GPS AND GIS APPLICATION AND ANALYSIS OF TIMBER HARVESTING OPERATIONS ON STEEP TERRAIN

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GPS AND GIS APPLICATION AND ANALYSIS OF TIMBER HARVESTING OPERATIONS ON STEEP TERRAIN

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GPS AND GIS APPLICATION AND ANALYSIS OF TIMBER HARVESTING OPERATIONS ON STEEP TERRAIN

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THESIS ABSTRACT

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This study examined the productivity and site disturbance of a tree length harvesting system in the steep slope conditions of the Appalachian Highlands. Timber harvesting is a major industry in this area but has the potential to severely affect water quality and is expensive compared to harvesting in areas with less severe slope. Water quality problems are caused by increased erosion from steep slopes. Harvest costs are increased due to decreased harvesting efficiency because of the terrain. We used electronic monitors and global positioning systems (GPS) to track harvesting efficiency and trafficking on a typical steep terrain harvest. In general utilization of in-woods operations were low due to limited truck capacity or markets. The GPS information from the skidder provided information that could predict hourly skidder productivity. Traffic mapping with positional data was able to identify high traffic areas but had limited utility in identifying areas with single or a few passes. The limits may have been related to position accuracy, position data collection frequency, or traffic data collection bias.

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Style manual or journal used:

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I. INTRODUCTION

Timber harvesting in the Appalachian Highlands creates jobs and the forest products industry represents a major portion of the regional economies (Kentucky Division of Forestry 2007, Tennessee Division of Forestry 2007, West Virginia Division of Forestry 2006, and Virginia Department of Forestry 2006).

Kentucky is about 47% forested, and the majority of forest area is located in the eastern third of the state. This eastern portion is a part of the Appalachian Highlands known as the Cumberland Plateau. Kentucky ranks third in the nation in hardwood production, and the industry employs more than 30,000 people (Kentucky Division of Forestry 2007). This timber generates more than $4.5 billion in revenue for Kentucky, making it one of the largest industries in the state (Kentucky Division of Forestry 2007). However, timber harvesting activities in the Appalachians are often seen as a threat to water resources because harvesting is widespread, occurs on steep terrain and has considerable aesthetic impact when compared to other forest activities (Kochenderfer et al. 1997).

Harvesting on steep slopes tends to cause more nonpoint source pollution than harvesting on less severe slopes, because more sediment is transported as slope percentage increases (Wang and Wu 2001). According to Hartsough et al. (2001) ground based logging systems should be limited to slopes of 40 percent or less due to the soil disturbance caused by skidding. Systems utilizing skidders may be limited to uphill slopes of 15 percent and downhill slopes of 25 percent, with the maximum desirable grade being 20 percent (McGonagill 1978). Minimizing the environmental damage from timber harvesting operations is important so economic and ecological benefits of forest management in this region can be maintained.

The runoff of sediments into streams from timber harvesting in steep terrain can result in significant degradation of water quality and aquatic habitat through increased turbidity and embeddedness (Novotny 2003). This increase in sediment movement is related to soil disturbance associated with road building and the trafficking of timber harvesting equipment.

Best Management Practices (BMPs) are implemented to minimize nonpoint source pollution from timber harvesting (Cubbage 2004, Kochenderfer et al. 1997, Lickwar et al. 1992). They include recommendations for activities such as harvest planning, streamside management zones (SMZs), haul roads, skid trails, log landings, stream crossings and soil stabilization (Shaffer et al. 1998). Most landowners in Kentucky who wish to harvest timber on their property are required by law to have a written Agriculture Water Quality Plan which indicates which BMPs are to be used in timber harvesting operations on their land. Loggers are responsible for implementing these BMPs and may also assist landowners with writing their plans (Stringer 1998).

SMZs are one of the more important BMPs because they protect stream water quality by shading from retained canopy cover and reducing sedimentation by minimizing machine traffic near the stream. The amount of canopy cover and the width of the SMZ vary by state, stream type or slope in the riparian area (Williams et al. 2004). In Kentucky SMZs have at least 50% of canopy trees retained within the SMZs for perennial water bodies (Stringer et al. 1998). The SMZ width varies from 25 feet from the stream bank if the slope is less than 15% to 55 feet if the slope is greater than 15%. Logging roads or landings should not be constructed within the SMZ. Ground disturbances associated with timber harvesting that result from felling, winching and skidding should be minimized within the SMZ. Intermittent and ephemeral streams do not require canopy cover in the SMZ, but roads or landings should be at least 25 to 65 feet from the streambank depending upon slope.

Minimizing nonpoint source pollution in Kentucky timber harvests may increase logging costs. SMZ implementation may increase harvesting costs because land is excluded from normal forest management (Kluender et al. 2000). In Kentucky, SMZ widths are greater in steep terrain, and therefore a higher percentage of the forestland is excluded from normal forest management.

1.1 Relationship of Trafficking to Water Quality and SMZ Protection in Steep Slope Applications

The most important water quality problem related to forest trafficking is sedimentation (Fulton and West 2002). Trafficking and road building removes the litter layer and exposes bare mineral soil. The soil particles on bare soil can be dislodged by rain impact and surface flow resulting in soil erosion. In addition to soil disturbance sediment movement is dependent upon the nature of the soil and slope (National Council for Air and Stream Improvement 1994). Wang and Wu (2001) also agree that slope is one of the main factors in the erosion process. Studying slopes from 15 to 60 percent, they found that soil loss increased with slope although it leveled off somewhat from 30-45%.

1.2 Mitigation of Harvesting Impacts with BMPs

The Amendments to the Federal Water Pollution Control Act of 1972 and the Clean Water Act Amendments of 1977 emphasized the need to protect and maintain water quality, and provided a strong mandate for control of nonpoint source pollution (Cubbage 2004, Kochenderfer et al. 1997, and Lickwar et al. 1992). Because of these requirements, Best Management Practices, or BMPs, were developed by many states to minimize the impact of forestry operations on water quality. BMPs include recommendations for activities such as harvest planning, streamside management zones (SMZs), haul roads, skid trails, log landings, stream crossings and soil stabilization (Shaffer et al. 1998). All 37 states east of the Rocky Mountains have state BMP guidelines (Blinn and Kilgore 2004). Many states have a voluntary approach to BMP implementation which relies on adoption by foresters, loggers and forest landowners, following education on the benefits of BMPs. Other states have developed mandatory approaches where BMPs are included as part of a broader state forest practices law (Shaffer et al. 1998).

1.2.1 SMZs

SMZs are one of the more important aspects of BMPs since riparian areas are the boundary between aquatic and terrestrial ecosystems, and are one of the most diverse parts of a forest ecosystem (Blinn and Kilgore 2004). SMZs have many roles which include providing shade that reduces water temperature, causing deposition of sediments and other contaminants in runoff, stabilizing streambanks with vegetation, reducing erosion within the SMZ, providing riparian wildlife habitat, providing visually appealing greenbelts and environmental corridors and recreation opportunities (Novotny 2003).

Factors which affect buffer effectiveness include the size and slope of the buffer, resistance to flow, infiltration capacity and the moisture holding ability of the soil (Phillips 1989). Slope and saturated hydraulic conductivity are the most important factors. State SMZ guidelines differ, but usually have two common basic components that define the SMZ: minimum SMZ width and minimum canopy and ground cover following timber harvesting activity. They may offer additional guidelines that address other operations within the management zone (Blinn and Kilgore 2004).

SMZ widths may be based on a number of factors such as waterbody type, slope of stream banks, or specific site conditions such as composition, vegetation age and condition, site geomorphology, watershed level issues and animal and plant species found on the site (Blinn and Kilgore 2004). In the Southeast, SMZ width requirements for perennial and intermittent streams range from 25 feet to 300 feet, with the majority being slope class dependant (Hodges and Visser 2004). The amount of residual trees left in the SMZ after harvest are usually defined by a basal area or crown spacing method compared to a fully stocked stand (Blinn and Kilgore 2004). In the southeast, most states either use a residual stand density of 50 ft^2/ac, or specify that 50% of the canopy cover must be retained (Hodges and Visser 2004). Some common additional SMZ recommendations include locating roads, skid trails and landings outside of the SMZ, minimizing stream crossings and removing logging debris from streams (Blinn and Kilgore 2004). Several southeastern states also have guidelines for special concern areas, such as cold water fisheries, which often occur in mountainous areas, and wetlands (Hodges and Visser 2004).

Carroll et al. (2004) found that SMZ application maintained favorable pre-harvest streamwater temperature, stream habitat and macroinvertebrate density in the sand-clay hills of Mississippi. Ward and Jackson (2004) found that SMZs trapped transported sediment following a timber harvest in the Georgia piedmont, with SMZ efficiencies ranging from 71 to 99 percent.

1.3 Analysis of Machine Trafficking with Geospatial Information

Several studies have mapped traffic intensities from harvesting operations and compared site disturbances or soil impacts (McDonald et al. 1998, Carter et al. 1999, Carter et al. 2000, McDonald et al. 2002). Other studies used geographic information systems (GIS) to map SMZs and determine the area in SMZs (Kluender et al. 2000, Williams et al. 2003).

McDonald et al. (1998) collected positional data and transformed the data into a raster map with cell values equaling the number of passes over that point with a resolution of 1.64 x 1.64 feet. This data was then compared to visual site disturbance estimates and soil property measurements. It was found that the visual disturbance method overestimated the amount of area in skid trails and decks and underestimated the amount of undisturbed ground compared to the global positioning system (GPS) data. They found only a small correlation between number of passes and changes in soil physical properties.

Carter et al. (1999) did a similar study and used the same GPS systems and methods of creating maps of traffic intensity. Their findings were similar to McDonald et al. (1998) as well. It was determined that 94 percent of the harvest area received 10 or fewer passes, with the remaining 6 percent making up the landing and skid trail network. Untrafficked areas were the most frequently occurring traffic class. This study also showed little correlation between traffic intensity and soil physical responses with soil bulk density and gravimetric water content peaking after only one to three passes.

Carter et al. (2000) found that landings and skid trails were associated with the most traffic passes and accounted for about 6 percent of the area, while areas receiving 10 or fewer passes accounted for the remaining 94 percent. They also found that the soil properties bulk density and cone index both responded to increases in traffic intensity and achieved maximum levels after a small number of passes.

McDonald et al. (2002) also collected GPS data and used it to create traffic maps. This study investigated the effect of GPS errors on traffic mapping and the accuracy of the data in traffic maps. They concluded that traffic maps made from GPS data are not accurate enough to determine the number of machine passes at a given point, but that they are good for assessing the total area trafficked. The authors suggest that pass frequency could be classified but not specifically enumerated.

McDonald et al. (1998), Carter et al. (1999) and McDonald et al. (2002) all feel that traffic maps can be archived and used in the years following harvest. The data could be used to help make decisions about site preparation activities and assess regeneration potential within a tract (Carter et al. 1999), to address sustainability issues (McDonald et al. 2002), or to consult about later problems with a harvested tract (McDonald et al. 1998).

1.4 Production/Time Study in Steep Terrain

Timber harvesting productivity is important in determining the cost of harvesting since it is one of the most capital intensive forest management activities (Cubbage 1983). Productivity is even more important in the Appalachian region because it offers some of the most challenging timber harvesting conditions in the country, including steep, irregular topography and large sawtimber (Egan and Baumgras 2003).

The four basic timber harvesting steps are: (1) tree felling; (2) timber extraction to a central landing area; (3) delimbing and bucking of the timber; and (4) loading of the timber onto trucks (McDonagh et al. 2004). These steps can either be performed in this order, or with delimbing and bucking performed before timber extraction. Felling has traditionally been done using chainsaws, but is quickly being replaced by mechanized felling (McDonagh et al. 2004). Timber extraction is done with a tracked or rubber tired skidder with either a grapple or a winch with a set of chokers (McDonagh et al. 2004). It can also be done with a forwarder which loads the timber onto a trailer to be transported (McDonagh et al. 2004). In the Appalachians, articulated four-wheel-drive rubber-tired skidders are primarily used for hardwood harvesting operations (Biller and Baumgrass 1988). Delimbing and bucking can be done in the woods before skidding using a chainsaw or a machine with a processing head. It can also be done after skidding using these methods or with a loader mounted on a trailer and a hydraulic bucking saw (McDonagh et al. 2004). A loader typically sorts the stems by product and grade before loading them onto trucks.

The elements of a feller-buncher cycle can be defined as move to tree, cut tree, move to pile and drop (Wang and LeDoux 2003). The elements of a cable skidder cycle consist of travel unloaded, setting chokers and winching, travel loaded, and unhooking and decking (Baumgras and LeDoux 1992, Erickson et al. 1992, Huyler et al. 1984, and Wang et al. 2004). Grapple skidder elements are similar, and consist of travel empty, bunch building, travel loaded and deck time (Klepac and Rummer 2000, Kluender and Stokes 1996, and Kluender et al. 1997).

Timber harvesting takes place in a dynamic environment which changes with each harvest and within each harvest. Harvesting productivity is a function of timber stand and harvest site attributes (Baumgras et al. 1993). Tree size is important to cycle time per tree and productivity since machine activities can be more productive if each tree is larger and activities take longer since the machine is closer to its capacity. Authors have used diameter at breast height (DBH) (Cubbage 1983, Klepac and Rummer 2000, and Wang et al. 2004), height (Cubbage 1983, and Wang et al. 2004), size (Howard 1988, and McDonald et al. 2001), volume (Biller and Baumgras 1988), weight, and butt and/or top diameters (Howard 1988, and Wang et al. 2004) to indicate tree size.

Some factors may be related to processing time. Important characteristics may be species (Cubbage 1983, Howard 1988, and Wang et al. 2004), log merchantable length (Howard 1988, and Wang et al. 2004), length to first limb and limbiness (Cubbage 1983). Tree size is also important for determining the length of each element (Cubbage 1983, Biller and Baumgras 1988, Howard 1988, Klepac and Rummer 2000, McDonald et al. 2001, and Wang et al. 2004).

Stand and site characteristics can also affect productivity. Some factors represent either the travel time between trees or potential obstacles for machine activity. Those factors include basal area (Klepac and Rummer 2000), distance between trees (Wang et al. 2004), spatial distribution of trees (McDonald et al. 2001), stand density (Baumgras et al. 1993, Blinn et al. 1986, and Egan and Baumgras 2003), stand volume (Baumgras et al. 1993, and Cubbage 1983) and stocking (Cubbage 1983).

Terrain factors may describe machine stability or affect the time needed to travel between trees or piles. Slope (Baumgras et al. 1993, Erickson et al. 1991, Howard 1988, and McDonald et al. 2001), terrain or topography (Baumgras et al. 1993, Blinn et al. 1986, and Cubbage 1983), soil conditions (Cubbage 1983) and soil moisture (McDonald et al. 2001) contain that kind of information.

Some factors are more directly related to machine and operator performance. In many cases those factors result from the interaction of site and tree characteristics and machine capability. Harvesting characteristics affecting productivity include: the number of trees removed (Egan and Baumgras 2003), number of products removed (Blinn et al. 1986), residual stand damage (Egan and Baumgras 2003), number of bunching moves (Egan and Baumgras 2003), winching distance (Baumgras and LeDoux 1992, and Biller and Baumgras 1988), amount of winch line pulled (Erickson et al. 1991), whether or not an operator sets his own chokers (Erickson et al. 1991), number of times per cycle that trees were unhooked or rehooked to winch additional trees or reposition the skidder (Biller and Baumgras 1988), number of trees per skid (Baumgras and LeDoux 1992, Biller and Baumgras 1988, Egan and Baumgras 2003, Erickson et al. 1991, Erickson et al. 1992, Howard 1988, Klepac and Rummer 2000, and Wang et al. 2004), load size (Klepac and Rummer 2000), volume per skid (Baumgras and LeDoux 1992, Egan and Baumgras 2003, Erickson et al. 1991, Erickson et al. 1992, and Klepac and Rummer 2000) and skidding distance.

Equipment and crew factors can also affect productivity, such as equipment size or horsepower (Egan and Baumgras 2003, Howard 1988, and Klepac and Rummer 2000), grapple size (Klepac and Rummer 2000), and equipment condition, worker experience and motivation, and crew size and organization (Howard 1988). Environmental constraints, contract restrictions (Howard 1988) and weather (Blinn et al. 1986, and Howard 1988) also have an effect on productivity. All of these factors affect productivity because they influence the ease and speed that trees can be felled, limbed, topped, bucked, extracted and processed.

1.5 Study Approach and Objectives

GPS has recently been utilized as a tool for conducting timber harvesting productivity studies (McDonald 1999 and McDonald and Fulton 2005). Instrumenting a machine with a GPS device allows for the collection and timing of machine variables such as machine working time, machine speed, distance travelled and elevation changes. This method will be tested under steep slope harvesting conditions in order to investigate its feasibility. The objective of the productivity portion of this study was to examine the productivity of a tree length system in steep slope conditions and to examine production relationships for grapple skidders in this system.

GPS can also be used to monitor the movements of harvesting machine traffic and estimate the impact on the site (McDonald et al. 1998, Carter et al. 1999, Carter et al. 2000, McDonald et al. 2002). This is done by recording machine positional data, analyzing it using GIS and relating it to site disturbance in order to determine its predictive ability. The objective of this portion of the study was to relate machine movements with site disturbance through the use of traffic mapping and disturbance sampling.

The productivity portion of the study may help forestry in Kentucky by improving the efficiency of similar harvests by revealing limiting factors in the production process through the analysis of individual machine productivity and the development of a skidder production model. The disturbance part of the study may be useful in determining the extent of site damage related to machine traffic patterns. The traffic maps generated from the GPS data could identify highly trafficked areas including landings and main skid trails which tend to cause the most nonpoint source pollution concerns and require more BMPs. It is expected to help develop methodology that may assist in determining the machine trafficking within the SMZs.

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II. PRODUCTIVITY OF TIMBER HARVESTING OPERATIONS ON STEEP TERRAIN

2.1 INTRODUCTION

In the Appalachian Highlands region the conventional harvesting system is a tree length system where trees are felled, limbed and toppped at the stump. In the woods a cable skidder operator skids trees to the landing or bunches them for a grapple skidder. A knuckleboom loader with a ground saw bucks and merchandizes trees and loads trucks. These systems frequently add a bulldozer to construct skid trails as well as pre-bunch trees for the skidder. However logging in this region is becoming more mechanized with increasing application of grapple skidders and tracked feller-bunchers.

Several studies have measured the production of the conventional harvesting components. Biller and Baumgras (1988), Huyler et al. (1994), and Egan and Baumgras (2003) measured the production of cable skidders in Appalachian hardwood forests. Wang et al. (2004a) determined both cable skidding and manual felling productivity. Erickson et al. (1991) also studied the productivity of cable skidders in steep terrain and measured the adverse slope encountered during each skidding cycle and included it in the production model. One field production study that studied a mechanized harvesting system was done by Wang et al. (2004b) which analyzed the production of a feller-buncher and grapple skidder in the Appalachian hardwood forests.

Several computer simulation models estimate timber harvesting system productivity. Baumgras et al. (1993) developed a ground based harvesting system simulation (GB-SIM) model that included chainsaw felling and limbing, cable skidder extraction and loading, to estimate production rates for conventional harvesting systems in Appalachian hardwood stands. Wang and LeDoux (2003) developed a computer simulation model using object oriented methodology to predict system productivity of mechanized equipment, including chainsaw, feller-buncher, and harvester felling, and grapple skidder and forwarder extraction. McDonagh et al. (2004) created a system dynamic model using four different harvesting systems from the southeastern United States. Systems included a chainsaw and cable skidder system, a feller-buncher and grapple skidder system, a shovel system and a cut-to-length system.

The objectives of this study were to examine productivity of a tree length system in steep slope conditions and to examine production relationships for grapple skidders in this system.

2.2 MATERIAL AND METHODS

2.2.1 Study Area and Harvesting System

The study was conducted on a large site in Whitley County in Eastern Kentucky (Figure 2.1). This harvesting site was selected because it was typical of Eastern Kentucky harvests, with steeply sloping terrain and eastern hardwood timber species. The site was also large enough (430 acres) to collect several months of data.

The entire site was harvested by the same crew. The harvesting equipment was one Timbco 445 tracked feller-buncher with a shear felling head, two John Deere 650 bulldozers, one Caterpillar 545 grapple skidder with a dual function arch, one Barko 225 loader and two tractor trailers. The crew had 5 machine operators, two chainsaw operators and two truck drivers. The feller-buncher cut and bunched trees in areas containing smaller timber (dbh range 8 to 15 inches). The chainsaw operators felled trees in areas with bigger trees and in areas not accessible by the feller-buncher. One bulldozer worked with each chainsaw operator to construct skid trails and bunch the felled trees along the trails for the skidder. One of the bulldozers broke down and was sold a little over one month into the study, so there was only one chainsaw operator and one bulldozer working over the final four months of the study. The bunched trees were skidded to the landing where they were processed by the loader and sorted by product class. The loader then loaded the trucks, which hauled the products to one of eight mills.

The crew utilized two landings during the course of the study. The first was located about 0.7 miles from the main road, with the second located about one half mile to the southwest of the first (Figure 2.2). The first landing was used for the first 59 days of the study, while the second was used for the final 92 days.

2.2.2 Data Collection

The feller-buncher, bulldozers, skidder and loader were instrumented with a data collection device called a Multi-Purpose Datalogger, or MultiDAT, manufactured by Geneq incorporated (Geneq 1997-200). The device is rugged and uses a GPS and a motion sensor to record positional data and working time, respectively.

The MultiDATs on the feller-buncher, bulldozers and skidder were equipped with Garmin GPS to track machine movements. An external antenna was connected to these

MultiDATs and was installed in a place where it could get optimal reception from GPS satellites. The MultiDATs were programmed to record a GPS point every 82 feet when the machine was working, and every sixty minutes when the machine was idle. The MultiDAT on the loader did not require a GPS since it is a stationary machine. The recording mode was set to “stop recording when full” so that no data would be recorded over, and the dataloggers were left to record data for the length of the project. The data files were downloaded periodically with the data shuttle and transferred to a PC and into the MultiDAT program.

2.2.3 Machine Productivity

The amount of wood removed from the site per day was calculated from the load tickets collected throughout the duration of the study. Information from each load ticket, date and product quantity (tons or Doyle BF), was recorded. The entries in Doyle board feet were converted into tons using a conversion factor of 6.5 tons per thousand board feet (MBF) (Doruska et al. 2006). The machine production rate was defined as the wood hauled to a mill each day divided by the motion sensor hours for each machine. The utilization rate per day for each machine was then calculated as: productive machine hours (PMH) divided by scheduled machine hours (SMH). The crew’s working day was scheduled to be ten hours long.

2.2.4 Skidder Productivity Equation

Other variables for the skidder were obtained from the GPS data gathered by the MultiDAT. This data was exported from the MultiDAT program into several different files, including a shape file and a DBF file.

The distances between points were calculated using the latitude, longitude and the radius of the earth in miles from a formula from Meridian World Data (1998-2007). These distances were then screened to exclude all distances over 164 feet, which was twice the distance that the MultiDAT was set to record. These were likely the result of some type of error. Recorded distances occurring between 5:30 pm and 6:00 am were also excluded, as the machines were never operated during these times.

The speed at which the machine travelled between consecutive points was calculated by dividing the distance between the two points by the elapsed time between them. These speeds were then screened to exclude those points with speeds over 17.1 miles per hour and those occurring during off duty hours. This speed is the maximum speed listed for the Cat 545 (Caterpillar 2006).

In order to calculate the change in elevation between subsequent points a 10 meter National Elevation Dataset for Whitley County Kentucky was downloaded from the USDA/NRCS Geospatial Data Gateway (Figure 2.3) (United States Department of Agriculture 2007). This raster dataset was then imported into ArcMap, along with the shapefile generated in MultiDAT. The “extract values to points” spatial analyst tool was then used to compute the elevation of each point from the elevation raster. These values were then exported from ArcMap, added to the original Excel file and converted into English units (feet). The change in elevation was then found by taking the absolute value of the difference between successive points. These elevations were then screened to exclude those points recorded during off duty hours.

The sum of the distance travelled by the skidder each day, the average speed of the skidder per day and the total change in elevation for each working day were calculated. The variables distance traveled per hour and elevation change per hour were created. These variables were calculated by dividing the daily value of the variable by the motion sensor hours for that day.

Several gaps were observed in the data, most likely due to either the loss of satellite reception or lost electrical connection. Any days with working hours falling within these gaps were excluded from the dataset because the variables obtained from the GPS data were incomplete. Days with no motion sensor hours were also excluded since the machines were not operated on these days.

2.2.5 Continuous Time Study

Continuous time study information was collected on the bulldozers using a wristwatch and clipboard. The dozer activities were recorded for two full working days, about a week apart. The watch was synchronized with a GPS device, so that the time would match that recorded by the MultiDAT.

Dozer elements have not been defined in the literature, so they were created based on the activities observed in the field. Five elements were defined and included travel empty, attach choker(s)/winch, travel loaded, unchoke and delays. The descriptions of these elements are shown in Table 2.1.

Another very common activity for the dozer was road building. This activity consisted of the bulldozer using its blade to create a flat and clear path for the grapple skidder. The total road building time and the total time spent building loads for the skidder were summed.

2.2.6 Data Analyses

Graphs and statistical software were used to analyze the data in order to find trends in production. Multiple linear regression was performed using the Statistical Analysis System (SAS System for Windows V9.1 2002-2004).

It was desired to relate production to some form of the variables distance, speed and elevation change. The dependent variables used in this model were daily skidder production and production spikes which were the sums of daily production leading up to and including each large increase in production. The spikes were caused by large quantities of logs built up on the landing. Independent variables used in the model included daily total distance traveled, average speed, total change in elevation, average distance travelled per hour, the squared average distance travelled per hour and average hourly change in elevation.

2.3 RESULTS AND DISCUSSION

2.3.1 Machine Productivity

Table 2.2 shows the productivity results for each machine. The loader had the highest utilization rate at 47.5 percent, while the feller-buncher had the lowest utilization rate at 18.1 percent. The utilization rate of the feller-buncher was low because it was frequently broken down. It was not an essential machine as there were also chainsaw operators felling and limbing trees.

Machine hours per week for the skidder and the loader are more closely related to production than the dozers and the feller buncher (Table 2.3). Correlation coefficients for production and skidder and loader hours are high. Bulldozers and the feller-buncher were not limiting in the production process but the skidder and the loader were. The feller-buncher was often broken down and not working and was not a key component of production. The chainsaws and bulldozers always had enough bunches made so that they were several days ahead of the skidder. Bulldozers also spent much of their time building roads which supported the production process. The skidder and the loader directly supplied and processed the wood for the trucks. Table 2.3 also shows a relatively strong relationship between the motion sensor hours for the skidder and the dozer meaning that they worked similar hours.

2.3.2 Skidder Productivity Equation

Table 2.4 lists several sample statistics for the selected variables. Average daily production was 56.74 tons per productive machine hour with a 95% confidence interval from 33.18 to 80.30. Average daily production was chosen over production spikes because it produced a more significant model with more observations. The average distance travelled by the skidder per hour was 8503 feet with a 95% confidence interval from 6723 to 10283. The average daily speed of the skidder was 2.66 miles per hour with a 95% confidence interval from 2.52 to 2.81. The average daily elevation change was 2980 feet per hour with a 95% confidence interval from 1944 to 4017.

A total of 47 days of productive time were used to build the productivity model for the skidder, including all working days which had data for the entire on-duty time. Trial and error was used to find the most significant variables, since different forms of each variable were being tested. The dependent variable chosen for the model was daily skidder production, and the independent variables chosen were average distance travelled per hour per day, the squared average distance travelled per hour per day, average speed per day and average hourly change in elevation per day. Fifteen regression models were run for all 1, 2, 3 and 4 independent variable combinations (Table 2.5).

The models have F-values ranging from 4.12 for the model containing only speed, to 961.61 for the model including only distance squared. The R^2-values of the models range from 0.08 for the model containing only speed to 0.97 for several models. Only the one model has an R^2-value of less than 0.80. All models are significant at the $\alpha = .05$ level.

Distance per hour had a negative impact on production in 6 of the 8 models in which it was included. Distance per hour squared had a positive impact on production in all 8 of the models in which it was included. Speed had a negative impact on production in 5 of its 8 models where it was included. Elevation change per hour had a positive impact on production in 6 of the 8 models in which it was included.

Table 2.6 shows a small negative correlation between production and the three variables distance, distance squared and speed. Elevation is more closely related to production than the other three variables with a positive correlation. Distance and distance squared have a very strong correlation as expected since one is a transformation of the other.

Figure 2.4 shows the effect on production of changing the speed and elevation change of the skidder using model 10. In the graph it can be seen that production increases as skidder speed per hour increases. From the three lines representing the range in elevation it can be seen that production also increases as elevation change increases.

The relationship between production and distance is shown in figures 2.5 and 2.6 using models 5 and 9. Production decreases with distance in model 5 until about 7500 feet but then increases thereafter. In model 9 production increases as skid distance increases.

2.3.3 Continuous Time Study

One of the bulldozers was observed for two full working days (seventeen hours). The percentage of time spent on each element and activity is shown in Figure 2.7. The delay consumed about 36% of the total time. About half of this time was used for crew breaks while a little less than half was spent waiting on the chainsaw operator. A small amount of time also spent on planning and service.

The second most time consuming bulldozer activity was the combination of driving to the next tree to be winched while working on the road. This accounted for about 30% of the total time. Each time the bulldozer operator returned from dropping a load he would not drive straight to the next tree, but would spend one to ten minutes working on the road, grading it with his blade and pushing debris out of the way. These two activities were not timed separately, but road building probably made up the majority of this time. The other three dozer elements: attach chokers, travel loaded and unchoke, accounted for 11%, 9% and 7% of the total dozer time, respectively. A small amount of time was also spent exclusively on road building, with the remaining time being used to travel back and forth between the landing and the work site.

A comparison was made to determine the amount of time spent road building versus load building. The combination travel loaded/road building was added to the road building activity to get the total road building time. The elements attach chokers, travel loaded and unchoke times were summed to get the total load building time. Road building was found to make up 34% of the total dozer time while load building made up only 27%.

2.4 CONCLUSION

For this operation it was found that the loader and the skidder had higher utilization rates than the dozers and feller-buncher. This was the case because the loader and skidder were more limiting than the other machines. Trucking was the bottleneck of the operation, and the loader and skidder were kept busy stockpiling logs for the trucks. The feller-buncher was not found to be a major part of the operation, as it was used only around the landing and a few other small areas. Most of the felling was done with chainsaws. The dozers were found to spend less than half of their productive time on bunching/load building with the majority of their time going to road building.

The instability in the parameter estimates for the models (Table 2.5) demonstrate the correlation among the variables. Traditional relationships indicate that increasing skid distance should reduce productivity. A number of models have a negative sign for distance. The positive sign for elevation probably indicates a multicolinear relationship with distance since the logical sign would be negative. Production should be lower with greater change in elevation. The signs indicate speed had a negative effect on production. This seems illogical, but it could be possible that the skidder was more likely to achieve greater speeds on longer skid distances.

It appeared that none of the three or four parameter models added enough value to be preferred above the 2 factor models. Of those models 5, 8 and 9 seem logical given the relationships discussed previously. Model 5 is certainly a typical configuration. The other two models might be useful if users desired to explore those differences modeling productivity from specific tracts. Relationships for models 5 and 9 are shown in figures 2.6 and 2.7. Production decreases with distance in model 5 until about 7500 feet but then increases thereafter. In model 9 production increases as skid distance increases. This illogical relationship indicates a multicolinear relationship with speed.

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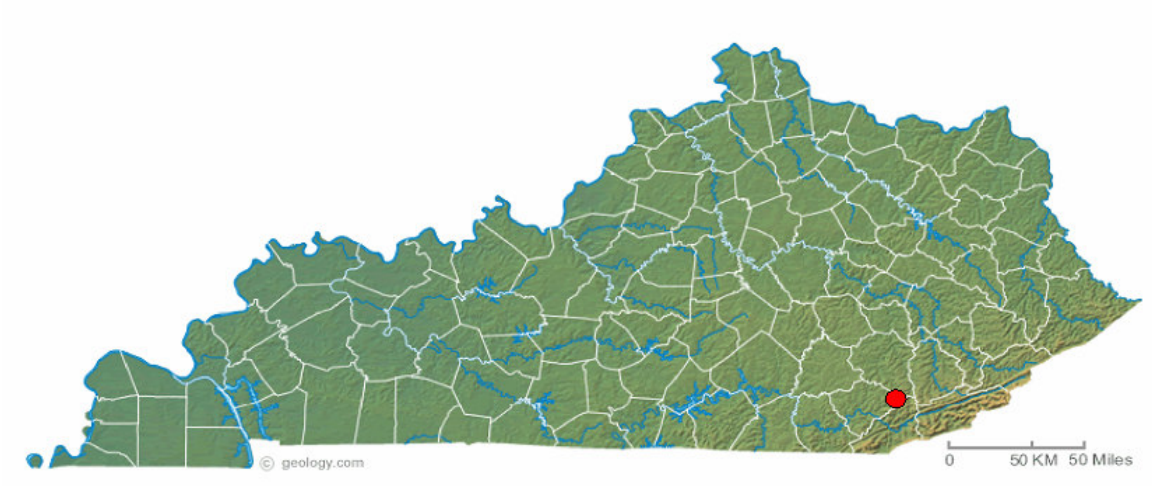

Figure 2.1. **Location of the study site in Whitley County Kentucky, near Pine Mountain.**

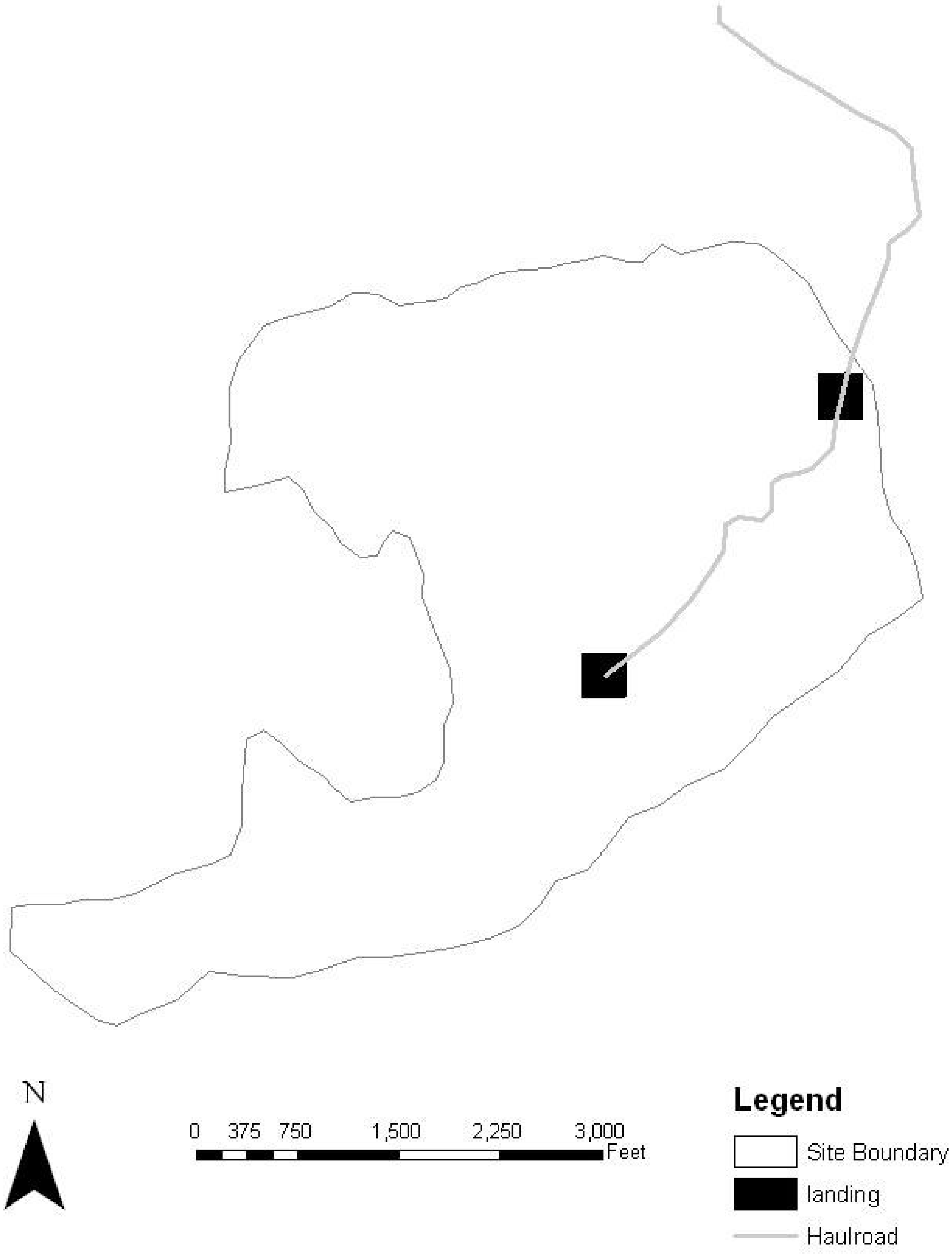

Figure 2.2. Harvest shape, landing locations, and haul road.

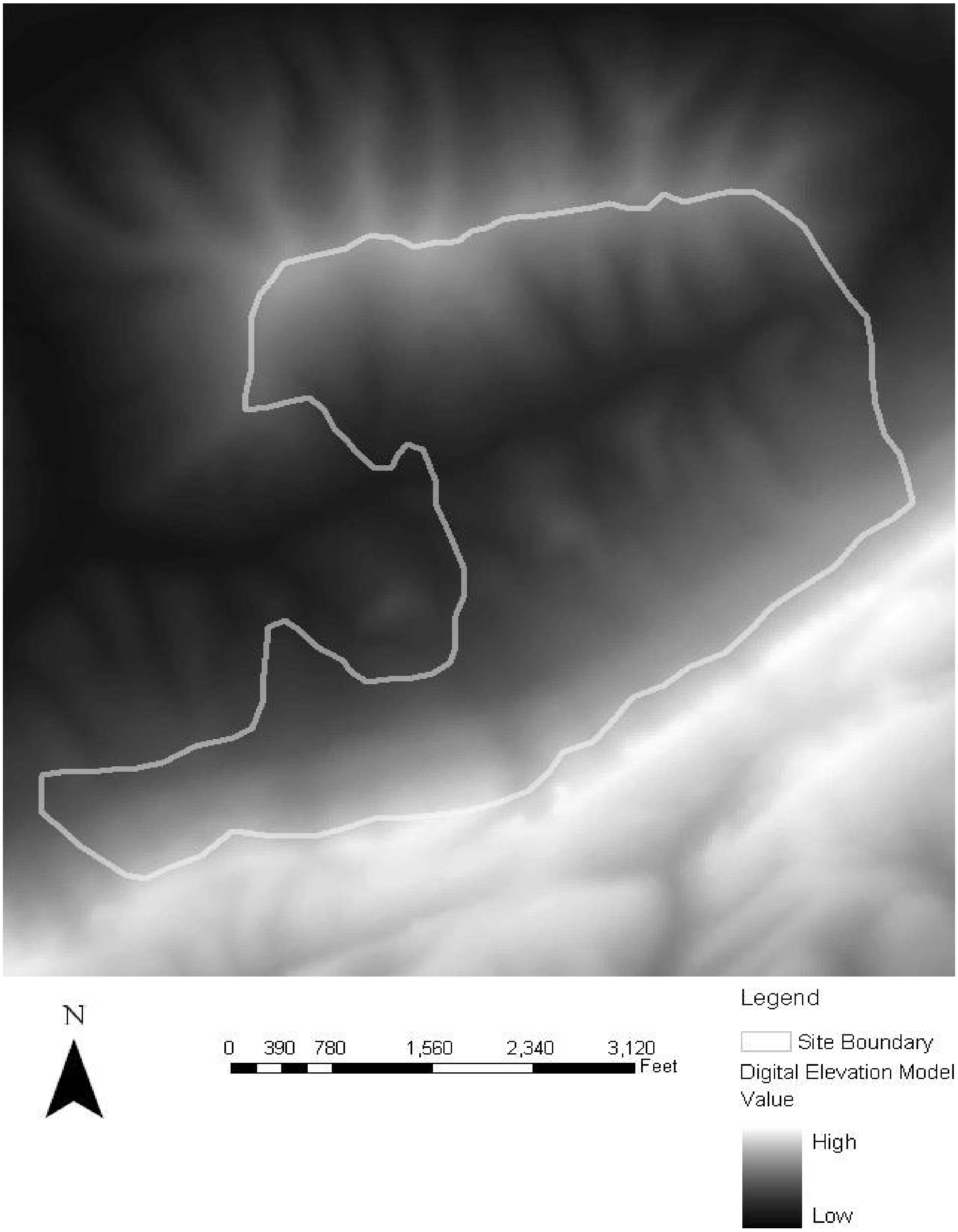

Figure 2.3. **Digital elevation model showing the elevation of the study site.**

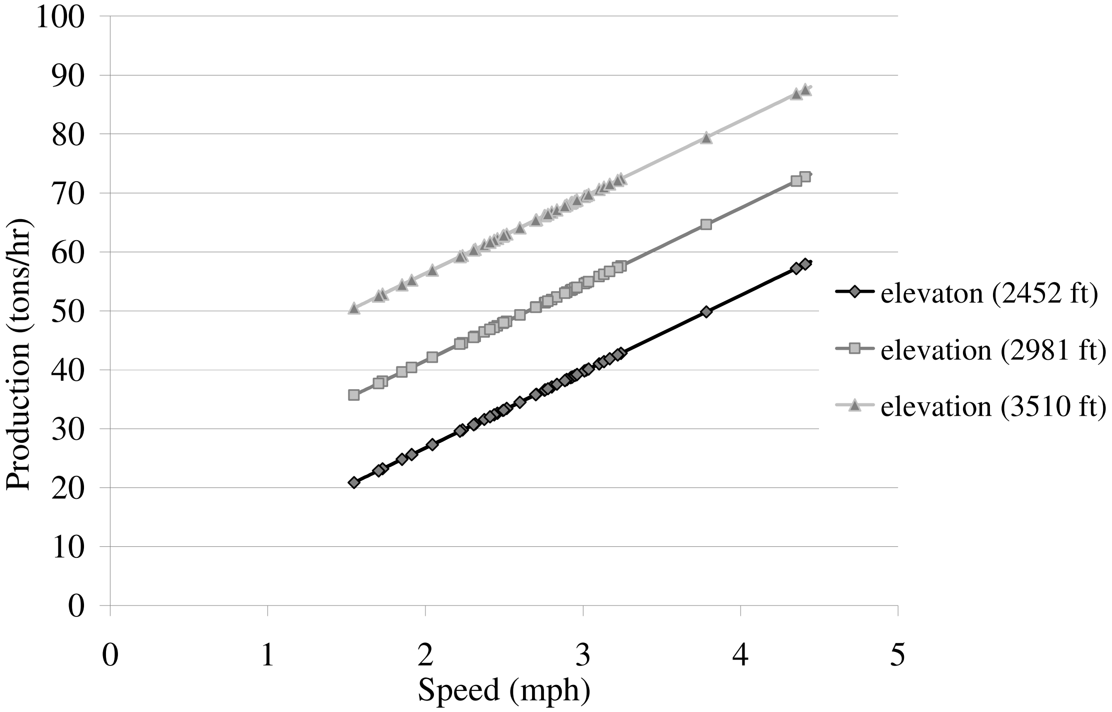

Figure 2.4. **The skidder production model across the range of speeds. The three production lines represent model number 10 using speed and elevation per hour plus or minus one standard error.**

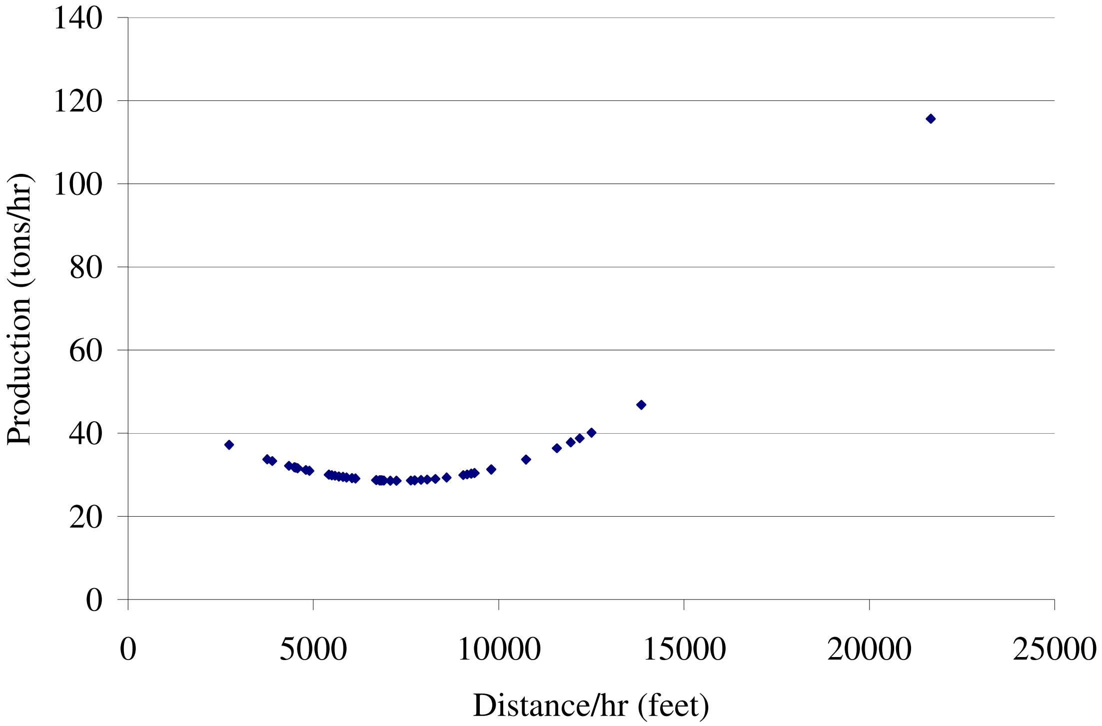

Figure 2.5. Relationship of production to distance using model 5.

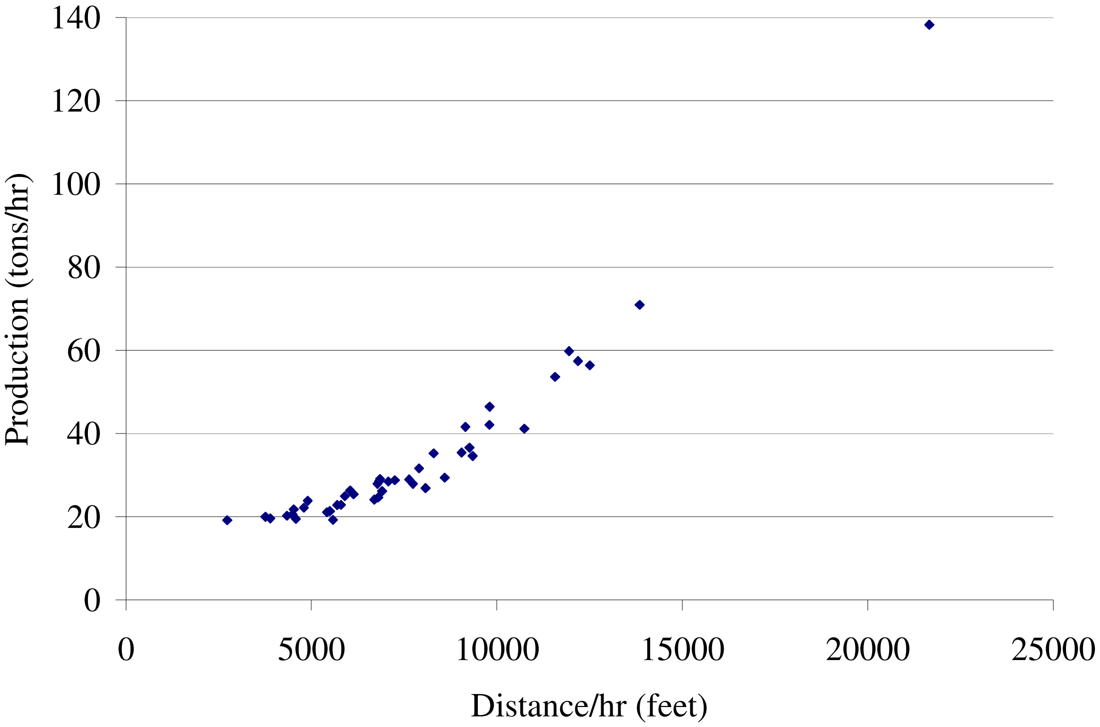

Figure 2.6. Relationship of production to distance using model 9.

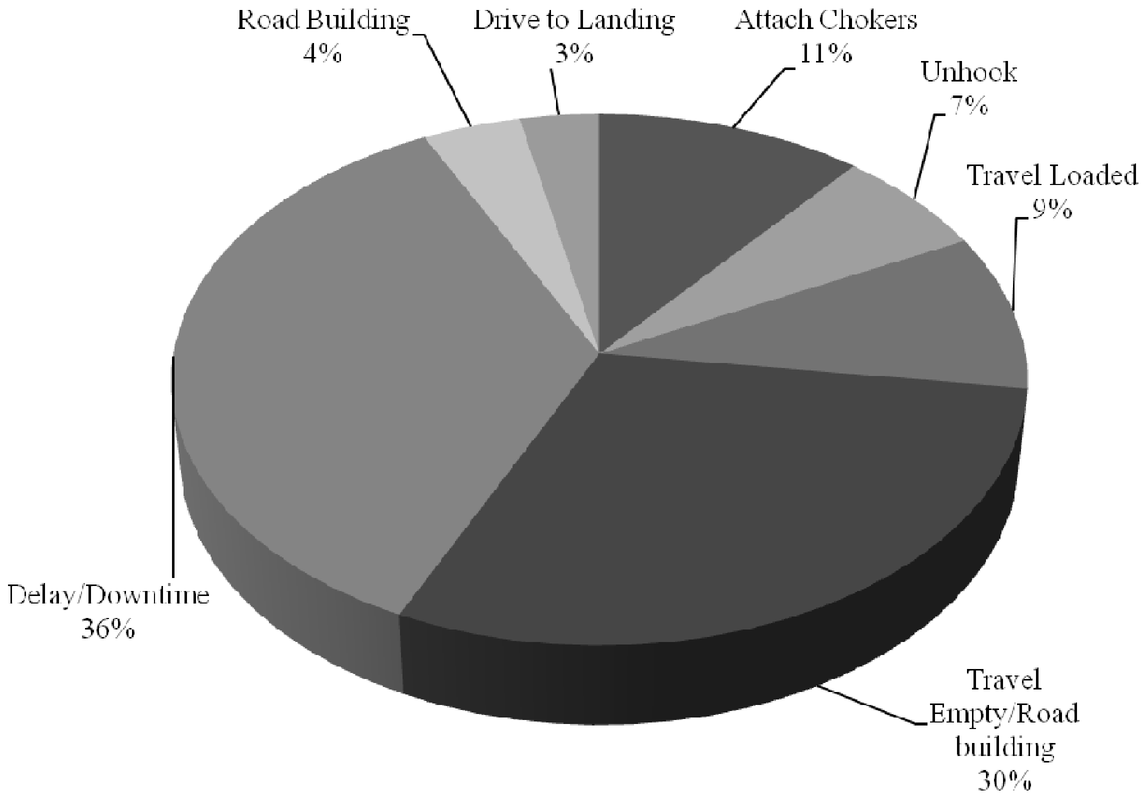

Figure 2.7. Activities carried out by the dozers, and the percentage of time spent on each.

Table 2.1. **Definitions of dozer elements created based on field observations.**

Element	Definition	Start and End Point
Travel empty	The dozer travels empty from the drop site of the previous log(s) to the next felled log(s)	Begins when the dozer starts moving, and ends when the dozer stops in position to hook up the next log(s)
Attach choker(s)/winch	The operator gets off of the dozer, pulls out the cable, attaches the choker(s) to the log(s), gets back on the machine, and winches in the log(s)	Begins when the dozer stops in position to hook up the log(s), and ends when the dozer starts forward movement
Travel loaded	The dozer either moves to the next felled log(s) or toward the drop-off point for the log(s)	Begins when the dozer starts forward movement, and ends when the dozer stops at the bunching point
Attach chokers/rewinch	The operator gets off of the dozer, pulls out the winch, attaches the choker(s) to the new log(s), gets back on the machine, and winches in the log(s)	Begins when the dozer stops in position to hook up the log(s), and ends when the dozer starts forward movement
Unhook	The operator gets off the dozer, unhooks the choker cables, gets back on the machine, and winds the winch up	Begins when the dozer stops at the bunching point, and ends when the dozer starts back out for the next load
Delays or downtime	Delays or downtime occurring between the first four elements, such as waiting on the chainsaw operator, breaks/lunch, service, etc	

Table 2.2. **Daily productivity means for each machine, as well as the two dozers, combined. Numbers in parentheses are standard errors.**

Variable	Skidder	Loader	Feller/ Buncher	Dozer One	Dozer Two	Combined Dozers
Motion Sensor Hours	4.08 (0.17)	4.75 (0.23)	1.77 (0.21)	3.45 (0.20)	2.43 (0.47)	4.02 (0.26)
Production (Tons/PMH)	56.7 (12.02)	35.9 (5.21)	N/A	39.3 (3.64)	49.9 (10.34)	38.5 (3.65)
Utilization Rate % (PMH/SMH * 100)	40.8 (1.66)	47.5 (2.31)	18.1 (2.09)	34.5 (1.95)	24.3 (4.74)	32.8 (1.88)

Table 2.3. Correlation coefficients between weekly motion sensor hours for each machine and weekly tonnage.

	Tons	Skidder	Loader	Dozers	Feller/Buncher
Production (tons)	1	0.34	0.31	0.23	0.14
Skidder		1	0.43	0.74	0.40
Loader			1	0.26	0.59
Dozers				1	0.26
Feller/Buncher					1

Table 2.4. Sample statistics for skidder variables.

Variable	Mean	Standard Error	Standard Deviation	Lower 95% CI	Upper 95% CI
Production (tons/hr)	56.74	12.02	114.04	33.18	80.30
Distance / hr (feet)	8503	908	6857	6723	10283
Speed (mph)	2.66	0.074	0.56	2.52	2.81
Elevation Change (ft) / hr	2981	529	3993	1944	4017

Table 2.5. **Analysis of variance table for skidder productivity equations. Significance of parameter estimates are indicated by: * < 0.10 and ** < 0.01.**

Model	Intercept	disthr	distsq	speed	elevhr	F-value	P-value	R^2	MSE
1	-80.21 **	0.015 **				203.99	<0.0001	0.82	550388
2	12.27 **		$3.1*10^{-7}$ **			961.61	<0.0001	0.96	641772
3	210.65 *			-59.07 *		4.12	0.0482	0.084	56401
4	-30.75 **				0.027 **	390.37	<0.0001	0.90	602367
5	50.75 **	-0.0061 **	$4.2*10^{-7}$ **			628.45	<0.0001	0.97	324541
6	-50.55	0.015 **		-10.22		101.32	<0.0001	0.82	275978
7	-12.49	-0.0051 **			0.036 **	201.24	<0.0001	0.90	302800
8	15.58		$3.1*10^{-7}$ **	-1.19		470.47	<0.0001	0.96	320896
9	19.12 *		$3.5*10^{-7}$ **		-0.0041	481.21	<0.0001	0.96	321217
10	-67.85 *			12.95	0.028 **	198.31	<0.0001	0.90	302359
11	51.87 *	-0.0061 **	$4.2*10^{-7}$ **	-0.41		409.49	<0.0001	0.97	216361
12	51.21 *	-0.0079 *		22.52 *	0.0069 **	432.15	<0.0001	0.97	216746
13	-66.27 **	-0.0080 **	$3.8*10^{-7}$ **		0.042	145.59	<0.0001	0.91	203864
14	33.05		$3.6*10^{-7}$ **	-4.41	-0.0052	316.28	<0.0001	0.96	214226
15	36.15 *	-0.0086 **	$3.7*10^{-7}$ **	5.62	0.0092 *	321.86	<0.0001	0.97	262645

Table 2.6. Correlation coefficients between skidder variables.

	Production	Distance	Distance^2	Speed	Elevation
Production (tons/hr)	1	-0.21	-0.19	-0.17	0.50
Distance / hr (miles)		1	0.97	0.56	-0.089
(Distance / hr)^2 (feet^2)			1	0.55	-0.15
Speed (mph)				1	-0.33
Elevation Change (ft) / hr					1

III. TRAFFIC MAPPING AND DISTURBANCE ANALYSIS OF TIMBER HARVESTING OPERATIONS ON STEEP TERRAIN

3.1 INTRODUCTION

Timber harvesting activities in the Appalachians are often seen as a threat to water resources because harvesting is widespread, occurs on steep terrain and has considerable aesthetic impact (Kochenderfer et al. 1997). Harvesting on steep slopes tends to cause more environmental problems than harvesting on less severe slope, because more sediment is transported as slope percentage increases (Wang and Wu 2001).

Best Management Practices (BMPs) were developed by many states to minimize the impact of nonpoint source pollution from forestry operations on water quality. SMZs are one of the more important aspects of BMPs since riparian areas are the boundary between aquatic and terrestrial ecosystems and are one of the most diverse parts of a forest ecosystem (Blinn and Kilgore 2004). SMZs act to separate runoff and pollutant contributing areas from surface waters (Phillips 1989).

SMZs vary by stream type and may consist of canopy cover retention and/or minimization of trafficking near the stream. Carroll et al. (2004) found that SMZ application maintained favorable pre-harvest stream conditions, while Ward and Jackson (2004) found that SMZs efficiently trapped sediment following a timber harvest.

Several studies have been done to map traffic intensities from harvesting operations and compare them to site disturbance or soil impact (McDonald et al. 1998, Carter et al. 1999, Carter et al. 2000 and McDonald et al. 2002). Other studies used GIS to locate SMZs and determine the area in SMZs (Kluender et al. 2000 and Williams et al. 2003).

The primary objective of this study was to relate machine movements with site disturbance through the use of traffic mapping and disturbance sampling. This study may be useful in determining the extent of site damage related to machine traffic patterns. This project was also developed as a pilot study for a future SMZ study in the same region. It is expected to help develop methodology that may assist in determining the machine trafficking within the SMZs.

3.2 MATERIALS AND METHODS

3.2.1 Study Area

The same 430 acre site in Eastern Kentucky that was used for the production portion of the study was also used for the disturbance study.

3.2.2 Disturbance Sampling

Disturbance sampling points were then chosen by using the "create random points" data management tool in ArcToolbox to create 200 random points within the site boundary. The site boundary and disturbance sampling points can be seen overlaying a topographic map of the area in Figure 3.1. This disturbance sampling points layer was then assigned a geographic coordinate system using the "project" data management tool, and each point was then given coordinates using the “add XY coordinates” data management tool. These coordinates were converted from decimal degrees to degrees, minutes and seconds and imported into a handheld Trimble GeoXT GPS device.

At the completion of the harvest this GPS device was used to navigate to each of the disturbance sampling points. An alarm was set to sound when the operator was within 16.4 feet of the selected point. The plot center was the location at which the alarm sounded, and the plot size was 50 feet x 50 feet, approximately three times the width of a typical skid trail. The plot was then classified by disturbance level and traffic type (Tables 3.1 and 3.2) (Aust et al. 1998 and Berger et al. 2004), with class assignment being the highest level occurring on at least ten percent of the plot.

This disturbance classification data was then compared to the trafficking data of all of the machines. The shape files containing each machine’s GPS data created previously using the MultiDAT software was imported into the ArcMap file containing the site boundary and disturbance sampling points. The two dozer layers were combined to create a single dozer layer using the “merge” data management tool, and this new layer was combined with the skidder and feller layers in order to create an overall machine disturbance layer.

A new field was then created in the attribute table of each point layer using the field calculator, and was made to equal one for each GPS point. Rasters of these point layers were then created using the “point to raster” conversion tool. The value field used for this process was the newly created field of one’s, and the cell assignment type was set to sum, making the value of each cell equal to the number of GPS points contained within it. Cell size was set to 50 square feet to match the disturbance sampling plots.

The values of cells containing random sampling points were then found for each raster layer using the “identify” tool, and were recorded in the spreadsheet containing the disturbance sampling data.

3.2.3 Traffic Mapping

Traffic maps were also created in order to get a clearer visual look at the traffic patterns of each machine or machine group. To do this, the properties of the previously created raster layers were modified. The cell values were classified into five different groups of 1 to 5, 6 to 10, 11 to 25, 26 to 50 and more than 50 GPS points, and were color coded.

3.2.4 Data Analyses

Graphs and statistical software were used to analyze the data in order to find trends in machine disturbance. Several discriminant analyses were performed using the Statistical Analysis System (SAS System for Windows V9.1 2002-2004) in order to relate observed disturbance with GPS patterns. This procedure is used to relate group membership to response variable measures. It develops a discriminant criterion to classify each observation into one of the groups. The distribution for each group is assumed to be normal a discriminant function is developed and is determined by a measure of generalized squared distance (SAS/STAT User’s Guide 1998). This function can be expressed mathematically as (Klecka 1980):

$$f_t = u_0 + u_1 X_{1t} + u_2 X_{2t} + \ldots + u_p X_{pt}$$

where:

f_t = the predicted discriminant score for group t

X_i = the value on the discriminating variable X_i

u_i = coefficients which produce the desired characteristics in the function

For these analyses the classification variables were the disturbance level and traffic type categories assigned to each random disturbance sampling point. Three quantitative variables were used including the disturbance sampling point cell values of the rasters for the skidder, the feller-buncher and the combined dozers. The response variable measures were transformed using the log and square root transformations because the data was not normally distributed across disturbance categories. The disturbance categories were also combined in several different ways to search for the best fit for the data.

3.3 RESULTS AND DISCUSSION

3.3.1 Traffic Mapping

Figures 3.2, 3.3 and 3.4 show the disturbance levels based off of the GPS data for the skidder, the combined dozers and the feller-buncher, respectively. From the map of the skidder it can be seen that this machine traveled several distinct trails which followed the contours of the hillsides as well as one through the valley which followed the power line cut. It appeared to stick primarily to the trails with the only major clusters of points occurring around the two landings.

The map of the two dozers is somewhat similar to that of the skidder in that a few trails can be detected because of areas of higher point densities. However, the dozer map shows much more activity throughout the rest of the site confirming that the dozers traveled over a greater proportion of the site in order to winch and bunch trees.

The feller-buncher disturbance map shows only four clusters of activity on the site. This indicates that the machine was not used extensively for timber harvesting and was often kept idle on the landing. It was used only to cut around landings and in two other areas of the tract. Figure 3.5 combines these three maps to show total harvesting system traffic.

3.3.2 Disturbance Sampling

Slightly over half of the disturbance sampling points were located in areas of no machine disturbance (Figures 3.6 and 3.7). In relation to the disturbance levels, 12 percent of the plots had compressed ground as the most severe disturbance, with 16 percent in areas with bare mineral soil and minimal residual damage as the most severe disturbance, and 20 percent where bare mineral soil and much residual damage was the highest level of disturbance. When it came to the traffic types, 5 percent of plots had nontrail traffic as the most severe traffic type, 7 percent tertiary skid trails, 16 percent secondary skid trails, 18 percent primary skid trails and 2 percent occurred where landings were the most severe traffic type.

Using the non transformed variables both models did a poor job of classifying the points into the correct category, with only 26.5 percent being classified into the correct disturbance level class, and 30.5 percent being put into the right traffic type class (Tables 3.3 and 3.4). Only one of the disturbance levels had a large proportion of points classified correctly. Disturbance level 3, bare mineral soil with minimal residual damage, had over 90 percent of its observations classed properly while all of the others were well below 50 percent.

Similar results were seen with traffic type data with only one class, secondary skid trails, having a large amount of its points classified correctly. Over 90 percent of its observations were classed properly while traffic type 6, landings, was the only other class over 50% at 66.6%. Class 5, primary skid trails, was just under 50%, but the other three were all 20% or less. Once again, the majority of points in all classes were classified into the same category; secondary skid trails, which was defined the same as the disturbance level that most points were classified into.

The square root transformed data gave the best results for the analysis because the response variables were count data. The linear discriminant functions for disturbance and traffic types are shown in Tables 3.5 and 3.6. Both models did a better job of classifying the points into the correct category, with 49.5 percent being classified into the correct disturbance level class, and 46 percent being put into the right traffic type class (Tables 3.7 and 3.8). All of the disturbance level classes had more points classified into the correct category than in any other category, with the undisturbed and compressed classes having a majority classified correctly.

Similar results were seen with the traffic type data with all classes except non-trail traffic having more points classified into the correct category than in any other category. The untrafficked, tertiary skid trail and landing classes had a majority of their points classified correctly while the nontrail traffic category had no points classed properly.

3.4 CONCLUSION

GPS data had a relatively weak relationship with the ground disturbance data, with about 48 percent classified correctly with discriminant analysis. The quality of the relationship between GPS and ground data may be confounded by a number of errors.

GPS error was introduced by the blocking of satellite signals by the surrounding canopy and mountains. Other GPS error, such as mutipath error, caused by mountains and trees located on the site might also be important. Also, the Position Dilution of Precision (PDOP) was set high in order to collect more data points, which likely led to a lower probability of GPS accuracy. The recording mode on the GPS devices could also have had an effect on the results. Recording more points and recording based on time rather than on distance may have improved the relationship. In addition ground data collection methods introduced bias since the plot center was relocated to the path the person collecting the data was walking to the point on a path that was clear.

While characterizing high traffic areas can be easily accomplished using the traffic maps, one of the objectives of this research might be to identify single or multiple intrusions into SMZs where water quality could be significantly affected. The traffic class data shows relatively poor classification for classes 2, 3 and 4, but the disturbance classification is much better for disturbance classes 2, 3 and 4. Observers might be better at observing the site conditions than the factors that contributed to the condition.

For this operation it was found that over half of the harvesting area was left undisturbed. The remainder sustained some level of damage as a result of timber extraction. These results differ from other soil disturbance studies related to steep terrain timber harvesting since the plots were classified according to the most severe disturbance. McMinn (1984) found that only 9% of a steep slope harvest site had bare mineral soil exposed and scarified with 7% having bare mineral exposed with no scarification, compared to this study which found 16% of the harvest area to have bare mineral soil and much residual damage and 20% to have bare mineral soil with minimal residual damage. Miller and Sirois (1986) found that landings occupied 6.4% of the harvested area while skid trails occupied only 21.4%, compared to 2% for landings and 41% for skid trails found in this study. They also found only 17.7% of the tract to be disturbed down to mineral soil, while this study found it to be 36%. Martin (1988) found that only 8% of the site had bare mineral soil exposed due to the lack of bladed skid trails, compared to 36% for this study. Stuart and Carr (1991) found that only 19 to 26% of the harvested area on 10 different sites was disturbed down to mineral soil and only 3 to 10% of the tracts' areas contained skid trails, compared to 36% and 41% respectively for this study.

The validity of the classification makes it unlikely that it would be effective in monitoring SMZ disturbance, although it could be used effectively to address other nonpoint source pollution and BMP concerns. The traffic maps generated from the GPS data were effective in identifying highly trafficked areas including landings and main skid trails, which tend to cause the most nonpoint source pollution concerns and require more BMPs.

3.5. REFERENCES

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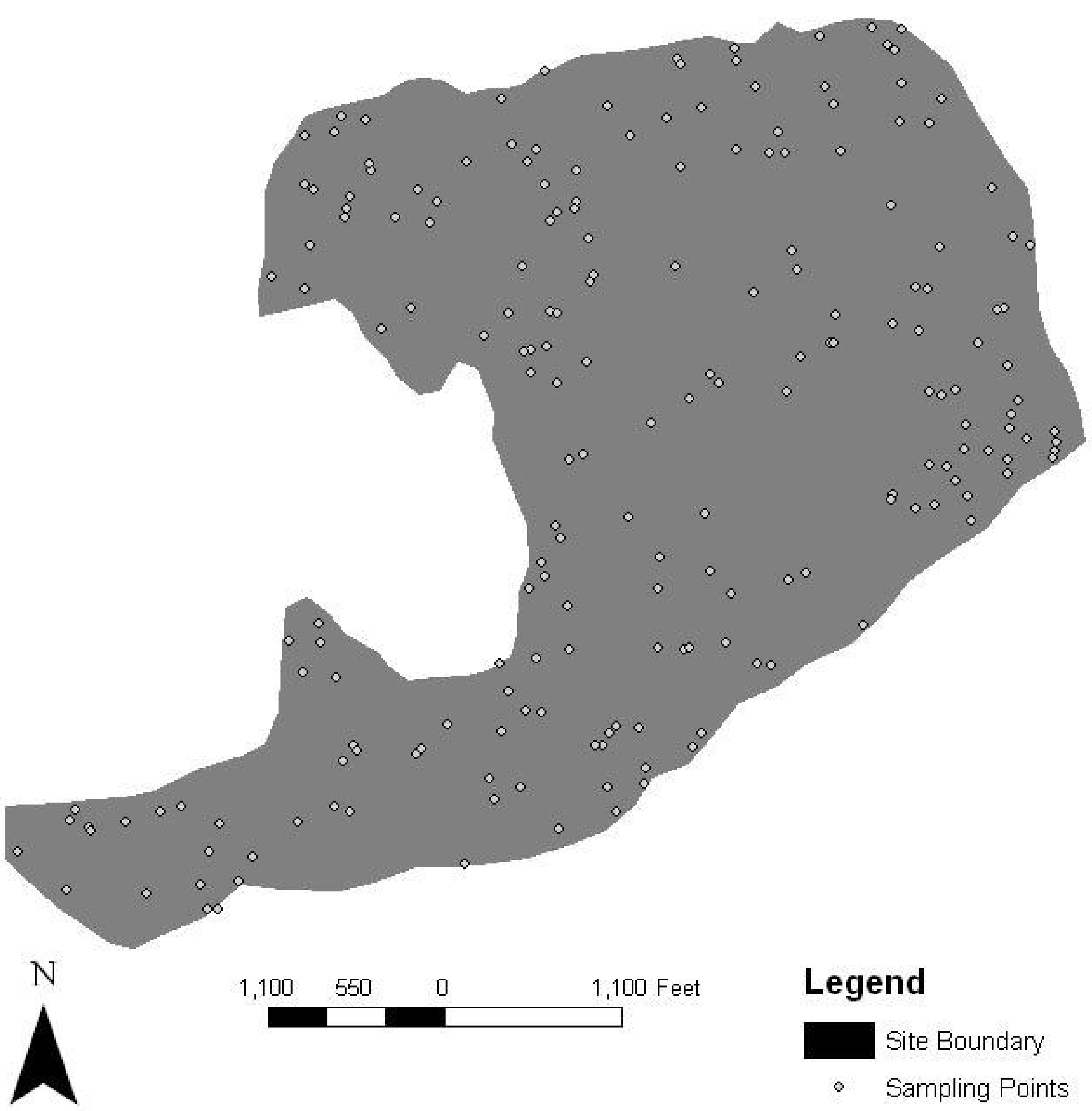

Figure 3.1. Disturbance sampling points.

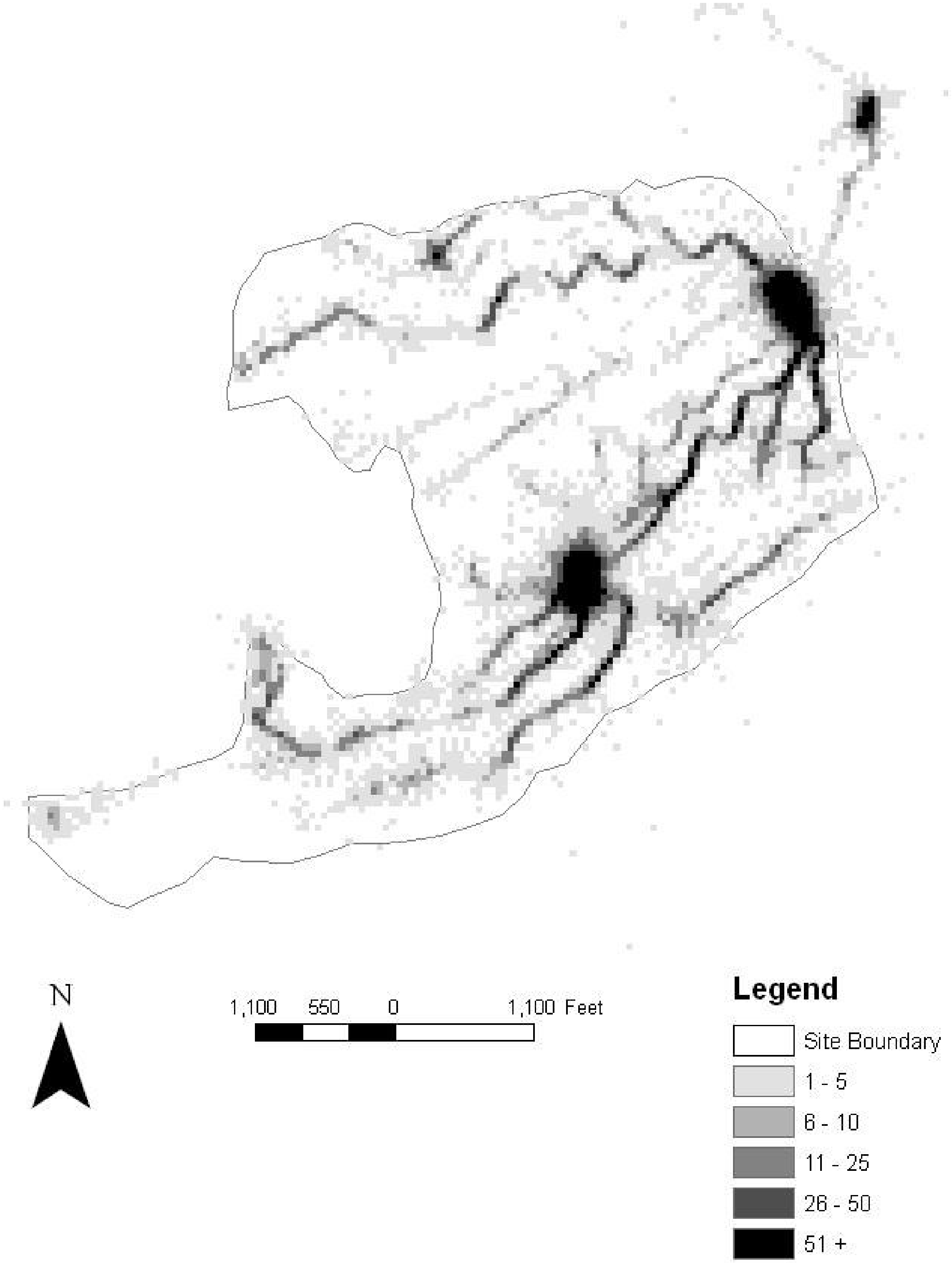

Figure 3.2. **Skidder disturbance levels based off of GPS data.**

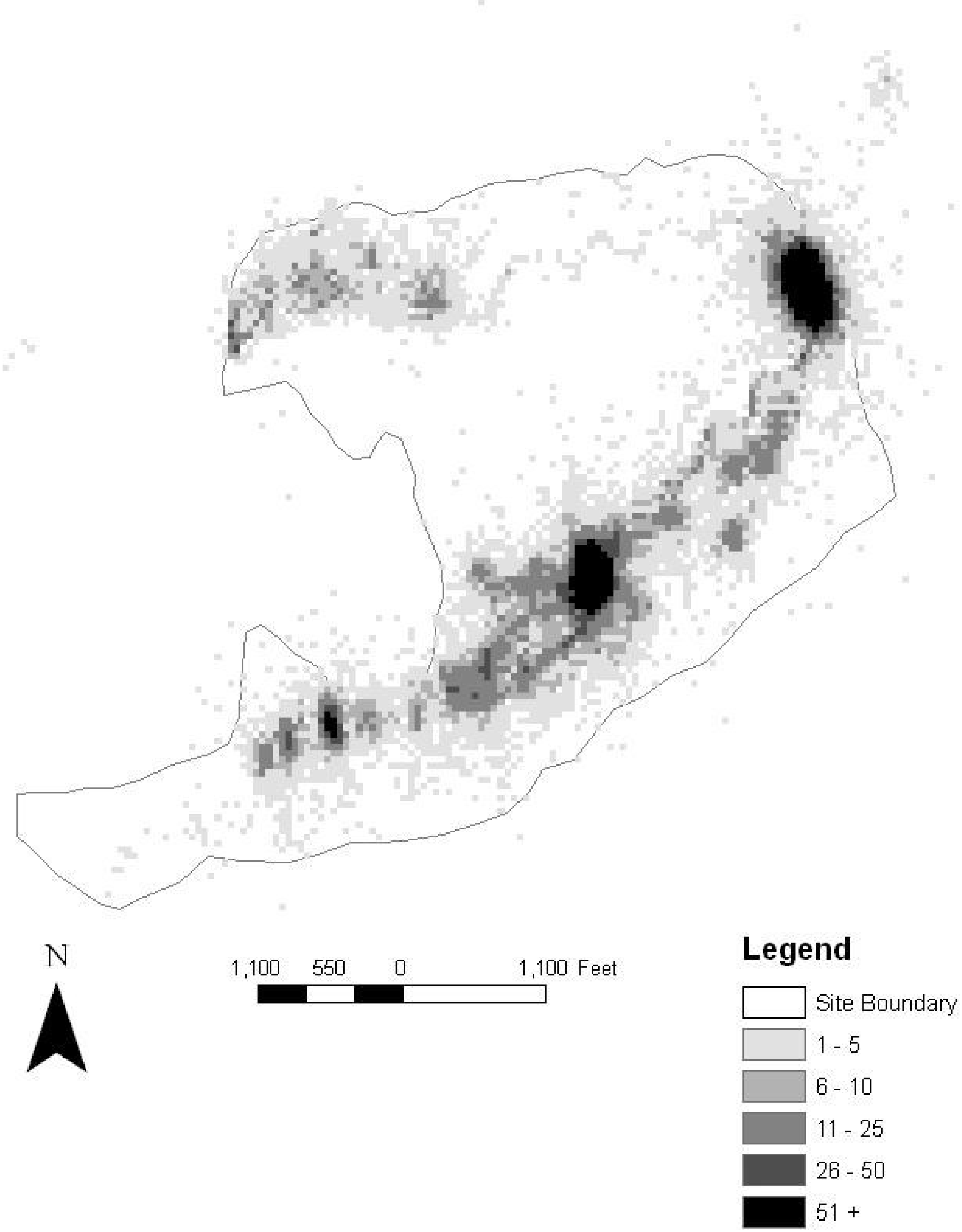

Figure 3.3. Dozer disturbance levels based off of GPS data.

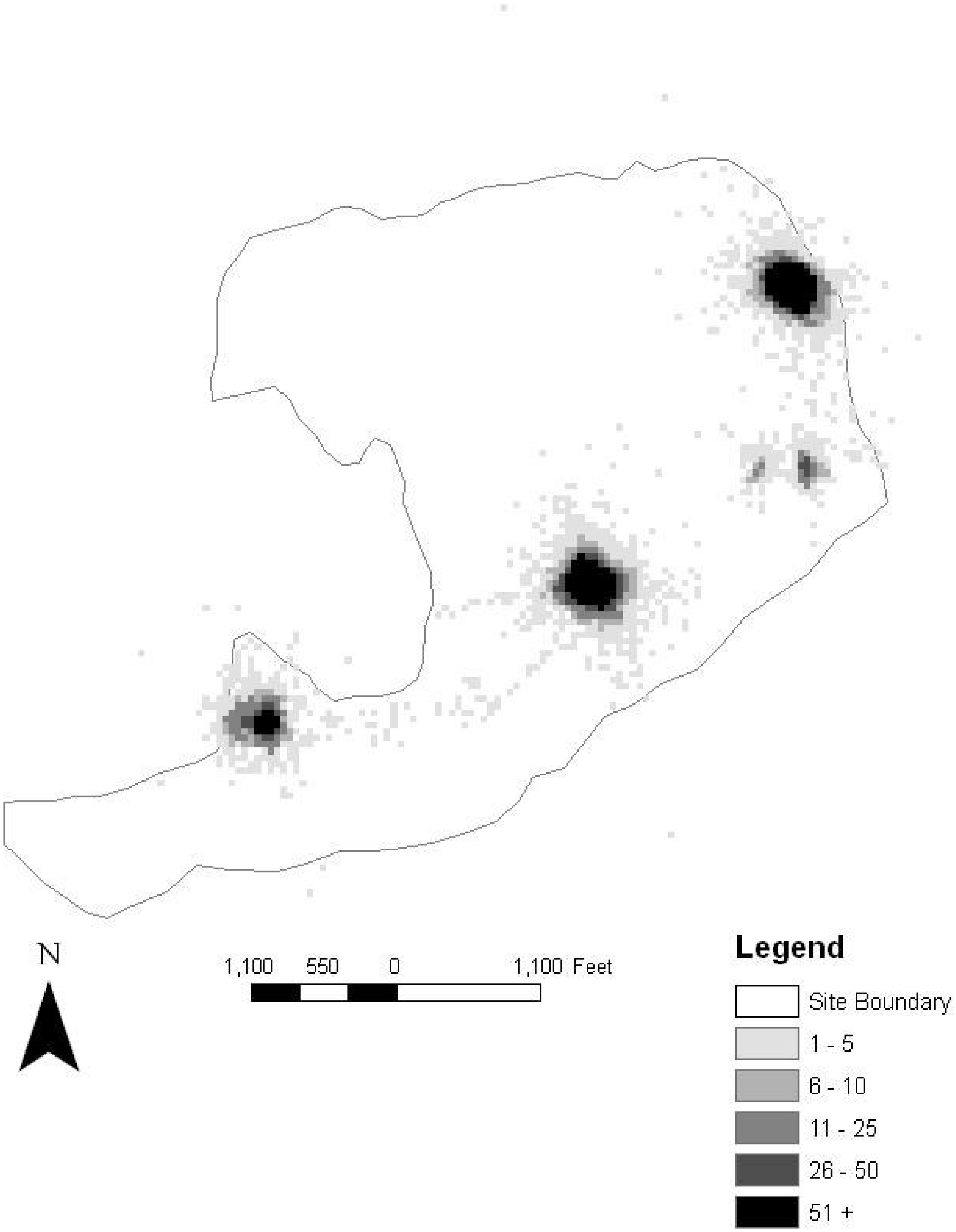

Figure 3.4. Feller-buncher disturbance levels based off of GPS data.

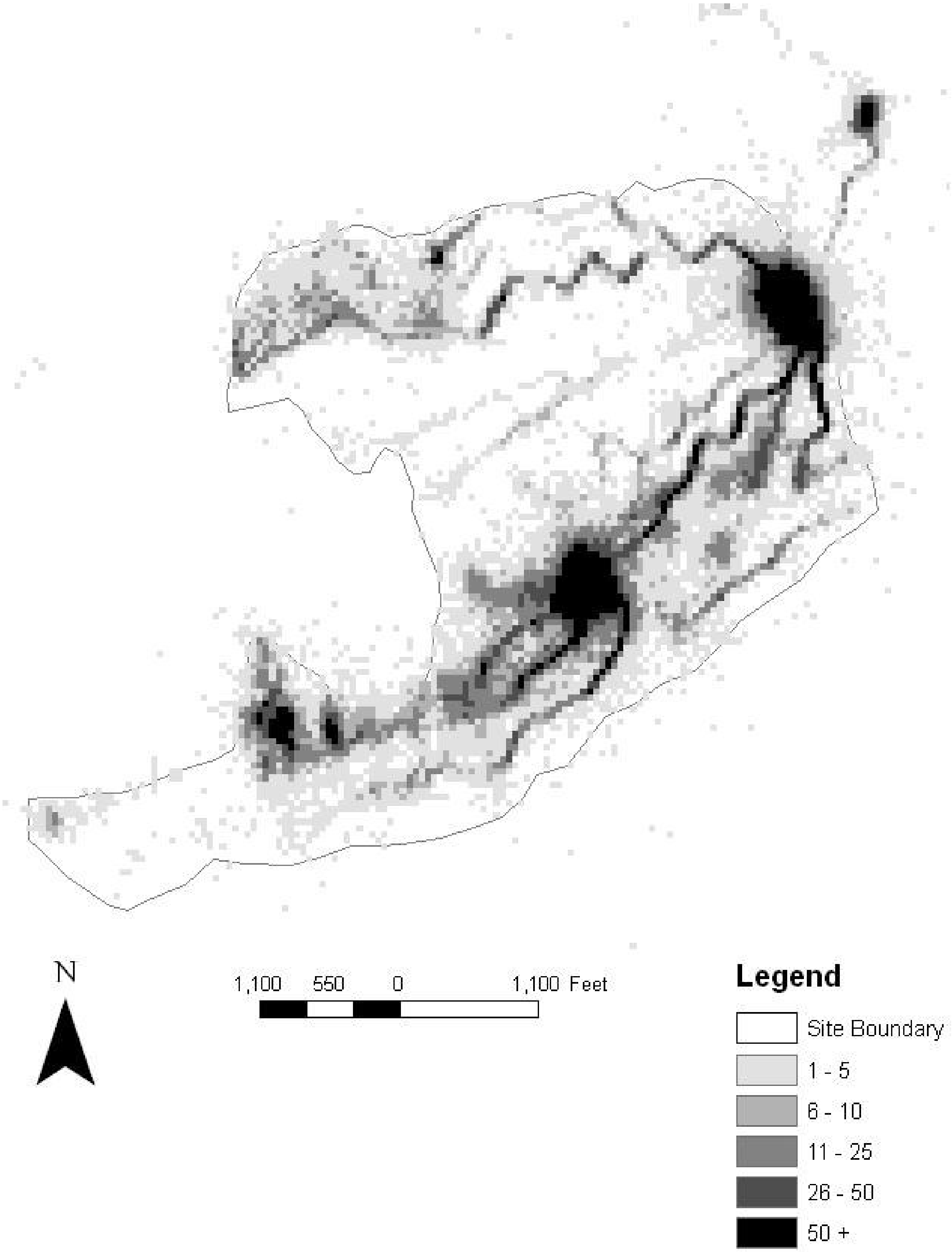

Figure 3.5. Total disturbance levels based off of GPS data.

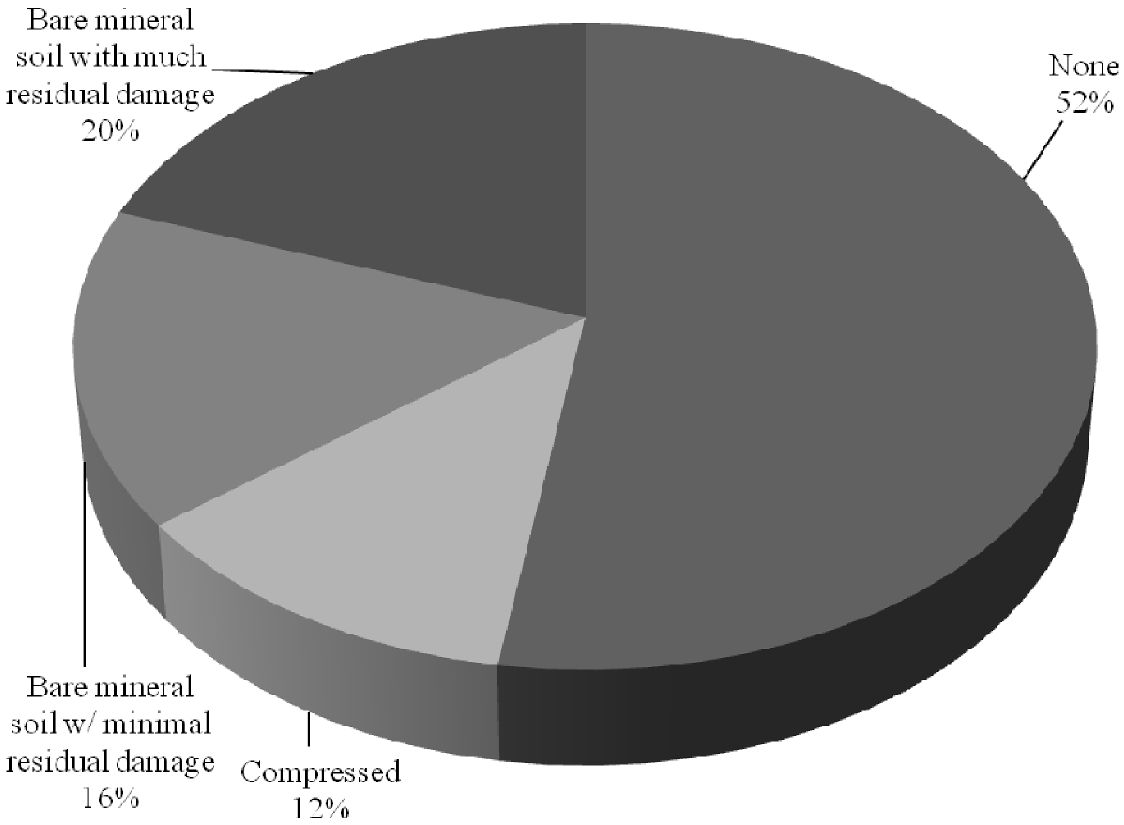

Figure 3.6. Percentage of random sampling points with the most severe disturbance levels.

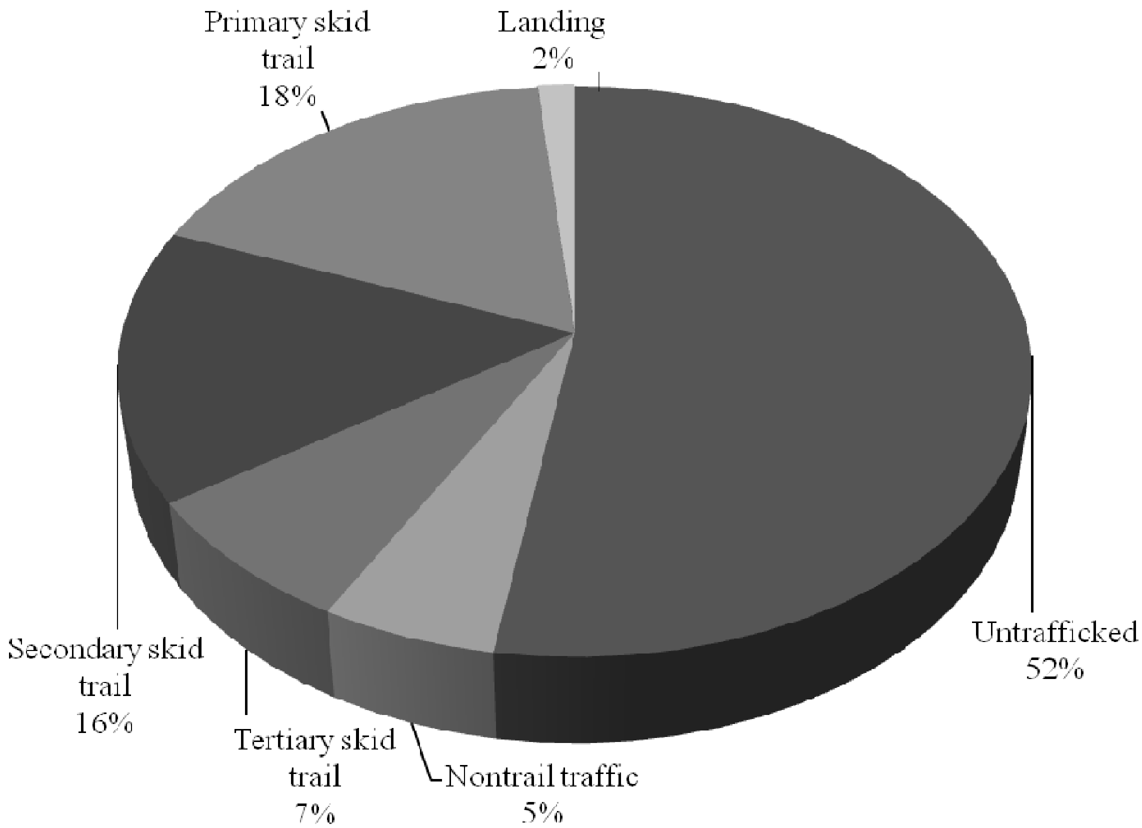

Figure 3.7. **Percentage of random sampling points with the most severe traffic classes.**

Table 3.1 Disturbance levels used to classify disturbance sampling points and their definitions.

Class	Disturbance Level	Definition
1	None	No visible disturbance from machine traffic
2	Compressed, no bare mineral soil	Litter layer has been disturbed, but most organic material still remains (unbladed)
3	Bare mineral soil with minimal residual damage	Litter layer completely removed down to bare mineral soil, turn trees, other residual trees, and stumps in or near trail not very damaged (most of the bark is still left)
4	Bare mineral soil with much residual damage	Litter layer completely removed down to bare mineral soil, turn trees, other residual trees, and stumps in or near trail severely damaged (most of the bark has been knocked off)

Table 3.2 Traffic types used to classify disturbance sampling points and their definitions.

Class	Traffic Type	Definition
1	Untrafficked	No visible machine traffic
2	Nontrail Traffic	Very few machine passes occurring off of any trail
3	Tertiary skid trail	Unbladed trail
4	Secondary skid trail	Litter layer completely removed down to bare mineral soil, turn trees, other residual trees, and stumps in or near trail not very damaged (most of the bark is still left)
5	Primary skid trail	Litter layer completely removed down to bare mineral soil, turn trees, other residual trees, and stumps in or near trail severely damaged (most of the bark has been knocked off)
6	Landing	Area of very high traffic where trees were skidded, processed, and loaded onto trucks

Table 3.3. Number of observations classified into each disturbance level, with percentages in parentheses. Highlighted numbers represent correctly classified observations.

Disturbance Level	1	2	3	4	Total
1	11	12	80	2	105
	(10.48)	(11.43)	(76.19)	(1.90)	(100.00)
2	2	9	13	0	24
	(8.33)	(37.50)	(54.17)	(0.00)	(100.00)
3	1	2	29	0	32
	(3.13)	(6.25)	(90.63)	(0.00)	(100.00)
4	2	11	22	4	39
	(5.13)	(28.21)	(56.41)	(10.26)	(100.00)
Total	16	34	144	6	200
	(8.00)	(17.00)	(72.00)	(3.00)	(100.00)

Table 3.4. **Number of observations classified into each traffic type, with percentages in parentheses. Highlighted numbers represent correctly classified observations.**

Traffic Type	1	2	3	4	5	6	Total
1	11 (10.48)	1 (0.95)	6 (5.71)	78 (74.29)	9 (8.57)	0 (0.00)	105 (100.00)
2	1 (9.09)	0 (0.00)	2 (18.18)	6 (54.55)	2 (18.18)	0 (0.00)	11 (100.00)
3	1 (6.67)	1 (6.67)	3 (20.00)	8 (53.33)	2 (13.33)	0 (0.00)	15 (100.00)
4	1 (3.23)	0 (0.00)	2 (6.45)	28 (90.32)	0 (0.00)	0 (0.00)	31 (100.00)
5	1 (2.86)	0 (0.00)	1 (2.86)	16 (45.71)	17 (48.57)	0 (0.00)	35 (100.00)
6	0 (0.00)	0 (0.00)	0 (0.00)	1 (33.33)	0 (0.00)	2 (66.67)	3 (100.00)
Total	15 (7.50)	2 (1.00)	14 (7.00)	137 (68.50)	30 (15.00)	2 (1.00)	200 (100.00)

Table 3.5. **Linear discriminant function results for the disturbance type classification, with response variables square root transformed.**

Variable	Class 1	Class 2	Class 3	Class 4
Constant	-0.07956	-0.34122	-0.12097	-1.14488
Buncher	-0.04543	-0.62905	-0.81535	-1.66392
Skidder	-0.09163	-0.14897	0.23939	0.51289
Dozer	0.30231	0.70395	0.12299	0.57783

Table 3.6. Linear discriminant function results for the traffic type classification, with response variables square root transformed.

Variable	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Constant	-0.08911	-0.25240	-0.37543	-0.17808	-0.95246	-47.67538
Buncher	-0.03120	-0.49215	-0.72486	-0.83658	-1.59055	-0.65018
Skidder	-0.4622	-0.10980	-0.10825	0.33901	0.59477	4.28017
Dozer	0.29215	0.59383	0.72472	0.12164	0.54054	0.08050

Table 3.7. Number of observations classified into each disturbance level, with response variables square root transformed, and percentages in parentheses. Highlighted numbers represent correctly classified observations.

Disturbance Level	1	2	3	4	Total
1	57 (54.29)	25 (23.81)	20 (19.05)	3 (2.86)	105 (100.00)
2	9 (37.50)	16 (54.17)	2 (8.33)	0 (0.00)	24 (100.00)
3	11 (34.38)	7 (21.88)	12 (37.50)	2 (6.25)	32 (100.00)
4	7 (17.95)	7 (17.95)	8 (20.51)	17 (43.59)	39 (100.00)
Total	84 (42.00)	52 (26.00)	42 (21.00)	22 (11.00)	200 (100.00)

Table 3.8. **Number of observations classified into each traffic type, with response variables square root transformed, and percentages in parentheses. Highlighted numbers represent correctly classified observations.**

Traffic Type	1	2	3	4	5	6	Total
1	57 (54.29)	1 (0.95)	21 (20.00)	19 (18.10)	7 (6.67)	0 (0.00)	105 (100.00)
2	5 (45.45)	0 (0.00)	5 (45.45)	0 (0.00)	1 (9.09)	0 (0.00)	11 (100.00)
3	5 (33.33)	0 (0.00)	8 (53.33)	2 (13.33)	0 (0.00)	0 (0.00)	15 (100.00)
4	10 (32.26)	0 (0.00)	5 (16.13)	11 (35.48)	5 (16.13)	0 (0.00)	31 (100.00)
5	7 (20.00)	0 (0.00)	7 (20.00)	7 (20.00)	14 (40.00)	0 (0.00)	35 (100.00)
6	0 (0.00)	0 (0.00)	0 (0.00)	1 (33.33)	0 (0.00)	2 (66.67)	3 (100.00)
Total	84 (42.00)	1 (0.50)	46 (23.00)	40 (20.00)	27 (13.50)	2 (1.00)	200 (100.00)