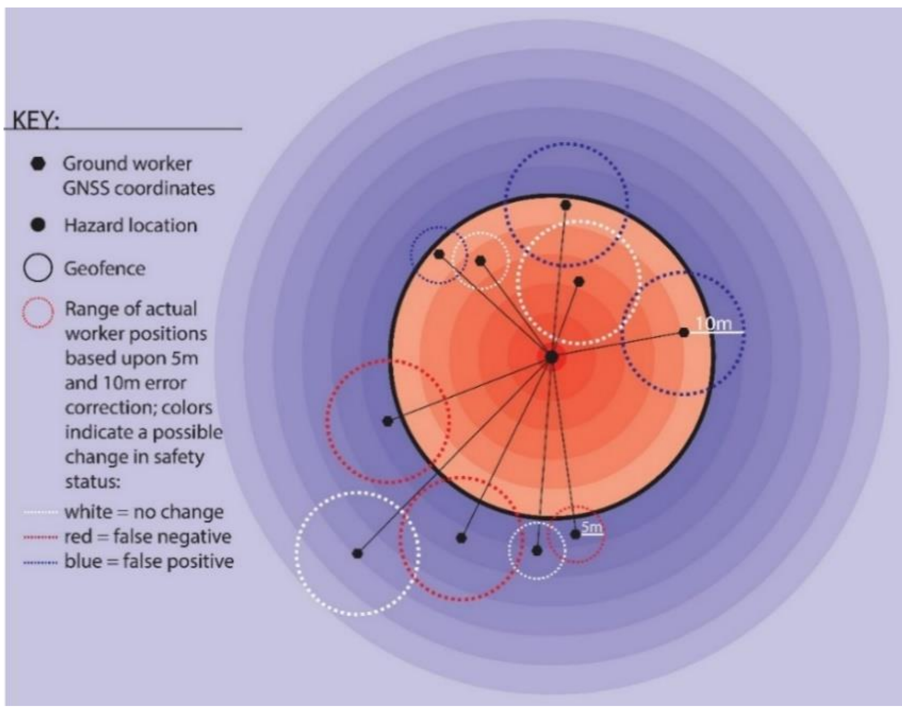

Figure 4.1. Effect of GNSS error on worker safety status relative to a geofence.

High-accuracy GNSS receivers are recommended for fine-resolution LS applications, such as worker positioning around mobile hazards. Meter, or sub-meter, accuracies are unattainable under forest canopies with differential GPS (DGPS) (Kaartinen et al. 2015), or real-time kinematic (RTK) techniques (Bakula et al. 2009; Haughlin et al. 2007), respectively, but these methods can be expensive (Takasu and Yasuda 2008). Additionally, there is relatively little research quantifying the extent to which they can provide highly accurate paths of equipment or workers in continuous motion under forest canopies. Error correction methods may not be as critical for more generalized positioning applications, however, such as injury response, in which errors are unlikely to increase injury risks for workers.

In addition to demonstrating a specific application of LS and quantifying associated device accuracy, we showed in Chapter 3 that there is wide support among Idaho loggers for use of LS in logging safety applications. Surveyed loggers agreed on the importance of finding new safety solutions (indicated by 87% of participants) and on perceived safety benefits of multiple LS features, including geofencing (77%), automatic updates for coworkers (73%), emergency buttons to contact coworkers (83%), supervisors (62%), or emergency response (79%), and messaging (72%). Loggers value knowing when coworkers need help (42% of participants deemed it “very good”) and having the ability to find injured coworkers faster (55% “very good”), and they generally felt these outcomes were more likely and more valuable than knowing when coworkers were in safe areas (29% “very good”). Thus, LS devices may be most successful at improving logging safety as an instrument for communicating and responding to workplace injuries. Emergency response may also be a more appropriate implementation of LS based on lower resolution requirements negating the need for high GNSS accuracy. Approximately half of surveyed loggers indicated they are likely to use a) automatic LS for hand fallers (56%), b) PLDs on workers and heavy equipment (51%), and c) PLDS for general situational awareness (47%). According to the Theory of Planned Behavior, the intent indicated by loggers is a strong predictor of future actions. Thus, our results indicate overall favorable perceptions of LS for logging safety and support its further development. Survey results are also valuable for advising revision of draft recommendations for use of LS in logging.

In conclusion, LS has demonstrated applications for logging safety with some caveats on use based on positioning error observed in multiple field experiments (Wempe et al. 2017; Zimbelman et al. 2017; Zimbelman et al. 2018). Idaho loggers indicated support for LS and are likely to use LS devices for logging safety. Recommendations outlining appropriate and inappropriate uses are advised, however, to avoid inadvertent misuse of the technology. Future studies should focus on evaluation of other GNSS-RF LS devices, such as lower-cost, recreational-grade units, including smartphone-based LS receivers, that may be more user-friendly and appealing to logging workers concerned about cost. With these devices, LS may be coupled with smartphone sensor measurements from accelerometers, gyroscopes, and microphones to quantify worker activities in more advanced ways. Assessing the accuracy and reliability of these and other promising solutions for data sharing in remote environments will further help to inform recommendations for how to effectively deploy devices in logging safety applications.

REFERENCES

Adamos, G.; Nathanail, E. Predicting the effectiveness of road safety campaigns through alternative research designs. *Journal of Safety Research* **2016**, *59*, 83-95, doi: 10.1016/j.jsr.2016.10.003.

Anderson, D.M. Virtual fencing—Past, present and future. *Rangel. J.* **2007**, *29*, 65–78, doi:10.1071/RJ06036.

Ajzen, I. The Theory of Planned Behavior. *Organizational Behavior and Human Decision Processes,* **1991,** *50*, 179-211, doi: 10.1016/0749-5978(91)90020-T.

Armitage, C. J.; Conner, M. Efficacy of the Theory of Planned Behavior: a meta-analytic review. *British Journal of Social Psychology* **2001**, *40*, 471-499, doi: 10.1348/014466601164939.

Associated Logging Contractors, Personal communication, 11 June 2018.

Associated Logging Contractors, Pro-Logger Program. Available online: http://www.idahologgers.com/pro-logger.html (accessed on 6 March 2018).

Bakula, M.; Oszczak, S.; Pelc-Mieczkowska, R.; Performance of RTK Positioning in Forest Conditions: Case Study. *Journal of Surveying Engineering* **2009**, *135*(3), 125-130, doi: 10.1061/(ASCE)0733-9453(2009)135:3(125).

Becker, R.M.; Keefe, R.K.; Anderson, N.M. Use of real-time GNSS-RF data to characterize the swing movements of forestry equipment. *Forests* **2017**, *8*, 1–15, doi:10.3390/f802044.

Bell, J.L.; Helmkamp, J.C. Non-fatal injuries in the West Virginia logging industry: Using workers' compensation claims to assess risk from 1995 through 2001. *Am. J. Ind. Med.* **2003**, *44*, 502–509, doi:10.1002/ajim.10307.

Bell, T. Automatic tractor guidance using carrier-phase differential GPS. *Computers and Electronics in Agriculture* **2000,** *25*(1-2), 53-66, doi: 10.1016/S0168-1699(99)00055-1.

Bettinger, P.; Wing, M.G. *Geographic Information Systems: Applications in Forestry and Natural Resource Management*; McGraw-Hill, Higher Education: New York, NY, USA, 2004; p. 230, 0072562420.

Blue, C. L.; Wilbur, J.; Marston-Scott, M.V. Exercise among blue-collar workers: application of the Theory of Planned Behavior. *Research in Nursing and Health* **2001**, *24*, 481-493, doi:10.1002/nur.10008.

Blum, R.; Bischof, R.; Sauter, U.H.; Foeller, J. Tests of reception of the combination of GPS and GLONASS signals under and above forest canopy in the Black Forest, Germany, using choke rings antennas. *Int. J. For. Eng.* **2015**, *27*, 2–14, doi:10.1080/14942119.2015.1122945.

Bordas, R.M.; Davis, G.A.; Hopkins, B.L.; Thomas, R.E.; Rummer, R.B. Documentation of hazards and safety perceptions for mechanized logging operations in East Central Alabama. *J. Agric. Saf. Health* **2001**, *7*, 113–123, doi:10.13031/2013.2673.

Bureau of Labor Statistics 2014 Census of Fatal Occupational Injuries. Available online: www.bls.gov/iif/oshwc/cfoi/cfch0013.pdf (accessed on 17 October 2016).

Bureau of Labor Statistics 2015 Census of Fatal Occupational Injuries. Available online: https://www.bls.gov/iif/oshwc/cfoi/cfch0014.pdf (accessed on 25 April 2017).

Bureau of Labor Statistics Occupational Injuries/Illnesses and Fatal Injuries Profiles. Available online: https://data.bls.gov/gqt/InitialPage (accessed on 24 April 2017).

Bureau of Labor Statistics Quarterly Census of Employment and Wages, 2016 Annual Averages. Available online: https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables (accessed on 23 October 2017).

Businger, S.; Chiswell, S. R.; Bevis, M.; Duan, J.; Anthes, R. A.; Rocken, C.; Ware, R. H.; Exner, M.; VanHove, T.; Solheim, F. S. The Promise of GPS in Atmospheric Monitoring. *Bulletin of the American Meteorological Society* **1996**, *77*(1), 5-18, doi: 10.1175/1520-0477(1996)077<0005:TPOGIA>2.0.CO;2.

Butler, Z.; Corke, P.; Peterson, R.; Rus, D. From robots to animals: Virtual fences for controlling cattle. *Int. J. Robot. Res.* **2006**, *25*, 485–508, doi:10.1177/0278364906065375.

Carter, E.A.; McDonald, T.P.; Torbert, J.L. Application of GPS technology to monitor traffic intensity and soil impacts in a forest harvest operation. In Proceedings of the Tenth Biennial Southern Silvicultural Research Conference, Shreveport, LA, USA, 16–18 February 1999.

Colémont, A.; Van den Broucke, S. Measuring determinants of occupational health related behavior in flemish farmers: An application of the Theory of Planned Behavior. *Journal of Safety Research* **2008**, *39*, 55-64, doi: 10.1016/j.jsr.2007.12.001.

Davis, F.D. A technology acceptance model for empirically testing new end-user information systems: theory and results. Ph.D., Massachusetts Institute of Technology, Cambridge, Massachusetts, December 20, 1985.

Deckert, C.; Bolstad, P.V. Forest canopy, terrain, and distance effects on Global Positioning System point accuracy. *Photogramm. Eng. Remote Sens.* **1996**, *62*, 317–321.

DeJoy, D. M. Theoretical Models of Health Behavior and Workplace Self-Protective Behavior. *Journal of Safety Research* **1996**, *27*(2), 61-72, doi: 10.1016/0022-4375(96)00007-2.

D'Eon, R.G.; Serrouya, R.; Smith, G.; Kochanny, C.O. GPS Radiotelemetry error and bias in mountainous terrain. *Wildl. Soc. Bull.* **2002**, *30*, 430–439.

Dillman, D. A.; Smyth, J. D.; Christian, L. M. *Internet, Mail, and Mixed-mode Surveys The Tailored Design Method Third Edition*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2009, ISBN: 1118456149.

Egan. A. F. The introduction of a comprehensive logging safety standard in the USA—the first eighteen months. *Journal of Forest Engineering*, **1998**, *9*(1), 17-23, doi: 10.1080/08435243.1998.10702707.

Egan, A. F. Training preferences and attitudes among loggers in northern New England. *Forest Products Journal* **2005**, *55*(3), 19-26.

Egan, A. F.; Hassler, C.C.; Grushecky, S. T. Logger certification and training: a view from West Virginia's logging community. *Forest Products Journal* **1997**, *47*(7-8), 46-50.

Ferrari, E.; Spinelli, R.; Cavallo, E.; Magagnotti, N. Attitudes towards mechanized cut-to-length technology among logging contractors in Northern Italy. *Scandinavian Journal of Forest Research* **2012**, *27*(8), 800-806, doi: 10.1080/02827581.2012.693192.

Fogarty, G. J.; Shaw, A. Safety climate and the Theory of Planned Behavior: Towards the prediction of unsafe behavior. *Accident Analysis and Prevention* **2010**, *42*, 1455-1459, doi: 10.1016/j.aap.2009.08.008.

Fosbroke, D.E.; Kisner, S.M.; Myers, J.R. 1997. Working lifetime risk of occupational fatal injury. *American Journal of Industrial Medicine* **1997**, *31*, 459-467, doi: 10.1002/(SICI)1097-0274(199704)31:4<459::AID-AJIM13>3.0.CO;2-Z.

Francis, J.; Eccles, M. P.; Johnston, M.; Walker, A. E.; Grimshaw, J. M.; Foy, R.; Kaner, E. F. S.; Smith, L.; Bonetti, D. *Constructing questionnaires based on the theory of planned behaviour: A manual for health services researchers*, Centre for Health Services Research, University of Newcastle upon Tyne: Newcastle upon Tyne, UK, 2004, ISBN: 0-9540161-5-7.

Grayson, L.M.; Keefe, R.F.; Tinkham, W.T.; Eitel, J.U.H.; Saralecos, J.D.; Smith, A.M.S.; Zimbelman, E.G. Accuracy of WAAS-enabled GPS-RF warning signals when crossing a terrestrial geofence. *Sensors* **2016**, *16*, 1–8, doi:10.3390/s16060912.

Hankins, M.; French, D.; Horne, R. Statistical guidelines for studies of the Theory of Reasoned Action and the Theory of Planned Behavior. *Psychology and Health* **2000**, *15*, 151-161, doi: 10.1080/08870440008400297.

Hauglin, M.; Hansen, E.H.; Næsset, E.; Busterud, B.E.; Gjevestad, J.G.O.; Gobakken, T. Accurate single-tree positions from a harvester: A test of two global satellite-based positioning systems. *Scand. J. For. Res.* **2017**, doi:10.1080/02827581.2017.1296967.

Johnson, S. E.; Hall, A. The prediction of safe lifting behavior: an application of the theory of planned behavior. *Journal of Safety Research* **2005**, *36*, 63-73, doi: 10.1016/j.jsr.2004.12.004.

Kaartinen, H.; Hyyppä, J.; Vastaranta, M.; Kukko, A.; Jaakkola, A.; Yu, X.; Pyörälä, J.; Liang, X.; Liu, J.; Wang, Y.; et al. Accuracy of kinematic positioning using Global Satellite Navigation Systems under forest canopies. *Forests* **2015**, *6*, 3218–3236, doi:10.3390/f6093218.

Keefe, R.F.; Eitel, J.U.H; Smith, A.M.S.; Tinkham, W.T. Applications of multi-transmitter GPS-VHF in forest operations. In Proceedings of the 47th International Symposium on Forestry Mechanization and 5th International Forest Engineering Conference, Gerardmer, France, 23–26 September 2014.

Klen, T. Personal protectors and working behavior of loggers. Safety Science **1997**, *25*(1-3), 89-103, doi: 10.1016/S0925-7535(97)00036-2.

Larson, K. M.; Small, E. E.; Gutmann, E.; Bilich, A.; Axelrad, P.; Braun, J. Using GPS multipath to measure soil moisture fluctuations: initial results. *GPS Solutions* **2008**, *12*, 173-177, doi: 10.1007/s10291-007-0076-6.

Lefort, A.J.; Pine, J.C.; Marx, B.D. Characteristics of injuries in the logging industry of Louisiana, USA: 1986–1998. *Int. J. For. Eng.* **2003**, *14*, 75–89.

Liu, C.J.; Brantigan, R. Using differential GPS for forest traverse surveys. *Can. J. For. Res.* **1995**, *25*, 1795–1805, doi:10.1139/x95-1-94.

Marsh, R.E. Fenceless Animal Control System Using GPS Location Information. U.S. Patent 5868100 A, 9 February 1999.

Mathieson, K. Predicting user intentions: comparing the Technology Acceptance Model with the Theory of Planned Behavior. *Information Systems Research* **1991**, *2*(3), 173-191, doi: 10.1287/isre.2.3.173.

McDonald, T.P.; Fulton, J.P. Automated time study of skidders using global positioning system data. *Comput. Electron. Agric.* **2005**, *48*, 19–37, doi:10.1016/j.compag.2005.01.004.

Montaño, D. E.; Kasprzyk, D. Theory of Reasoned Action, Theory of Planned Behavior, and the Integrated Behavioral Model. In *Health Behavior: Theory, Research, and Practice Fifth Edition*; Glanz, K.; Rimer, B.K.; Viswanath, K., Eds.; Jossey-Bass: San Francisco, CA, USA, 2015; pp. 95-103, ISBN: 1118629051.

Montorselli, N.; Lombardini, C.; Magagnotti, N.; Marchi, E.; Neri, F.; Picchi, G.; Spinelli, R. Relating safety, productivity and company type for motor-manual logging operations in the Italian Alps. *Accident Analysis & Prevention* **2010**, *42*(6), 2013-2017, doi: 10.1016/j.aap.2010.06.011.

Morris, M.G.; Venkatesh, V. Age differences in technology adoption decisions: implications for a changing work force. *Personnel Psychology* **2000**, *53*, 375-403, doi: 10.1111/j.1744-6570.2000.tb00206.x.

Newman, S.M.; Keefe, R.F.; Brooks, R. H.; Ahonen, E.Q. Human factors affecting situational awareness of loggers in Idaho and the potential for technology-based safety solutions to reduce accident-related injuries. *Safety.* In review.

Occupational Safety and Health Administration. Regulations (Standards-29 CFR), 1910.266 2014. Available online: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9862 (accessed 3 May 2017).

Oregon Occupational Safety and Health Division. Oregon Administrative Rules, Chapter 437, Division 7 Forest Activities 2003. Available online: http://osha.oregon.gov/OSHARules/div7/div7.pdf (accessed on 3 May 2017).

Parkinson, B.W.; Enge, P. Differential GPS. In *Progress in Astronautics and Aeronatics: Global Positioning System: Theory and Applications*; Parkinson, B.W., Spilker, J.J., Eds.; American Institute of Aeronautics and Astronautics, Inc.: Washington, DC, USA, 1994; Volume 2, pp. 3–49, 1600864201.

Perloff, R. M. *The Dynamics of Persuasion: Communication and Attitudes in the Twenty-First Century 4th edition*; Taylor and Francis: New York, NY, USA, 2010, ISBN: 9780203870327.

Quick, B. L.; Stephenson, M. T.; Witte, K.; Vaught, C.; Booth-Butterfield, S.; Patel, D. An examination of antecedents to coal miners' hearing protection behaviors: a test of the theory of planned behavior. *Journal of Safety Research* **2008**, *39*, 329-338, doi: 10.1016/j.jsr.2008.02.032.

R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016. Available online: https://www.R-project.org/ (accessed on 30, December, 2016).

Reclus, F.; Drouard, K. Geofencing for fleet & freight management. In Proceedings of the 9th International Conference on Intelligent Transport Systems Telecommunications, Lille, France, 20–22 October 2009; pp. 353–356, doi:10.1109/ITST.2009.5399328.

Rempel, R.S.; Rodgers, A.R. Effects of differential correction on accuracy of a GPS animal location system. *J. Wildl. Manag.* **1997**, *61*, 525–530, doi:10.2307/3802611.

Scott, D. F. A study of logger fatalities from 1992-2000. *Injury Prevention* **2004**, *10*, 239-243, doi: 10.1136/ip.2003.004663.

Shaffer, R.M.; Milburn, J.S. Injuries on feller-buncher/grapple skidder logging operations in the Southeastern United States. *For. Prod. J.* **1999**, *49*, 24–26.

Sheppard, J.K.; McGann, A.; Lanzone, M.; Swaisgood, R.R. An autonomous GPS geofence alert system to curtail avian fatalities at wind farms. *Anim. Biotelem.* **2015**, *3*, 1–8, doi:10.1186/s40317-0-15-0-087-y.

Shiau, R.; Smith, R.L.; Shaffer, R.M.; Cesa, E.T. Effective communication of technology in logging: a portable timber bridge example. *Southern Journal of Applied Forestry* **2002**, *26*(1), 5-12, doi: 10.1093/sjaf/26.1.5.

Strandgard, M.; Mitchell, R. Automated time study of forwarders using GPS and a vibration sensor. *Croat. J. For. Eng. J. Theory Appl. For. Eng.* **2015**, *36*, 175–184.

Sygnatur, E.F. Logging is Perilous Work. *Compens. Work. Cond.* **1998**, *3*, 1–7.

Solheim, F. S.; Vivekanandan, J.; Ware, R. H.; Rocken, C. Propagation delays induced in GPS signals by dry air, water vapor, hydrometeors, and other particulates. *Journal of Geophysical Research* **1999**, 104(D8), 9663-9670, doi: 10.1029/1999JD900095.

Takasu, T.; Yasuda, A. Evaluation of RTK-GPS Performance with Low-cost Single-frequency GPS Receivers. International Symposium on GPS/GNSS, Tokyo, Japan, November 2008.

Taylor, S.E.; McDonald, T.P.; Veal, M.W.; Grift, T.E. Using GPS to evaluate productivity and performance of forest machine systems. In Proceedings of the First International Precision Forestry Symposium, Seattle, Washington, DC, USA, 17–20 June 2001.

University of Idaho Extension LEAP update 2018. Available online: https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/Extension/forestry/events/leap-update-2018.ashx?la=en&hash=05A45BAC4429A9F97C91E546F0C47CB326CDAD61 (accessed 6 March 2018).

Umstatter, C. The evolution of virtual fences: A review. *Comput. Electron. Agric.* **2011**, *75*, 10–22, doi:10.1016/j.compag.2010.10.005.

Wang, L.; Li, Z.; Zhao, J.; Zhou, K.; Wang, Z.; Yuan, H. Smart device-supported BDS/GNSS real-time kinematic positioning for sub-meter-level accuracy in urban location-based services. *Sensors* **2016**, *16*, 1–15, 10.3390/s16122201.

Welbourne, J.; Booth-Butterfield, S. Using the Theory of Planned Behavior and a Stage Model of Persuasion to Evaluate a Safety Message for Firefighters. *Health Communication* **2005**, *18*(2), 141-154, doi: 10.1207/s15327027hc1802_3.

Wempe, A.M.; Keefe, R.K. Characterizing rigging crew proximity to hazards on cable logging operations using GNSS-RF: Effect of GNSS positioning error on worker safety status. *Forests* **2017**, *8*(10), 357, doi: 10.3390/f8100357.

Wightman, A. R.; Shaffer, R. M. Evaluation of a logger training and education program in Virginia. *Journal of Extension* **2000**, *38*(11).

Wing, B.M.; Ritchie, M.W.; Boston, K.; Cohen, W.B.; Olsen, M.J. Individual snag detection using neighborhood attribute filtered airborne lidar data. *Remote Sens. Environ.* **2015**, *163*, 165–179, doi:10.1016/j.rse.2015.03.013.

Yzer, M. Reasoned Action Theory: Persuasion as Belief-Based Behavior Change. In *The SAGE Handbook of Persuasion: Developments in Theory and Practice*. J. P. Dillard, J.P.; Shen, L., Eds.; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2012, ISBN: 978145221840.

Zimbelman, E.G.; Keefe, R. K. Real-time positioning in logging: Effects of forest stand characteristics, topography, and line-of-sight obstructions on GNSS-RF transponder accuracy and radio signal propagation. *PLoS ONE* **2018**, *13*(1), doi: 10.1371/journal.pone.0191017.

Zimbelman, E.G.; Keefe, R.F.; Strand, E.K.; Kolden, C.A.; Wempe, A.M. Hazards in motion: Development of mobile geofences for use in logging safety. *Sensors* **2017**, *17*, 822, doi:10.3390/s17040822.

APPENDIX A: PERMISSIONS FROM *FORESTS*

From: yuliya.min@mdpi.com
To: Wempe, Ann (awempe@uidaho.edu)
Cc: Forests Editorial Office
Subject: Re: Copyright release for manuscript forests-221129
Date: Wednesday, May 30, 2018 6:32:05 PM

Dear Dr. Wempe,

Thank you for your email.

You could use the manuscript as a chapter in your thesis without our copyright permission. More details you could visit following website for confirmation:
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Should you need any further information, please do not hesitate to contact us.

Kind regards,
Yuliya

Yuliya Min
Assistant Editor
Forests (http://www.mdpi.com/journal/forests)
Twitter: @Forests_MDPI

We are pleased to announce that /Forests'/
2016 Impact Factor has increased to *1.951* (Q1)!

APPENDIX B: PROTOCOL APPROVAL FROM INTERNAL REVIEW BOARD

University of Idaho
Office of Research Assurances
Institutional Review Board
875 Perimeter Drive, MS 3010
Moscow ID 83844-3010
Phone: 208-885-6162
Fax: 208-885-5752
irb@uidaho.edu

To:	Robert Keefe
Cc:	Ann Wempe
From:	Jennifer Walker, IRB Coordinator
Approval Date:	February 28, 2018
Title:	Role of Location-Sharing Technology in Logging Safety: Idaho Logger Perspectives
Project:	18-037
Certified:	Certified as exempt under category 2 at 45 CFR 46.101(b)(2).

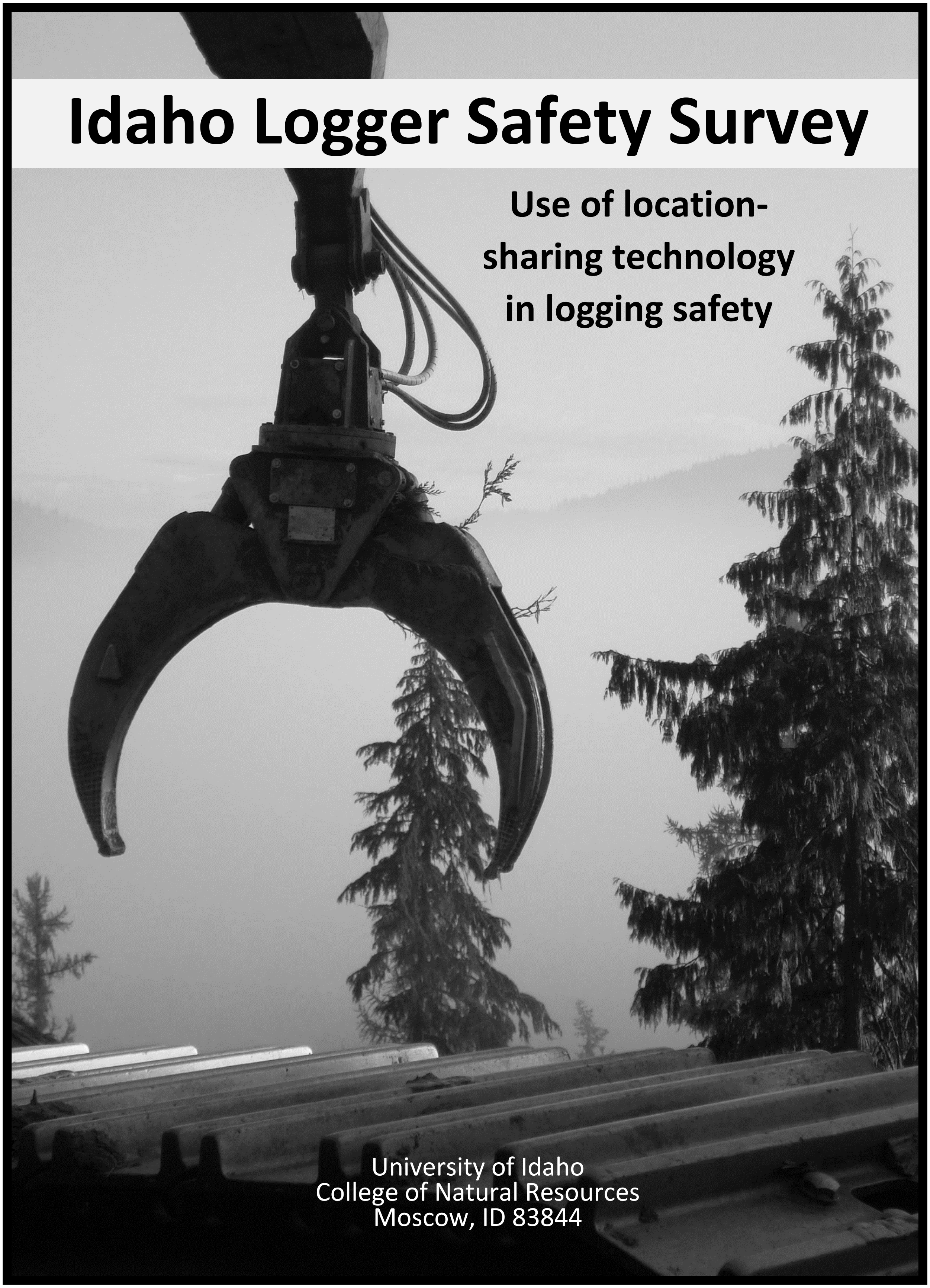
On behalf of the Institutional Review Board at the University of Idaho, I am pleased to inform you that the protocol for the research project Role of Location-Sharing Technology in Logging Safety: Idaho Logger Perspectives has been certified as exempt under the category and reference number listed above.

This certification is valid only for the study protocol as it was submitted. Studies certified as Exempt are not subject to continuing review and this certification does not expire. However, if changes are made to the study protocol, you must submit the changes through VERAS for review before implementing the changes. Amendments may include but are not limited to, changes in study population, study personnel, study instruments, consent documents, recruitment materials, sites of research, etc. If you have any additional questions, please contact me through the VERAS messaging system by clicking the 'Reply' button.

As Principal Investigator, you are responsible for ensuring compliance with all applicable FERPA regulations, University of Idaho policies, state and federal regulations. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice. The Principal Investigator is responsible for ensuring that all study personnel have completed the online human subjects training requirement.

You are required to timely notify the IRB if any unanticipated or adverse events occur during the study, if you experience and increased risk to the participants, or if you have participants withdraw or register complaints about the study.

APPENDIX C: SURVEY INSTRUMENT



Please wait for presenter instructions before starting the survey.

1. Have you ever used the following location-sharing devices during logging operations?

	Yes	No	Unsure
Emergency search and rescue receivers (e.g. SPOT, inReach)	○	○	○
2-way radios with location-sharing (e.g. Garmin Rino)	○	○	○
Devices that use smartphones to share locations (e.g. goTenna)	○	○	○

2. In your opinion, would the following types of location-sharing devices improve safety on active logging operations?

	Yes	No	Unsure
Emergency search and rescue receivers (e.g. SPOT, inReach)	○	○	○
2-way radios with location-sharing (e.g. Garmin Rino)	○	○	○
Devices that use smartphones to share locations (e.g. goTenna)	○	○	○

STOP

3. In your opinion, would the following features of location-sharing devices help improve workplace safety?

	Yes	No	Unsure
Alerts when workers enter dangerous areas	○	○	○
Automatic updates of user positions to coworkers at the jobsite	○	○	○
Automatic updates of user positions to supervisors at the office	○	○	○
SOS or Help button to contact coworkers at the jobsite	○	○	○
SOS or Help button to contact supervisors at the office	○	○	○
SOS or Help button to contact emergency services	○	○	○
Messaging through text, voice, or video	○	○	○

4. Would you be concerned about worker privacy if workers' real-time locations were seen by the following people?a

	Yes	No	Unsure
Coworkers at the jobsite	○	○	○
Supervisors or others at a remote office or shop	○	○	○

STOP

5. a. Do you own a smartphone?

- O Yes
- O No → *Skip question 5.b.*

b. How often do you carry your smartphone with you while working on logging operations (either turned on or off)?

- O Always
- O Often
- O Rarely
- O Never

6. How concerned would you be about having to carry an extra device (such as on the belt or in a pocket) while working on logging operations?

- O Very concerned
- O Somewhat concerned
- O Not at all concerned

STOP

7. How can location-sharing devices best be used to improve safety on logging operations?
Please rank the following in order of importance (1, 2, 3, 4), where 1 = the most important safety application, and 4 = the least important safety application.

____ Contacting off-site emergency response
____ Finding injured workers quickly
____ Alerting coworkers when someone needs help
____ Preventing accidents on the jobsite

8. How important or unimportant is it to find new ways of improving safety on logging operations?

- O Very important
- O Somewhat important
- O Neutral
- O Somewhat unimportant
- O Very unimportant

STOP

9. How likely or unlikely are the following results if personal location-sharing devices are used on logging operations?

Possible Result	Very Unlikely	Somewhat Unlikely	Unsure	Somewhat Likely	Very Likely
Improving overall workplace safety	○	○	○	○	○
Developing a dependence on the technology	○	○	○	○	○
Finding injured coworkers faster	○	○	○	○	○
Causing distraction from other work activities	○	○	○	○	○
Knowing when coworkers might need help	○	○	○	○	○
Causing workers to feel like they are being watched or monitored	○	○	○	○	○
Knowing when coworkers are in safe or unsafe areas	○	○	○	○	○

10. How good or bad are the following results of using personal location-sharing devices on logging operations?

Possible Result	Very Bad	Somewhat Bad	Neutral	Somewhat Good	Very Good
Improving overall workplace safety	○	○	○	○	○
Developing a dependence on the technology	○	○	○	○	○
Finding injured coworkers faster	○	○	○	○	○
Causing distraction from other work activities	○	○	○	○	○
Knowing when coworkers might need help	○	○	○	○	○
Causing workers to feel like they are being watched or monitored	○	○	○	○	○
Knowing when coworkers are in safe or unsafe areas	○	○	○	○	○

STOP

11. How likely or unlikely are *you* to use personal location-sharing devices (PLDs) in the following ways on active logging operations?

Safety Practice	Very Unlikely	Somewhat Unlikely	Unsure	Somewhat Likely	Very Likely
Using PLDs with local, automatic location sharing for hand fallers	○	○	○	○	○
Using PLDS on all ground workers and heavy equipment	○	○	○	○	○
Using GPS-based PLDs and geofences for general situational awareness	○	○	○	○	○

12. Within your company or organization, how much influence do you have in whether personal location-sharing devices get used?

- ○ A lot
- ○ Some
- ○ None

13. How likely or unlikely do you think *other loggers* are to use personal location-sharing devices (PLDs) in the following ways?

Safety Practice	Very Unlikely	Somewhat Unlikely	Unsure	Somewhat Likely	Very Likely
Using PLDs with local, automatic location sharing for hand fallers	○	○	○	○	○
Using PLDS on all ground workers and heavy equipment	○	○	○	○	○
Using GPS-based PLDs and geofences for general situational awareness	○	○	○	○	○

STOP

14. What is your age?

- ○ Less than 20 years
- ○ 20-29 years
- ○ 30-39 years
- ○ 40-49 years
- ○ 50 or more years

15. How many years have you worked in the logging industry?

- ○ 0-9 years
- ○ 10-19 years
- ○ 20-29 years
- ○ 30-39 years
- ○ 40 or more years

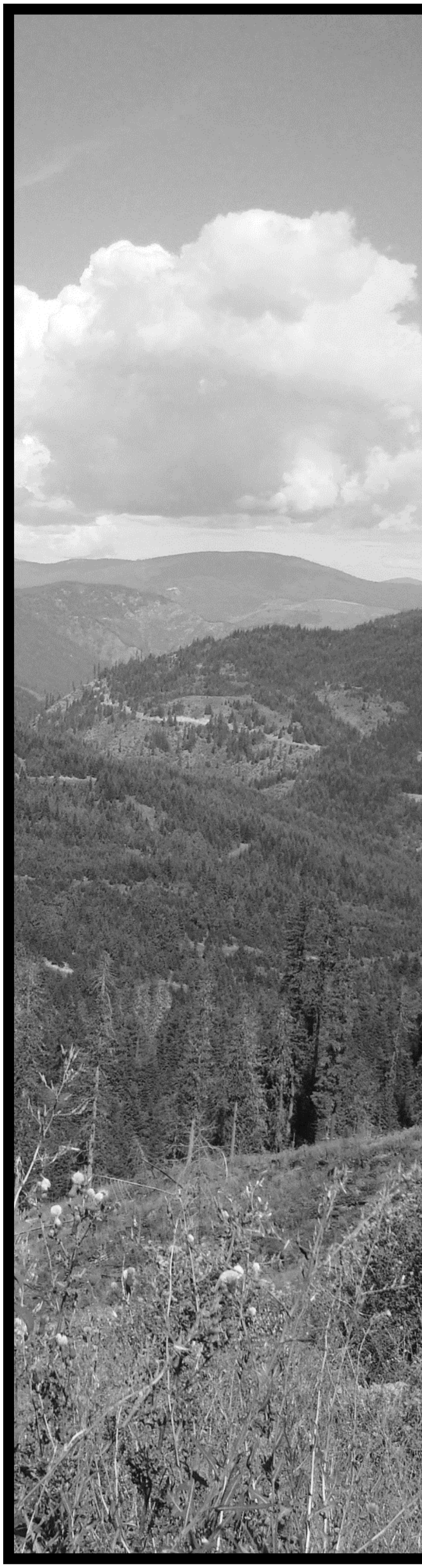
16. What is your current job? *Please select all that apply.*

- ☐ Hand Faller
- ☐ Chaser/Hooker
- ☐ Equipment Operator
- ☐ Truck Driver
- ☐ Owner
- ☐ Other — please specify: ____

17. On which of the following types of operations do you usually work? *Please select all that apply.*

- ☐ Mechanized ground-based logging (feller-buncher and skidder or shovel)
- ☐ Partially mechanized ground-based logging (hand faller and skidder or shovel)

- ☐ Cable logging
- ☐ Other – please specify: ____

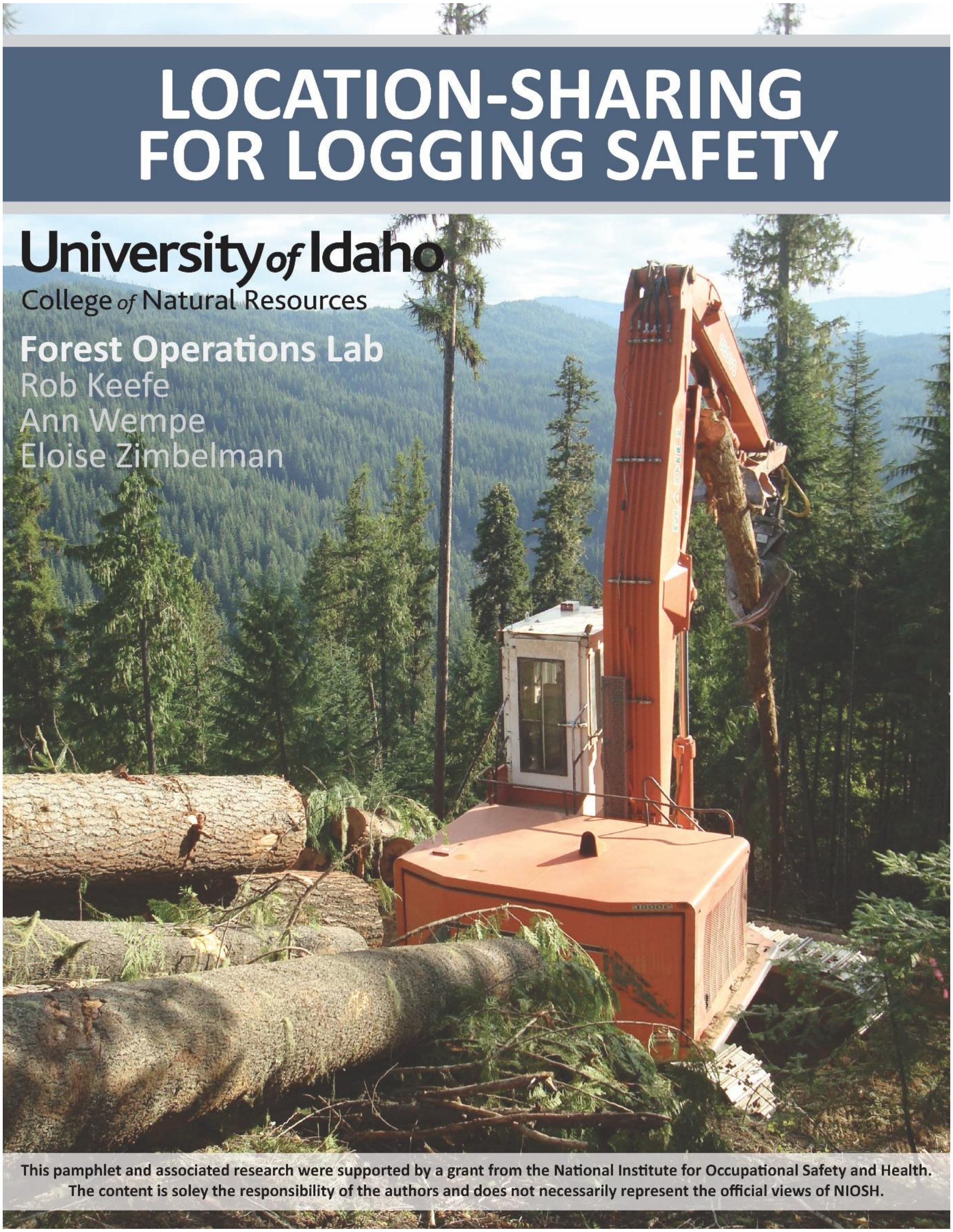


You have finished the survey! Thank you for your response!

COMMENTS

Please use this space to write in any comments or input you would like to provide. All responses from this survey, including comments, are anonymous.

APPENDIX D: SUPPLEMENTAL EDUCATIONAL MATERIALS



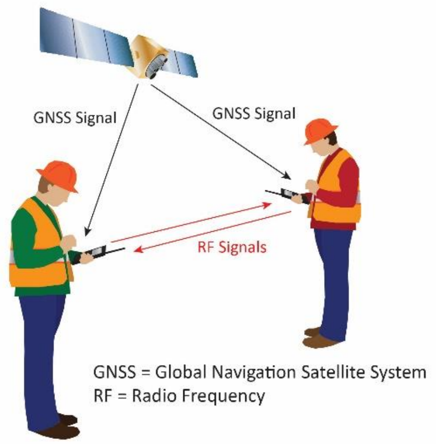
LOCATION-SHARING FOR LOGGING SAFETY

University of Idaho
College of Natural Resources

Forest Operations Lab
Rob Keefe
Ann Wempe
Eloise Zimbelman

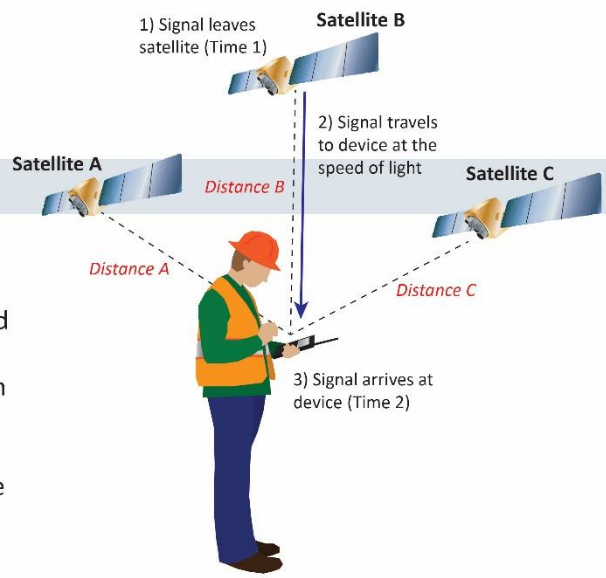
This pamphlet and associated research were supported by a grant from the National Institute for Occupational Safety and Health. The content is soley the responsibility of the authors and does not necessarily represent the official views of NIOSH.

WHAT IS LOCATION-SHARING?

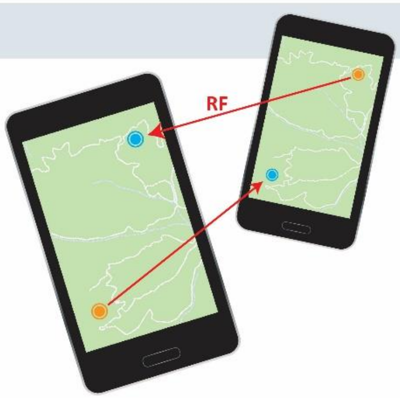


Location-sharing devices can determine where they are from groups of satellites in the Global Navigation Satellite System (GNSS), such as the United States' Global Positioning System (GPS). They can then share their position with other mobile devices through cellular networks, satellite data communication, or radio transmission.

Finding Your Location



Satellites communicate via microwaves, which travel to Earth at the speed of light. Positioning devices receive these signals and determine the amount of time the signals traveled. With speed and time, a device can calculate its distance from the satellite's position. Knowing distances from multiple satellites allows the device to tell you where on the Earth's surface you are located.



Sharing Your Location

Your location can be shared with others through a radio frequency (RF) transmission and then mapped on a mobile device, such as a tablet or smartphone, so others can see where you are. GNSS-RF communication does not require cellular networks or an internet connection, so these location-sharing devices can be used off the grid in remote areas, making them useful for forestry applications.

For more information contact: Rob Keefe
robk@uidaho.edu ◆ (208) 885-0749
University *of* Idaho
College *of* Natural Resources

LOCATION-SHARING & LOGGING SAFETY

Where is everyone?

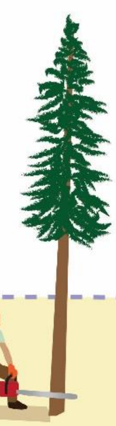
Loggers could use location-sharing technology with a mobile device, like a smartphone or tablet, to see the real-time locations of workers or equipment on a harvest map. Location sharing can help increase situational awareness of where everyone is in case of emergency.

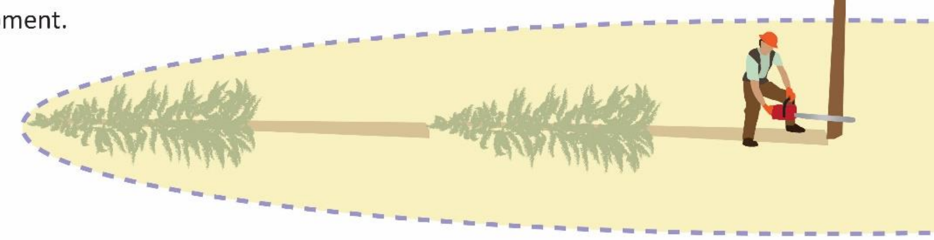
When do people need help?

Many location-sharing devices allow users to send alerts when they need help, or devices may be able to send an automatic warning under certain conditions, such as when someone has not moved in a long time and may be hurt.

When are people near hazards?

Some devices are able to use virtual boundaries known as geofences to mark dangerous areas on logging operations and send alerts when someone has moved into a geofenced area. For example, workers could receive a warning when they approach within two tree lengths of a hand faller, or when a member of the rigging crew is underneath the skyline carriage. The accuracy of geofences in forested environments varies widely among available devices and technology, so use of proximity alerts for these kinds of safety applications should be used with caution. The most important safety benefit of location sharing is usually just being able to see the approximate, current positions of fellow crew members and equipment.





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LOCATION-SHARING DEVICES

	Beartooth	(mesh) goTenna	Sonnet	Garmin Rino 750	Raveon Atlas PT	TrellisWare Ghost	Garmin inReach SE*	SPOT Gen3*
Requires mobile device	✓	✓	✓		✓	✓		✓
SOS		✓			✓		✓	✓
Texts	✓	✓	✓	✓		✓	✓	✓
Voice	✓	✓		✓		✓		
Images		✓				✓	✓	
Videos						✓		
Position update	manual	manual	30 sec	manual	1 sec	2-3 sec	2-10 min	2.5 min-1 hr
Geofencing					✓			
Mesh networking	✓	✓	✓			✓		
Battery life	4 days	24 hrs	24 hrs	14-18 hrs	24 hrs	9 hrs	75-100 hrs	10+ days
Range**	5 mi (talk) 10 mi (text)	3-9 mi/hop (16 hops max)	0.5-4 mi	20 mi	30 mi	26 mi/hop (8 hops max)	global	global
Price	~$250/2	~$90/2 ~$400/10	~$180/2 ~$580/8	~$550	~$1,800	~$4,200	~$400 + monthly subscription	~$170 + service plan

*satellite-based communication
**advertised ranges - actual ranges will vary

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