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An Evaluation of a Low-Cost UAV Approach to Noxious Weed Mapping

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AN EVALUATION OF A LOW-COST UAV APPROACH TO NOXIOUS WEED MAPPING

by

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of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of Brandon T. Jones in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

AN EVALUATION OF A LOW-COST UAV APPROACH TO NOXIOUS WEED MAPPING

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Master of Science

Mapping their location and extent is a critical step in noxious weed management. One of the most common methods of mapping noxious weeds is to walk the perimeter of each patch with a handheld GPS receiver. This is the method used at Camp Williams, a National Guard Bureau training facility in Utah where this study was conducted. It was proposed that a low-cost Unmanned Aerial Vehicle (UAV) that made use of a hobbyist remote control airplane equipped with a Global Positioning System (GPS) receiver and digital camera could be used along with automated post-processing techniques to reduce the cost of weed mapping compared to the on foot method. Two noxious weeds were studied: musk thistle (*Carduus nutans*) and dalmation toadflax (*Linaria dalmatica*). The musk thistle was visually identifiable in the imagery but the dalmation toadflax was confused with yellow sweet clover (*Melilotus officinalis*). It was found that after the automated post-processing the photos were not positioned well enough to produce a

consistent and accurate weed perimeter. A supervised classification was attempted with imagery of the musk thistle, however, the accuracy of the classification was too low to be able to identify the weed perimeter from the classification. To achieve accurate results the photos had to be registered to a base image and the perimeter of each patch hand digitized. The time it took to do so increased the costs well above the on foot method. A number of improvements to the UAV could make the image registration step unnecessary. There are other applications for which this low cost UAV could be used.

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I would like to thank those on my committee for the time they've taken to help me with my thesis, especially Dr. Mark Jackson. My parents have been a great source of support: their encouragement prevented me from giving up. I would also like to acknowledge those who have been a great help to me at Camp Williams, providing me with information, allowing me to operate my aircraft there, and cooperating in collecting data. Above all, however, I would like to show my appreciation to my wife. Whatever has been accomplished here it is as much her accomplishment as it is mine thanks to her support and her willingness for us to sacrifice financially for the time being, and for her to do this sacrifice with two kids at home. I may receive a degree in connection with this thesis and recognition from my peers and academic community but she will get little for herself for what she does at home, and yet, to me anyway, what she does there is far more important than what I have done here.

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Chapter One: Introduction

With increasing technological advancement, the impacts that humans have on the natural environment have also increased. Of particular concern for this study is the effect our activities have had on propagating the spread of invasive weeds which are costing millions of dollars and reducing biodiversity (DiTomaso, 2000; Wilcove *et al.*, 1998; Simberloff, 1996; Pimentel et al., 2000; Tempel et al., 2004). In addition to the costs of reduced productivity in agriculture and rangeland due to weed infestations, controlling weeds has proven to be quite costly as well. A significant part of controlling weeds is recording where the weeds are and quantifying their extent. Using a low-cost approach by using an off the shelf model airplane and other off the shelf components, it was thought that mapping weed infestation areas from georeferenced images taken from the aircraft could reduce these costs of recording and quantifying areas covered by weeds. The research performed to investigate this hypothesis failed to reject the null hypothesis. That is, it failed to reject reasonable doubt that a low-cost UAV could reduce the recording and quantifying costs.

The research was performed at Camp Williams which is a Utah Army National Guard (UTARNG) training facility that straddles the Salt Lake County and Utah County border (Figure 1.1). Camp Williams comprises approximately 25,000 acres of federal public land. There are a number of noxious weeds found at Camp Williams. A noxious weed is any invasive plant that is considered by some government entity to be harmful to industry or the environment. Noxious weeds have to be managed at Camp Williams in accordance with Executive Order 13112 Section 2 that reads “each Federal agency whose

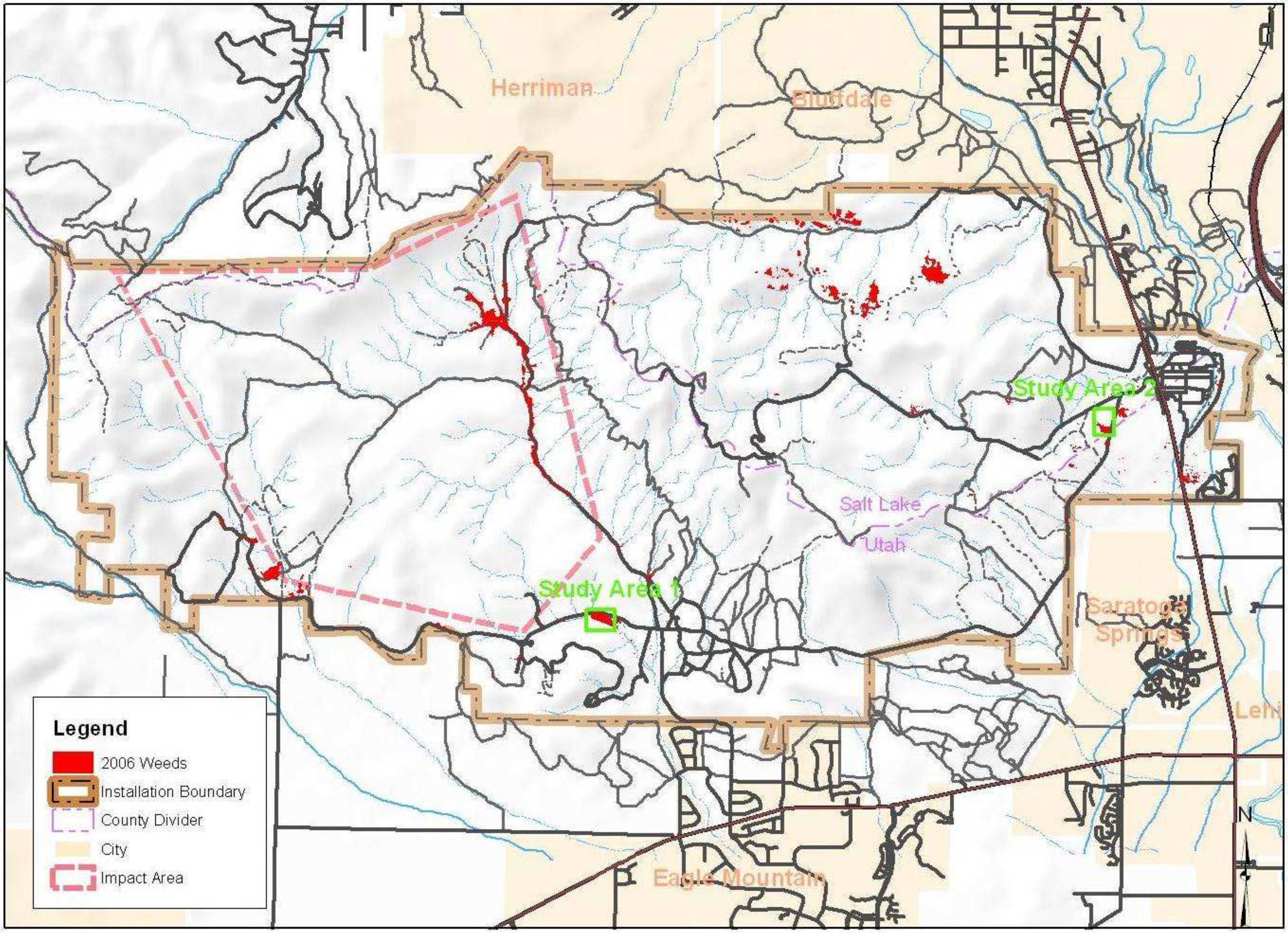


Figure 1.1: Camp Williams, a Utah Army National Guard training facility where this study took place.

actions may affect the status of invasive species shall . . . detect and respond rapidly to and control populations of such species in a cost-effective and environmentally sound manner; monitor invasive species populations accurately and reliably; . . .[and] conduct research on invasive species and develop technologies to . . . provide . . . sound control of invasive species" (National Invasive Species Information Center, 2006). The State of Utah also has a law called the Noxious Weed Act which requires all property owners to eradicate any weeds listed in the act if found on ones property (State of Utah Department of Agriculture and Food, 2007).

Every summer the Environmental Resource Management (ERM) office of the UTARNG hires several college students to control the noxious weeds at Camp Williams. The interns begin their duties by scouting the installation for noxious weeds. They do this by driving around in a vehicle on Camp Williams' roads and visually scanning the terrain as they go. Once a weed patch is discovered they get out of the vehicle and proceed to map the perimeter of the patch. This is done using a handheld GPS receiver which is set to record a polygon as they walk around the weed patch. This is a common approach as discussed by Stafford *et al.* (1996) and will be hereafter referred to as the *on foot method*. The interns are given little guidance as to what constitutes a weed patch in terms of density. They are instructed to look for any of the noxious weeds listed by the State of Utah or the federal government. The purpose of recording the noxious weed patches at Camp Williams is threefold: 1) to document (for analysis of trends and to quantify the extent of noxious weed invasions in a given year), 2) to determine the amount of area that needs to be treated (for bidding purposes if the extermination of the weeds is to be done by a third party), and 3) so those treating the areas (if they are a third party) can find those areas.

In 2006 the top five noxious weeds in terms of area covered at Camp Williams were: (1) Musk Thistle (*Carduus nutans*) at 147 acres, (2) Dalmation Toadflax (*Linaria dalmatica*) at 39 acres, (3) Whitetop or Hoary Cress (*Lepidium draba* L.) at 11 acres, (4) Scotch Thistle (*Onopordum acanthium*) at 4 acres, and (5) Medusahead (*Taeniatherum caput-medusae*) at 1 acre. Everything else was less than an acre. Approximately $30,000 was spent on managing noxious weeds at Camp Williams in 2006 which includes the wages for the crew and minor equipment costs (Johnson 2007).

A. The Study Areas

There were two study areas used in this study as indicated in Figure 1.1; also Figure 1.2 shows aerial imagery taken in 2003 of the study areas. The study areas were chosen because they have relatively flat terrain and a good smooth gravel road next to them for the aircraft to use as a runway. These study areas were chosen to test the limits of the UAV acquired imagery. Study area one was chosen as an area where the weeds of interest would be easily distinguished from the natural vegetation. It was known before hand at study area two that there was a plant that looked similar to the target weed. The goal for study area two was then to see if the imagery from the UAV would be good enough to differentiate between the two plants. Limited resources and the inaccessibility to many areas at Camp Williams by the UAV method restricted the number of study areas and noxious weeds to be studied.

Three flights were performed at study area one to ensure good data and two flights at study area two were sufficient. All the flights were performed the second half

(a) Study Area One

(b) Study Area Two

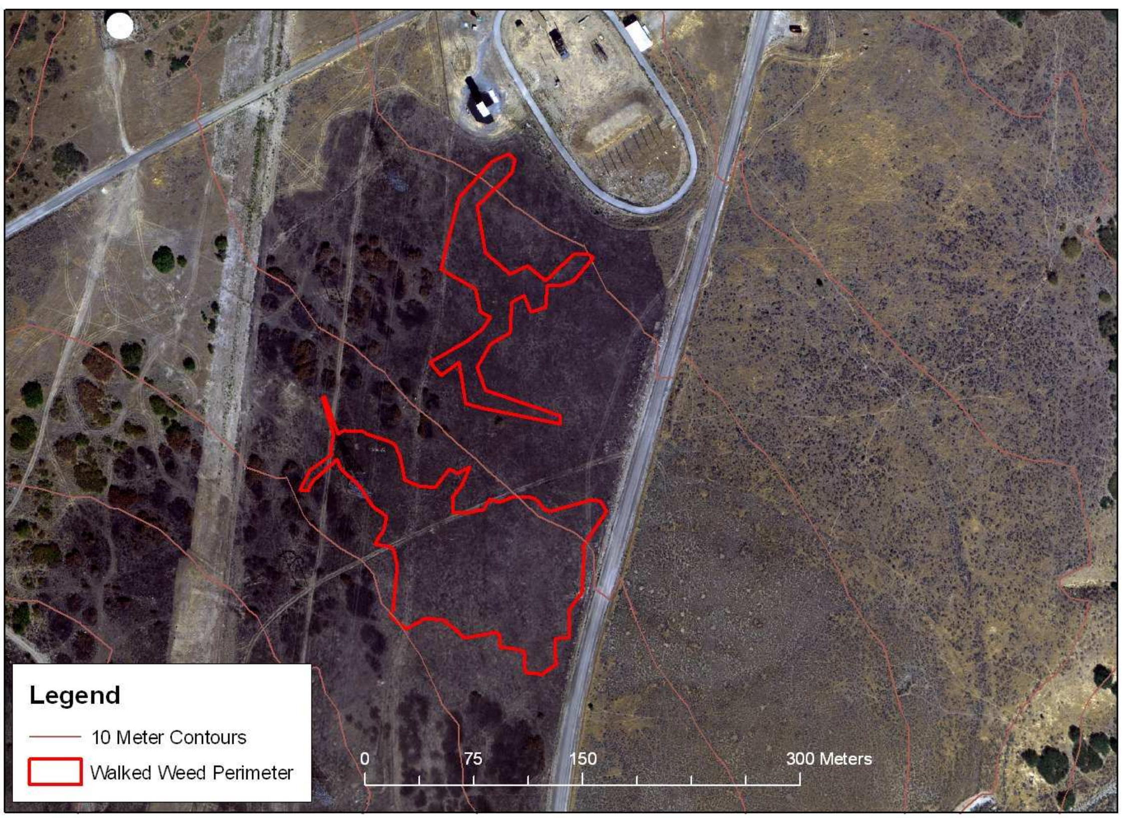


Figure 1.2: This is imagery from a 2003 aerial photograph with one foot resolution and 3 meter accuracy. The weed perimeters are those obtained by walking around the weed patches with a handheld GPS receiver.

of June 2006. Prior to that time approximately 10 months of after hours time had been put into preparation for the data collection with most of that time spent building the UAV.

B. Potential

There is a niche a low cost UAV could fill in the field of remote sensing if enough effort were put into researching and developing the methodology (which includes acquisition of data and post-processing of data), as well as testing various off-the-shelf components in the data collection process. That niche would include mapping weeds on small to medium sized farms as well as in larger land management situations within a kilometer of roads where most weeds are found (Gelbard and Belnap 2003; Parendes and Jones 2000; Trombulak and Frissell 2000; Tyser and Worley 1992; Watkins et al. 2003). It is similar to the printing of a few copies on your personal computer printer or printing thousands of copies on a press. Your personal computer printer has a price advantage when printing a few copies like a cheap UAV would have a price advantage compared to manned airplanes, satellites, or higher cost UAVs if used over a relatively small area.

There are many possibilities that could take advantage of this idea. With just a little more improvement in the equipment used for this project some important improvements in efficiency could be reaped in regards to mapping weeds and other targets. There are other possible applications for a low-cost UAV based georeferenced imaging system as well. In the area of land management, land impact monitoring over limited areas could be possible. This would require doing multiple flights on different dates of the same area and then comparing them for change detection. The low-cost UAV could also be used to do biological population surveys of plants and animals like that done by Jones *et al.* (2006). Costs are declining for off-the-shelf autopilots for recreational R/C aircraft (Espinar and Wiese 2006; Jones *et al.* 2006) and other important devices which will help improve the efficiency and effectiveness of using a low-cost UAV.

Chapter 2: Literature Review

The task of controlling invasive weeds can be separated into three land use types: agricultural, rangeland, and non-livestock government land. The required amount of control, and therefore ability, to detect and map the weeds is different in each category. In the agricultural setting it has been suggested that weeds should be detectable at a density of 1 or more plants per meter squared (Medlin *et al*., 2000). In rangeland and other government lands, which is the focus of this research, such a strict requirement is not necessary. The background literature used to support this study, therefore, did not focus on agricultural land management.

A. Impact

Fifteen percent of introduced species, not just weeds, “devastate farms and forests, impede waterways, foul lakes and ponds, affect human health, and invade natural areas and replace native species” (Simberloff, 1996). These invasive species are costing billions of dollars in damages and mitigation efforts. The effects of noxious plants in rangelands cost more than any other pest (DiTomaso, 2000). In 1996, 16 million acres of rangeland were heavily affected by non-native plants, a figure that was growing at a rate of 2,300 acres per day (Simberloff, 1996). Pimentel *et al.* (2000) point out that some of these weeds, leafy spurge (*Euphorbia esula*) for example, are toxic to cattle and wild animals. Some weed infestations can reduce the capacity of grazing by 50% while “direct losses due to poisoning of cattle and sheep in 1988 were estimated at $169 million with an additional $65 million in indirect losses associated with reduced reproduction and growth rates and lower quality milk or wool” (DiTomaso, 2000).

Wilcove *et al.* (1998) point out the devastating effect alien plant species are having on biodiversity. They also mention that alien plant species are a significant contributing factor to the demise of 57% of the plants considered imperiled by the Nature Conservancy or are included in the Endangered Species Act as endangered, threatened, or proposed species. As a general rule, human caused disturbances such as roads or trails, cultivation, grazing, trampling, and domestic ungulates are often considered to have more effect on the occurrence of noxious weeds than natural disturbances (Rew *et al.*, 2005).

There are a number of methods of locating and mapping these weeds. There is GPS-assisted field walking (Stafford *et al.*, 1996), intensive grid sampling (Goudy *et al.*, 1999), vehicular-based manual scouting (Rew *et al.*, 1996), predictive models (Rew *et al*., 2005; Rinella and Sheley, 2005), near ground imaging (Guyer *et al.*, 1986; Sadjadi, 1996; Yang *et al.*, 1999), and remote sensing from UAV or manned aircraft (Lamb and Brown, 2001; Shaw, 2005; Brown, 1994;Anderson *et al.,*1999; Everitt *et al.*, 1995; Medlin *et al.*, 2000; Rew *et al.*, 2005; Hunt *et al.*, 2004; Brown *et al.*, 1994; Lamb and Weedon , 1998; Herwitz *et al.*, 2003; Hardin and Jackson, 2005)**.**

B. Remote Sensing of Weeds

There are a number of limiting factors that have kept traditional remote sensing from becoming a truly effective tool in the control of weeds. As a basic rule, the higher the spatial resolution the greater the ability for remote sensing to distinguish the least dense weeds from the soil/plant background (Lamb and Brown, 2001). This is a limitation because as image resolution increases so does cost. Other limitations are the spectral resolution (how many and how narrow are the bands being detected of the electromagnetic spectrum), temporal frequency, processing time (Shaw, 2005), and high costs. Satellites are not useful in detecting small or foundling weed populations, although they have the advantage of covering a large geographic area over a short period of time. The major impediments to using satellite acquired data are low spatial resolution, and slow turnaround from acquisition to delivery (Shaw, 2005). Turnaround time is more critical in agriculture where Anderson *et al.* (1999) suggest that crop producers require imagery between 24 and 72 hours after acquisition. Shaw (2005) points out that it takes between 20 to 24 hours to produce finalized imagery from an aircraft. He continues by saying, "although detection of invasive species in [non-agricultural lands] is also time critical, the timing of detection is usually not considered as demanding as agronomic applications, on the order of weeks rather than hours or days."

In the agricultural setting in which there is zero tolerance for weeds, remote sensing may never be solely sufficient (Lamb and Brown, 2001). The margin of error is much greater in rangelands and other public lands; therefore, remote sensing may be sufficient in locating and monitoring weeds in those settings. The greatest drawback is the cost of remote sensing. Rapid development in digital aerial cameras and improved aerial positioning coupled with new methodologies will drive prices down while simultaneously increasing effectiveness.

C. UAVs

The acronym UAV became prominent in the public eye with the emergence and use of the Global Hawk and Predator aircraft recently used in Afghanistan (Coffey and

Montgomery, 2002). UAVs have been primarily used for military purposes despite the obvious potential they have for scientific research and civilian applications. There are a number of reasons why non-military use of UAVs has not yet become common. Besides the Global Hawk and Predator, UAVs are largely still in a research and development stage. Most UAVs being developed are required by the FAA to be flown in restricted airspace and to have a permit which has generally only been given out for a specific time and location. Only the Global Hawk has had "routine permission to fly, and only out of Edwards AFB"(Schoenung, 2003). Nyquist (1997) adds that one of the usual requirements for the FAA to grant a permit is that the "UAV has a 'see and avoid' capability . . ., or is followed by a manned chase plane, or that the operator maintains direct visual contact . . . at all times." Schoenung provides hope by saying that "efforts are underway by an industry team, working with government agencies, to develop routine access [for UAVs] to the National Air Space." Finally, many of the UAVs being developed generally are designed for long flights (from 6 to 96 hrs) at high altitudes (from 10,000 ft. to 70,000 ft.) with large payloads (from 5 to 1900 lbs) and are completely autonomous or nearly so. That kind of capability comes with a high price tag which puts UAVs out of reach for day to day operation by those with suitable applications.

An example of one of these higher cost UAVs is the Pathfinder UAV funded by a $3.76 million grant (Ames Research Center 2007) from NASA. Herwitz *et al.* (2003) demonstrated some of the capabilities of this UAV by flying it over a coffee plantation in Hawaii. It is a solar powered semi-autonomous unmanned craft designed for remote sensing. With their Kodak RGB camera they were able to detect outbreaks of invasive weeds and irregularities in fertilization on the plantation. With the multi-spectral camera they were able in some instances to tell ripeness levels. The biggest drawback to this platform is the costs associated with building and operating it.

Examples of lower cost UAVs do exist. Espinar and Wiese (2006) used a low-cost UAV made from off the shelf components including a hobby store scaled aircraft. Their UAV was not made for remote sensing but for air sampling. Another major difference with their UAV was its autonomous capabilities. This allowed for precise control of the location and flight pattern of their aircraft at all times while in flight. Even though they had autonomous flight capability, they were able to keep the cost under $6,000.

There have been some efforts at using low-cost UAVs for remote sensing. They tend to have a number of things in common: they have short flight durations (an hour at the most), can't fly very high (less than 3000 ft. AGL), can't carry much weight (around five pounds.), are not restricted by the FAA because of their low flight altitude, and cost less than $10,000.

Quilter and Anderson (2000) used a remote control airplane, alternately using a 35mm camera and digital camera (number of pixels not specified) inside the aircraft to obtain imagery for analysis and documentation. They were able to document and analyze the effect of structures called barbs that were placed in a river to cut down on bank erosion. They also analyzed plant stress using infrared film. They note their feelings of how helpful the bird's eye view is in communicating, documenting, and analyzing objects and patterns on the ground and that for small locations a UAV is much more practical than having a manned aircraft collect imagery. Althoff (2006) did a similar study using a lighter than air blimp with a digital camera hanging beneath to document and analyze vehicular impact on vegetation at Fort Riley. That package cost approximately $7,000. Nyquist (1997) describes a project developed by Oak Ridge National Laboratory (ORNL) that made use of a modified hobbyist aircraft with a 35 mm camera and a video camera inside which cost less than $5,000.

Hardin and Jackson (2005) used off the shelf remote control airplanes to locate noxious weeds. Their plane had a common GPS and camera in order to geo-locate the weeds found in the imagery. Their airplane was able to achieve altitudes of 1 kilometer and fly as far away horizontally as 1 kilometer while under pilot control. The images could be georeferenced to 3 meter accuracy but were not orthorectified. Their ability to detect weeds in the imagery is comparable to other remote sensing platforms. They were able to do this at a modest equipment cost of $1,500.

Jones *et al.* (2006) used a small autonomous aircraft which they had custom built. Their UAV cost approximately $35,000. They equipped their aircraft with a progressive scan video camera which captured live video that was sent to the ground by radio. The purpose of their UAV was to do surveys of wildlife populations. The imagery was not georeferenced in any way.

There are dozens of other low-cost UAV experiments taking place in the world that have not as yet made it into the literature. Currently the single largest obstacle to greater UAV implementation is the confusion over who can fly them as well as when and where they can be flown legally. When regular access to regulated airspace is granted to UAVs it is likely a great surge in research about UAVs, as well as research that takes advantage of them will happen.

Chapter Three: Research Methodology

This research was performed at two study areas at Camp Williams (Figures 1.1 and 1.2). The first study area was chosen to maximize the difference between the target weed species and the native vegetation. The purple flower and large size of the musk thistle (*Carduus nutans*) (Figure 3.1a) in this area makes it the easiest weed at Camp Williams to see in the imagery. Vegetation in study area one consisted primarily of sage brush, grasses, and musk thistle. Study area two was chosen to determine the discriminatory ability of the images in an area where two plants with similar characteristics coexist. The target weed species was dalmation toadflax (*Linaria dalmatica*) (Figure 3.1b). The other plant in the area was yellow sweet clover (*Melilotus officinalis*) (Figure 3.1c). Other vegetation in study area two included a variety of flowering plants, grasses, and oak brush.

A. Data Collection

A Kadet LT-40 (Sig Manufacturing Company, Montezuma, IA) R/C airplane equipped with an Airtronics radio receiver and servos and controlled by an Airtronics Radiant 6 channel computer transmitter (Airtronics Inc. , Anaheim, CA), all purchased at a local hobby store, were used for this study. The aircraft was also equipped with a Nikon Coolpix 5000 5 megapixel digital camera (Nikon Inc., Melville, NY), a Garmin Gecko 201 GPS receiver (Garmin Ltd., George Town, Grand Caymon, Caymon Islands), and a DigiSnap 2200 intervalometer (Harbortronics LLC., Gig Harbor, WA) which were used together to acquire imagery of the study areas. The intent was to georeference the

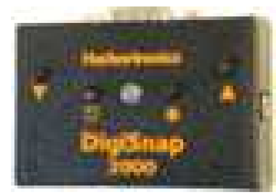
(a) Musk Thistle (*Carduus nutans*)

(b) Dalmation Toadflax (*Linaria dalmatica*)

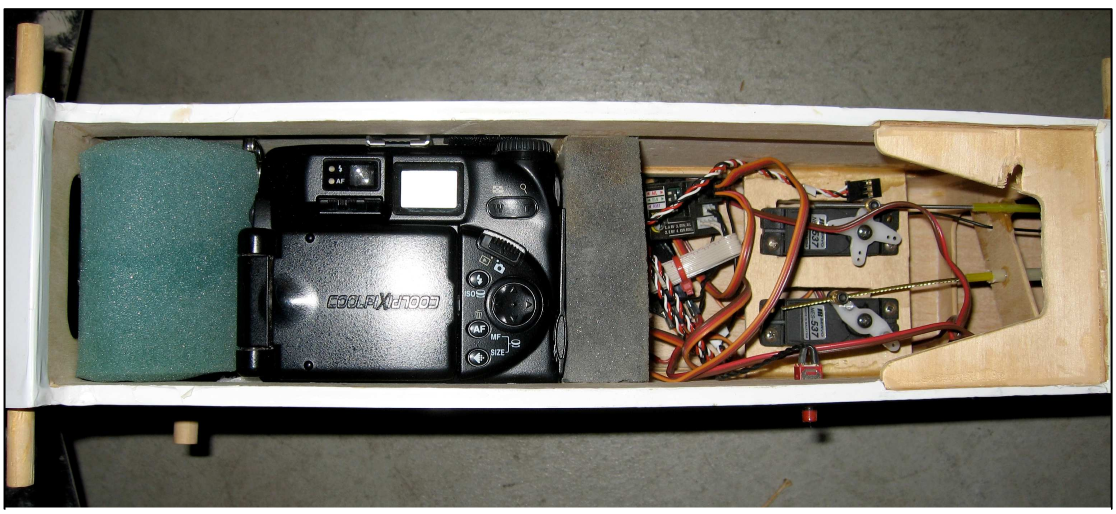
(c) Yellow Sweet Clover (*Melilotus officinalis*)

Figure 3.1: Important plants studied at Camp Williams for this research.

Garmin
Gecko 201



Harbortronics
DigiSnap 2200



The camera inside the aircraft.. The Digisnap was located under the nose hatch and the Gecko was secured on top of the nose hatch by Velcro and a rubber band.

Sig Kadet Lt-40

Nikon Coolpix 5000

Figure 3.2: Equipment used for data collection.

acquired imagery and map the weed infestation area (see Figure 3.2). The intervalometer was connected to the camera and set to trigger the camera every three seconds. The main reason for the three seconds between pictures was the fact that the camera could not write to the memory card faster than three seconds.

A desktop computer R/C flight simulator called Real Flight 2.0 (Hobbico Inc., Champaign, IL) was used to train the pilot. The pilot logged approximately 30 hours on the simulator before he attempted to fly a real R/C airplane. The 30 hours proved to be sufficient as he was able to fly the real R/C aircraft at that point.

The process of performing a flight was made up of a number of preparatory steps:

- A picture was taken of the clock on the GPS receiver. This was for post-processing at which time the amount of offset between the camera time and the GPS receiver time was accounted for. This was important because time was the variable used to link the pictures to the GPS data log.
- The camera was placed within the fuselage.
- The intervalometer was plugged into the camera
- The camera was turned on.
- The wing was placed on the aircraft using rubber bands.
- The engine was started.
- The intervalometer was started.
- The GPS track log was then started on the GPS receiver.

Once the intervalometer was started pictures were being taken from that point on until after the landing of the aircraft, at which time the intervalometer was stopped. This approach wasted space on the memory card by filling it with some useless photos;

however, the memory card storing the photos had a capacity of one gigabyte which was comfortably more than enough for the length of time the aircraft could stay aloft. The amount the memory card could hold also depended on the compression setting on the camera; for example, the photo quality setting for flights one, three, and four was *normal*, for flight two it was *high* and for flight five it was *fine*, however, none of the settings used up all the space on the card on any of the flights. To save space on the card one of the unused radio channels could have been used along with a servo and rod to allow the pilot to start the intervalometer when the aircraft was in the air ready to take photos. By starting and stopping the intervalometer on the ground it ensured the camera was working the entire flight.

When all the above steps were completed, the aircraft was ready to take off. It required about 20 to 50 meters of road to accelerate to takeoff speed. Once in the air the aircraft was immediately flown over the weed patch area. The aircraft was allowed to climb to somewhere between 50 and 100 meters (determined by user judgment). There was no way to tell exactly how high the aircraft was during the flight, but it was known that if the aircraft flew too low the photos would not likely cover the entire area of interest due to the small amount of area each photo would cover. It was also desirable to have as high a resolution as possible so it was undesirable to fly the aircraft too high. The average height above ground for flight three as determine in post-processing was about 57 meters. At this height the entire weed patch was able to be imaged in the time that the aircraft was flown, which was about 7 minutes. The plane had to be kept as level as possible in order to have usable imagery that could be georeferenced accurately. There are low-cost devices that can be put into R/C airplanes that automatically keep the plane level, however, they depend on the horizon to do so and the horizon at Camp Williams is obstructed substantially by the local terrain. The aircraft was flown over the same areas multiple times to ensure complete coverage of the study area. The aircraft was brought down for a landing after which everything was turned off and put away.

The on foot method, which is the method currently used at Camp Williams, is much more straight forward. The process involves walking around the perimeter of the weed area while recording a polygon on a Trimble GeoXT GPS receiver (Trimble Navigation Limited, Sunnyvale, CA). The polygon is stored in the receiver until transferred to a computer. Once on the computer the data is differentially corrected and then transformed from the native Trimble GPS file format to a shapefile which is then merged with the weeds database for that year using ArcMap (ESRI, Redlands, CA).

B. Post-Processing

Post-processing was only performed with photos from flight three. At study area one, three flights were performed. Only data from one of those flights was used, however, because experimentation with camera settings and poor flying conditions (i.e. high winds) resulted in poor quality photos from the other two flights. Two flights were performed at study area two. Good data were obtained from both flights, however, little analysis was done with that data due to the early realization that differentiating between the toadflax and the sweet clover would not be possible.

After collecting the data with the UAV a number of post-processing steps had to take place. The steps took place as follows:

Step 1 Image Selection

This step was necessary to reduce the amount of time the remaining steps took. Images that looked fuzzy or distorted in some way were excluded, as were images that were obviously taken while the plane was not level to the ground (that is the center of the image was off nadir). The images had to be grossly off nadir in order for it to be apparent by just looking at the photos. Images that were outside of the study area were also filtered out. Microsoft Window's Picture and Fax Viewer® was all that was used to do this. Each photo was briefly looked at and if any of the problems mentioned above were found the photo was immediately removed from further processing.

Step 2 Georeferencing Images

A Visual Basic program written by Hardin (2005) was modified for use with the data collected for this project. Its purpose was to take the GPS log, match a GPS record from that log with the correct image, and create a world file (.jpgw) for that image containing coordinate and scaling information. It also calculated the direction of flight at the moment when the photo was taken in order to rotate the image in the proper orientation. The direction of flight along with other information was written to a .csv file, a format that can be read in ArcMap.

A free downloadable software package called GPSTrackMaker was used to get the GPS log off of the Garmin Gecko. The log was then saved as a GPSTrackMaker text file. A short program had to be written to transform the GPSTrackMaker file into a format necessary for use in the georeferencing software (Figure 3.3). Hardin's (2005) program requires a text file that contains the following: the name of the site that was studied, the file name (including extension) for the GPS log, the date, the path to an

(a) Format generated by GPSTrackMaker.

```
t,d,40.404861,-112.023876,06/19/2006,16:05:49,1481.048,1
t,d,40.404861,-112.023876,06/19/2006,16:05:50,1481.048,0
t,d,40.404840,-112.023833,06/19/2006,16:05:51,1481.048,0
t,d,40.404840,-112.023854,06/19/2006,16:05:52,1481.048,0
t,d,40.404840,-112.023854,06/19/2006,16:05:53,1481.048,0
t,d,40.404840,-112.023833,06/19/2006,16:05:54,1525.75,0
t,d,40.404882,-112.023575,06/19/2006,16:05:55,1550.263,0
t,d,40.404904,-112.023425,06/19/2006,16:05:56,1561.799,0
t,d,40.404904,-112.023339,06/19/2006,16:05:57,1568.048,0
t,d,40.404925,-112.023296,06/19/2006,16:05:58,1571.412,0
t,d,40.404925,-112.023253,06/19/2006,16:05:59,1572.854,0
t,d,40.404925,-112.023232,06/19/2006,16:06:00,1573.335,0
t,d,40.404925,-112.023211,06/19/2006,16:06:01,1573.815,0
t,d,40.404947,-112.023189,06/19/2006,16:06:02,1574.777,0
t,d,40.404947,-112.023168,06/19/2006,16:06:03,1575.738,0
t,d,40.404947,-112.023168,06/19/2006,16:06:04,1576.219,0
t,d,40.404947,-112.023146,06/19/2006,16:06:05,1577.18,0
t,d,40.404947,-112.023146,06/19/2006,16:06:06,1577.18,0
t,d,40.404947,-112.023125,06/19/2006,16:06:07,1577.661,0
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(b) Format required by Dr. Hardin's program.

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D
1
160549,4024.291660,N,11201.432560,W,1, 09,1.1,1481.048,M
160550,4024.291660,N,11201.432560,W,1,09,1.1,1481.048,M
0
2
160550,4024.291660,N,11201.432560,W,1,09,1.1,1481.048,M
160551,4024.29040,N,11201.429980,W,1,09,1.1,1481.048,M
0
3
160551,4024.29040,N,11201.429980,W,1,09,1.1,1481.048,M
160552,4024.29040,N,11201.431240,W,1,09,1.1,1481.048,M
0
4
160552,4024.29040,N,11201.431240,W,1,09,1.1,1481.048,M
160553,4024.29040,N,11201.431240,W,1,09,1.1,1481.048,M
0
5
160553,4024.29040,N,11201.431240,W,1,09,1.1,1481.048,M
160554,4024.29040,N,11201.429980,W,1,09,1.1,1525.75,M
0
```

Figure 3.3: GPS log file formats.

ASCII national elevation model for the area of interest, the path to the directory storing the flight photos and GPS log file, the time stamp offset between the photos and the GPS log (determined by using the picture of the GPS showing time), the name of the camera, the focal length of the camera, the shutter speed setting for the camera, the f-stop setting for the camera, the datum that the coordinates in the GPS log are based on, a parameter indicating whether or not to rotate the photos 180 degrees, and a parameter indicating whether or not to write a simple world file that orients the photos North South East or West or to write a much more complicated world file that contains rotation information for the photo (information that would align the photos with the direction of flight of the aircraft when each photo was taken). Once this file was loaded into the program no more user input was required.

When a digital camera takes a picture it also stores information *about* the picture in the photo file. That information includes the settings of the camera when the picture was taken and the time it was taken according to the clock within the camera. Hardin's (2005) program makes use of a free program created by Wandel (2007) called "Jhead.exe". Hardin's (2005) program utilizes "Jhead.exe" to extract the photo times from each flight photo which is then matched with the corresponding record (taking into account the time offset between the camera and GPS receiver) in the GPS log file.

The GPS log file (Figure 3.3) that is read into Hardin's (2005) program contains this information for each record: the photo time in HHMMSS, the coordinates in Latitude and Longitude, a binary value indicating whether or not there was a Wide Area Augmentation System (WAAS) signal being picked up by the receiver, the number of satellites that the receiver was picking up, and the altitude above Mean Sea Level (MSL) of the GPS receiver in meters.

The coordinates from the GPS log file need to be converted to UTM before a world file can be written for the photo. The world file must have the same name as the image it is referring to with the exception of having a different extension, in this case ".jpgw". A world file contains six lines. The first line is the width of the area a single pixel in the image covers on the ground and the fourth line is the height of the area of a pixel on the ground. Lines two and three are row and column rotation values (set to zero in a simple world file). Line five contains the UTM easting and line six contains the northing for the coordinates of the upper left corner of the corresponding image. Hardin's (2005) program had the option to calculate the rotation values, but the results were not always correct. For this project only simple world files were created. The last two lines of the world file contain the coordinates of the upper left corner of the image.

The coordinates contained in the GPS log file are the coordinates of the center point of the image (depending on how level the plane was at the time the picture was taken). In order to determine the coordinate for the upper left corner of the image from the coordinate of the center of the image a scale factor has to be determined which leads to the size one pixel from the image would be on the ground. To do this the height the aircraft was above ground at the time the photo was taken has to be known. This is where the national elevation model comes in. Hardin's (2005) program subtracts the height above MSL of the UAV as recorded in the GPS log for each photo from the height above MSL of the ground below for each photo to get the height Above Ground Level (AGL) for each photo. Once the AGL is known a formula can be used to determine the dimensions of the area a pixel represents on the ground. The formula is: ((UAV AGL in meters * 1000) / camera focal length in centimeters) * (length of a side of CCD element in mm / 1000). A CCD is the sensor that interacts with the light coming into the camera to generate the digital image. A CCD is made up of elements, each element representing a single pixel in the resulting image.

Once the size of the area a pixel covers on the ground is known, one can count the number of pixels from the center of the photo to the left hand side and multiply that by the width of a single pixel on the ground and then subtract that from the easting for the center of the image to get the easting for the world file. The process is then repeated to determine the northing value.

Hardin's (2005) program also creates a .csv file containing information about each image that can be read as a spreadsheet in Microsoft Excel® or as a table in ArcMap®. The attributes for each image that this file contains are: the date, the time, the latitude of the UAV, the longitude of the UAV, the UTM easting of the UAV, the UTM northing of the UAV, the UAV altitude (MSL) at time of photo snap in meters, the elevation of the ground (MSL) below the UAV at the time of each photo in meters, the UAV altitude (AGL) in meters, the scale factor, the spatial extent of the photo in ground units (meters), the resolution of a pixel in meters, the speed the aircraft was traveling in meters per second, and the direction the UAV was traveling.

To calculate the speed of the aircraft the program groups all the photos into pairs like this: photo one with photo two, photo two with photo three, and so on. Using the Pythagorean Theorem the distance between the first image of the pair and the second can be determined. That distance is then divided by the difference in seconds between the time of the first photo of the pair and the time from the second to get the meters per second.

The direction of flight, and therefore the amount of photo rotation, is found by first determining the absolute value of the change in the easting and northing between the first photo in the pair and the second. If there was no movement North or South (which would mean the change in northing was zero) then the aircraft must have been moving directly East or West. The program then checks to see if the change in easting was positive or negative (going East or West) and then returns the result. The program then does the same check to see if the aircraft was moving directly North or South. If the aircraft was not moving in any of the cardinal directions, an angle between 0 and 90 is calculated by dividing the change of easting by the change in northing and then taking its Arctangent, which is then multiplied by 57.2957795 to convert from radians to degrees. All that remains is the need to determine what quadrant in the cardinal direction system the angle calculated above belongs in. If the change in easting is positive and the change in northing is positive, the program simply returns the angle (quadrant I). If the change in easting is negative but the change in northing is positive, then the program returns 360 minus the angle (quadrant II). If the change in easting is negative and the change in northing is negative, then the program returns the angle plus 180 (quadrant III). Finally, if the change in easting is positive but the change in northing is negative, then the program returns 180 minus the angle (quadrant IV).

Step 3 Rotation of Images

A macro, which is a program written within an existing program to use the underlying components for custom purposes, was written in ArcMap® to read in the .csv file and perform the rotation of the images to orient them to the direction of flight of the aircraft using a built in ArcMap® rotation tool. The process of using the macro involves loading into ArcMap® all the georeferenced images and then pressing the button that activates the macro. The macro brings up a dialog box that allows the user to browse to the .csv file, which contains the rotation direction for each photo. Since the name of each georeferenced photo or layer is the time at which it was taken, the macro matches up the layer with the corresponding record in the .csv file using the photo time column in the .csv table. Once the correct record is found in the .csv file, the values in the direction and coordinate fields of the .csv file are used as inputs for the ArcToolbox® rotate tool. The ArcToolbox® rotate tool can be found in the Data Management Tools toolbox under the Projections and Transformations toolset and then under the Raster toolset.

The rotate tool requires as inputs the name of the layer being rotated, the name of the new layer which will be the result of using the tool, the UTM coordinate within the photo about which the photo will be rotated (in this case the center), the re-sampling method (nearest neighbor in this case), and the amount of rotation in degrees. Since all the photos when loaded into ArcMap® with the simple world file are oriented north and south and the top of each photo is the direction the plane was flying, the amount of rotation to be specified to the tool is the same as the direction of flight with north being 0°, east being 90°, south being 180°, and west being 270°. This process is repeated for every image that was loaded into ArcMap. It was found that the rotation was off by as much as 40° in one case. There are a number of possible explanations for this which will be discussed in chapter 5.

Step 4 Registration of Images

Following this automatic processing, the images were compared to a base image. The base image used was a USGS high resolution orthoimage taken in 2003 that had a one-foot resolution and three-meter accuracy. This image was obtained from the Utah Automated Geographic Reference Center (2007). To assess the accuracy of the UAV photos as compared to the base image, a point that could be identified in each UAV photo that could also be recognized in the base image was used. The measuring tool in ArcMap® was then utilized to acquire the distance between the identified object in the UAV image and that same identified object in the base image. This process resulted in an average offset between the base image and the UAV images of 30 meters. Out of 20 offsets the worst inaccuracy was excluded resulting in a 95% positional confidence of 53 meters. As with the rotation error, possible explanations will be discussed in chapter 5. Because of this amount of positional error it was decided to register the photos to this base image.

Interactive positioning to align each photo to the base image was necessary. The lack of easily identifiable individual features within the area of study in the base image made it difficult to find true control points for a proper rectification. Consequently, the photos were moved on screen to get the best overall fit with the base image. This was done in ArcMap®. The swipe tool was used to swipe the layer being adjusted to see how it compared to the base image and then dragged and/or rotated into place using the shift and rotate tools located on the georeferencing toolbar. Common patterns in the distribution and shape of vegetation as well as a gully that ran through the study area and the edge of a previously plowed piece of ground were all helpful in fitting the UAV images to the base image. Visually identifying where the photos belonged without having them already in rough approximation of their true position would have greatly extended the time needed to register the images.

C. Information Extraction

The areal extent of the weed infestation was digitized on screen from a virtual mosaic of the registered photos (all the photos were being displayed in ArcMap® at the same time). Once all the images were displayed together in ArcMap®, an interpreter circumscribed what looked like the weed perimeter in the imagery to create a polygon. This polygon was the final product, which was compared to the polygon generated by the on foot method. There were actually two different UAV polygons created: one having completed all of the post-processing steps, and one leaving off the last step which was the registration of the images (refer to Figures 3.4 and 3.5). The reason for analyzing the UAV method with and without the registration step was to see how much it would have cost had the registration step not been necessary. This was also done to see if and how much improvement in accuracy there would be from the unregistered polygon to the registered polygon.

An attempt was also made to identify the weed vs. non-weed areas in two separate images from flight three using a supervised classification algorithm in ERDAS Imagine® (Leica Geosystems LLC, Norcross, GA). Training sites were created by identifying individual weeds in the images. This was done by drawing polygons around different land cover types in the imagery, including the musk thistle. These polygons were used by the software to identify other pixels in the image with similar characteristics as those within each polygon. The maximum likelihood classification algorithm was used for classification within the software.

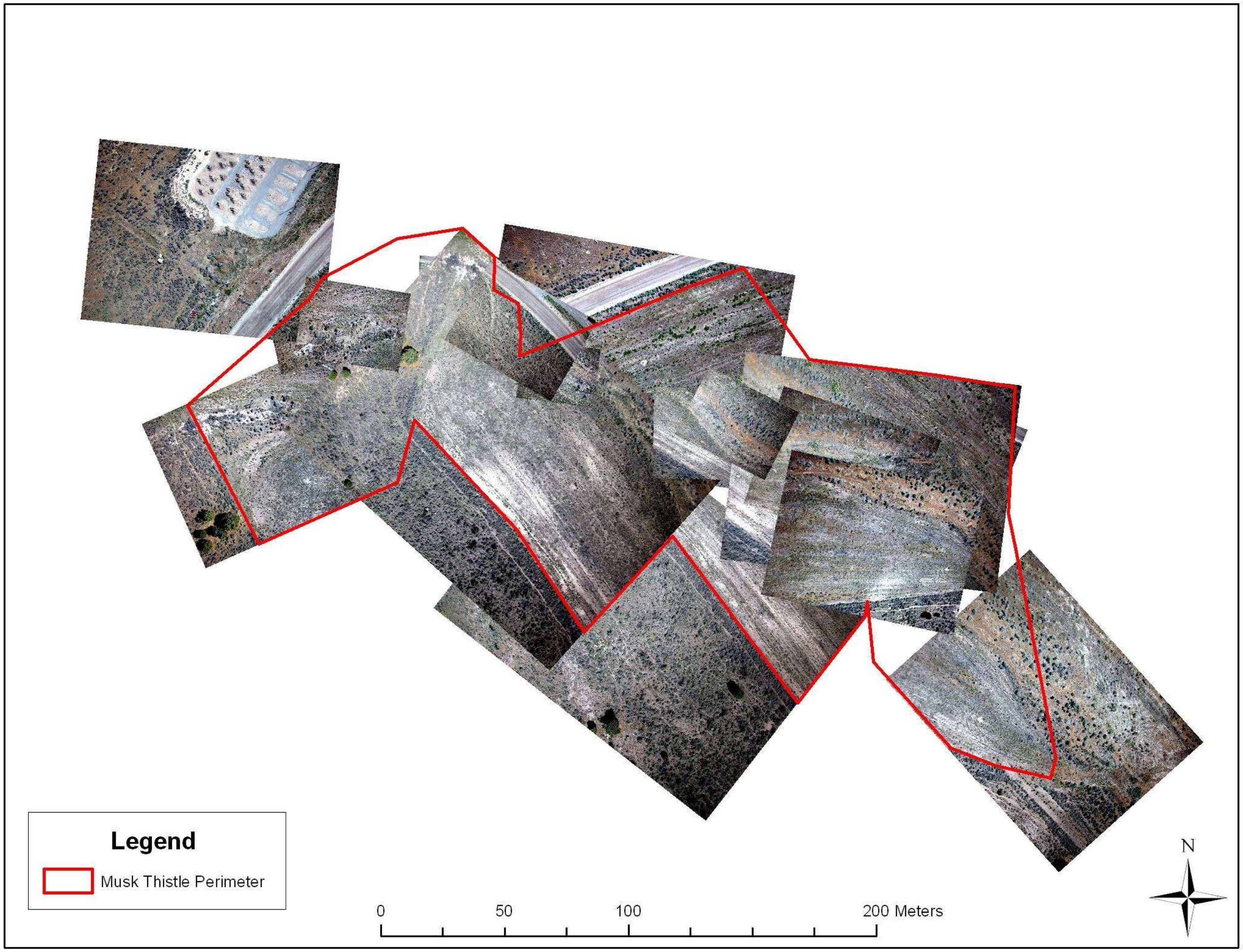

Figure 3.4: These are the georeferenced and rotated but not registered photos displayed together with the weed perimeter line extracted as best as possible from them given the fact that the photos do not match up at the edges. The resolution of all photos: Average 39mm, Maximum 7mm, and Minimum 79mm.

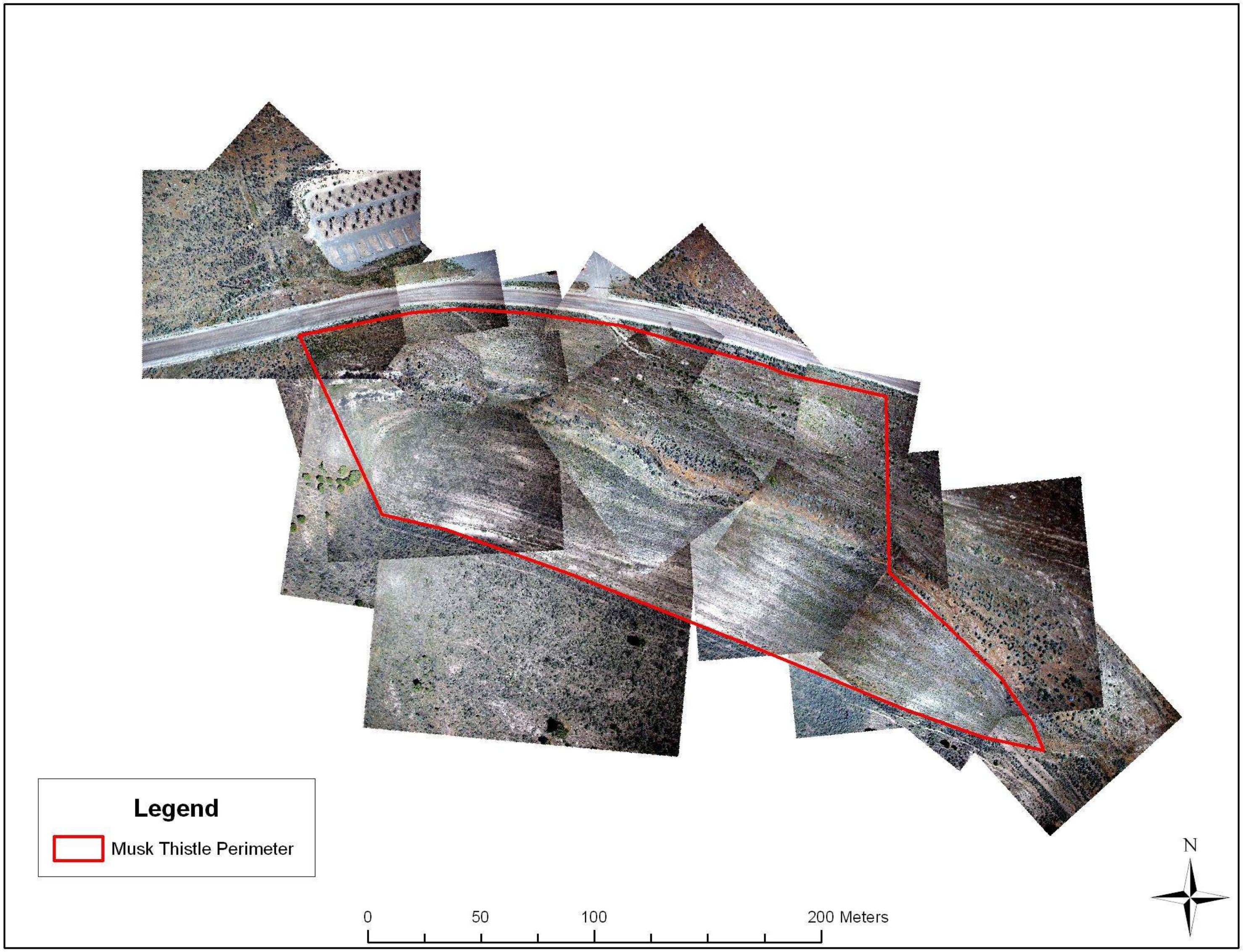

Figure 3.5: These are the registered photos being displayed together with the weed perimeter line that had been extracted from them. The resolution of all photos: Average 39mm, Minimum 7mm, and Maximum 79mm.

Evaluation of the classification accuracy for the musk thistle involved several steps:

1. The raster file of the classification created in Imagine® had to be converted to a vector layer.

2. The polygons from this vector layer representing the musk thistle had to be singled out.

3. The layer representing only musk thistle was then compared to a feature layer created by an interpreter representing the actual area covered by individual musk thistle plants. The comparison generated three separate feature layers representing either errors of omission, errors of commission, or correct classification.

4. Percentages of error were calculated.

To accomplish step one the raster was converted to vector in ArcMap®. Since the classification raster was a thematic raster using as values the names of each land cover type, the feature layer created from the raster layer contained in its attribute table a field for those names. Step two was performed by selecting only the musk thistle features in the feature layer. Once the selection was done a new layer was created from the selected features. For step three this layer was compared to another layer representing the location of musk thistle that was created by an interpreter who drew polygons around the weeds he could see in the imagery. This was the reference layer that the classified data were compared to for accuracy. The error of omission was the area represented by either the whole polygons or parts of those polygons drawn by the interpreter that were not coincident with any parts of the musk thistle classification polygons. In other words, those areas that the classification failed to classify as musk thistle that *were* musk thistle. To generate the error of omission feature class, the areas of the interpreted layer were erased where the classified layer existed.

The error of commission was the area classified as musk thistle that was not actually musk thistle according to the interpreted layer. An erase function was also used to generate the error of commission feature class, but this time the classification layer was the layer having areas erased from it and the interpreted layer was the layer containing the areas to be erased. A layer was created representing those areas that were correctly classified using a intersect function. The result, therefore, is a correct layer containing only those areas that overlap between the musk thistle classification and the interpretation.

Finally, step four took the three new layers (error of omission, error of commission, and correctly classified) and created percentages summarizing the accuracy of the classification. For error of omission the total area in square meters of all the polygons in the error of omission layer was divided by the total area in square meters of all the polygons in the interpreted layer and then multiplied by 100. For error of commission the total area in square meters of all the polygons in the error of commission layer was divided by the total area in square meters of all the polygons in the musk thistle classification layer and then multiplied by 100. To calculate the amount of correctly classified areas the total area in square meters for all the polygons in the correct layer was divided by the total area in square meters of all the polygons in the classification layer and then multiplied by 100.

D. Comparison of UAV Method and On Foot Method

In terms of positional accuracy the UAV method was compared to the on foot method (in this study it is the ‘truth’) by comparing the polygons (one polygon for the registered photos and one for the unregistered) generated by the UAV method to the polygon generated by the on foot method and quantifying the differences. The amount of area of the UAV polygon that went outside the area of the on foot polygon was called the error of commission while the amount of area of the on foot polygon that the UAV polygon failed to cover was called the error of omission; the area of overlap between the two polygons was called the correct area. Three separate layers were created to represent these three areas. These layers were created the exact same way that the three classification evaluation layers were created as described in the last section. For the layer representing the error of commission the on foot layer was erased from the UAV layer. For the layer representing the error of omission the UAV layer was erased from the on foot layer. For the layer showing the correct areas the UAV layer and the on foot layer were intersected.

Other points of comparison are in regards to the accuracy of the weed patch polygon required by the Natural Resource Manager at Camp Williams, Doug Johnson. His requirement is that the accuracy of where the weeds are is good enough for someone to find the weed patch. When asked if a WAAS enabled GPS without any other type of positional correction (on average about 3 meter accuracy) would be good enough his response was yes (Johnson 2007). To measure the UAV polygon’s positional accuracy a method was devised to measure the distance between the boundaries of the UAV and on foot polygons at ten meter intervals along the on foot polygon perimeter. This process was done in ArcMap® while displaying both polygons at the same time. The average distance and the maximum distance from the set of distance values were used as comparison parameters. Figure 3.6 illustrates the process. For bidding and contracting issues Mr. Johnson required that the calculated area be accurate to approximately 1/10 an acre (Johnson 2007). Therefore, the acres from the UAV polygon were subtracted from the on foot polygon to ascertain how closely the area of the UAV polygons each came to the area of the on foot polygon.

The operating cost for the UAV method was then compared to the operating cost for the on foot method. This was done by taking the time it took to perform each method from data collection all the way up to the production of the polygon representing the weed patch. The operating time for the on foot method was converted to a dollar amount by multiplying the time by the current pay rate for a environmental resource management summer weed technician at Camp Williams (Johnson 2007). The weed technician was paid $12 an hour in 2006. A GIS technician performed the UAV method and that position was paid $15.56 an hour in 2006 which was multiplied by the amount of time it took to perform the UAV method. The upfront costs were also compared for the two methods. This was the cost of equipment and training. Cost of fuel was also estimated by sampling prices from various vendors to come up with an approximate cost per eight ounces (the capacity of the fuel tank used in this study) which was eighteen cents.

A total cost comparison was then performed for the year 2006 between the two methods. This was done by extrapolating the operating costs from flight three to produce

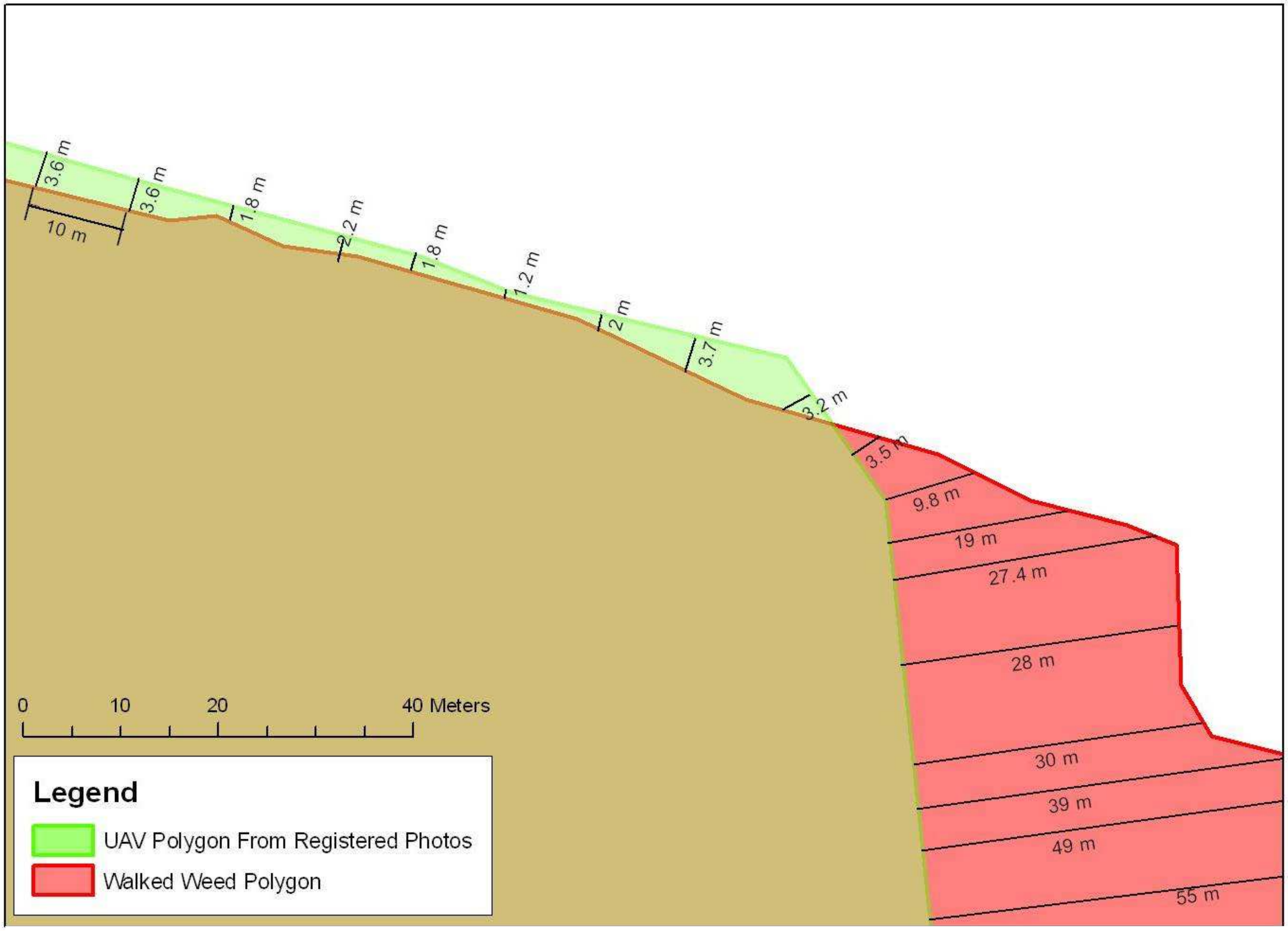

Figure 3.6: This illustrates the method used to quantify the amount of difference between the boundaries the on foot and UAV polygons. This was one of several methods used to compare the two weed mapping methods. Measurement lines are perpendicular to the UAV perimeter.

what would have been the total operating cost of the UAV for 2006 (if it had been used to map all the weeds at Camp Williams) and adding that to the total initial or upfront cost. This was compared to what the total cost was using the on foot method (which was also an extrapolation of operating costs combined with the upfront costs). A total cost for the on foot method was also calculated based on using a Garmin Gecko instead of the Trimble GeoXT that the weed technicians are currently using. This was done to see if downgrading the quality of the GPS receiver would increase weed mapping efficiency at Camp Williams more than using a UAV would.

The total operating cost for 2006 for the UAV method was extrapolated by calculating a cost rate per acre as observed from study area one and multiplying that by the total area of weeds (204 acres) at Camp Williams in 2006. The cost rate was calculated by dividing the operating cost of the UAV method at study area one by the number of acres of the weed area at study area one.

The total operating cost for 2006 for the on foot method was found by calculating a cost per meter of perimeter as observed from study area one and multiplying that by the total perimeter (92 kilometers) of weeds at Camp Williams in 2006. The cost rate was calculated similarly to the UAV method: the operating cost for the on foot method at study area one was divided by the length in meters of the perimeter of the weed patch.

The reason the two methods were not calculated exactly the same way is because in the case of the UAV the amount of time it takes to fly an area is more closely related to the amount of area than the length of the perimeter. If you had two patches of weeds covering the same amount of area, one being elongated and the other circular, the aircraft would take about the same amount of time to fly over and completely image each one. In the case of the on foot method, however, the elongated area would take noticeably longer because even though both patches cover the same amount of area, their perimeter lengths would be much different. For that reason using the length of perimeter better represents the time it takes to map weed patches using the on foot method than using the amount of area.

A comparison was then done projecting across ten years at one year intervals the results of the calculations of the different total costs for 2006 for the two methods. This was done by taking the total cost for each method for 2006 and cumulatively adding the operating costs for each year thereafter for ten years. This was done to simulate the cumulative growth of costs for the methods to see how they might compare over time and at what rate. The comparison assumed a one-time initial cost and a weed infestation that stayed exactly the same from year to year.

Chapter Four: Results

Examination of the photos revealed that the purple flower of the Musk Thistle was not helpful in identifying the weed. It was identifiable, however, by its distinct green hue which was different from surrounding plants. It also had a distinctive shape and was distributed in a regular and distinctive fashion (refer to the top right and bottom right corners of Figure 4.1). Although the human image analyst/interpreter was able to distinguish the thistle from the background range vegetation, the supervised classification had very little success in doing so.

The results will be broken down into polygon differences, costs, results of the supervised classification, and findings from study area two.

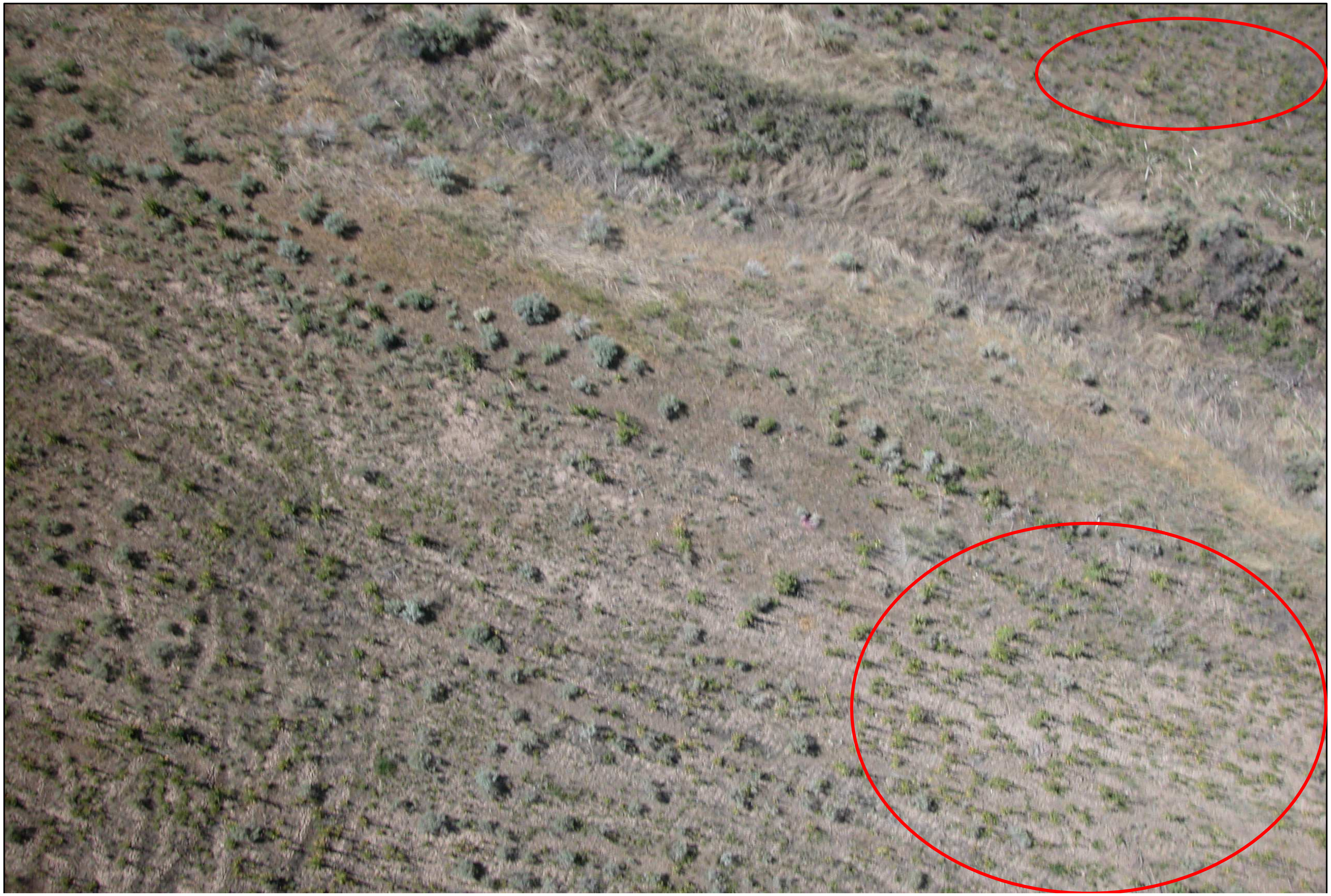

Figure 4.1: Uniform Musk Thistle weed patches areas designated by red circles.

A. Polygon Differences

The difference between the UAV method polygons and the on foot method polygons is displayed in Figure 4.2 and the parameters of comparison are tabulated in Table 4.1. Table 4.1 also contains a column containing the Camp Williams Natural Resource Manager's allowable error. The first four rows of Table 4.1 are based on the manager's stipulation that boundary be at least as good as one would get using a WAAS enabled GPS. The last row is his stipulation that the area calculated not be in error more than .1 of an acre) (Johnson 2007). The error of commission, or the part of the polygon created by the UAV method that was beyond the perimeter of the on foot method, was 4% of the total UAV polygon. The error of omission, or the part of the polygon created by the on foot method that was not covered by the UAV polygon, was 18% of the total area of the on foot polygon. This leaves 82% of the on foot polygon being correctly covered by the UAV polygon.

Figure 4.3 displays the difference between UAV method polygons and the on foot method polygons when the UAV method was done without performing **Step 4**, image registration. The error of commission in this comparison was 21% of the total UAV polygon. The error of omission was 17% of the total area of the on foot polygon leaving 83% of the on foot polygon being correctly covered by the UAV polygon.

The average distance between the registered UAV polygon edge and the on foot polygon edge as measured at ten meter intervals along the on foot polygon perimeter (Figure 3.6) was 9.9 meters with a maximum distance measure of 68 meters. The UAV polygon interpreted from the non-registered images had an average perimeter distance of 11.4 meters and a maximum of 38. The difference in the calculated area between the

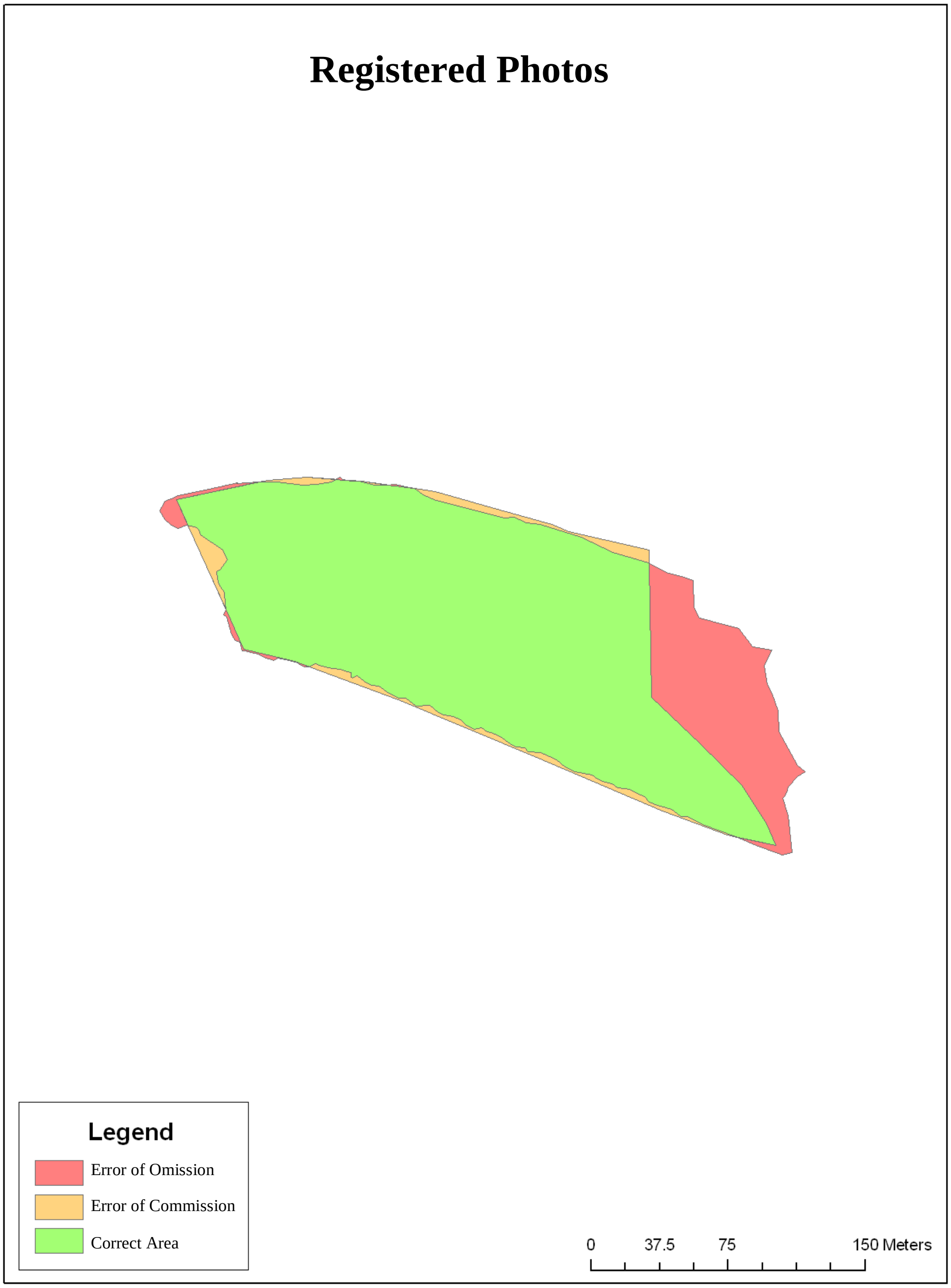

Figure 4.2: Areas of difference between the UAV polygon and the on foot polygon using the registered UAV photos.

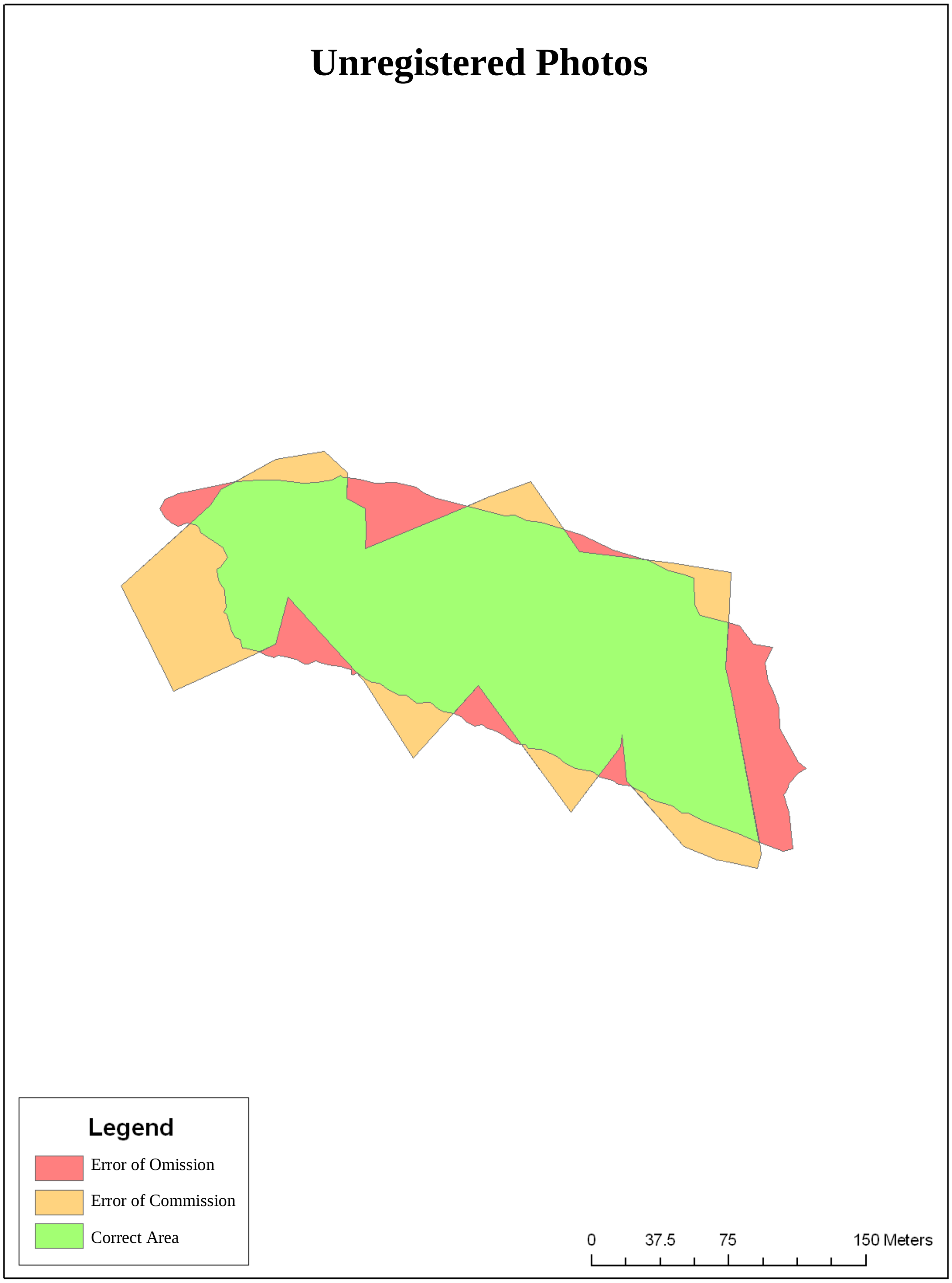

Figure 4.3: Areas of difference between the UAV polygon and the on foot polygon using the unregistered UAV photos.

polygon drawn from the registered photos and the on foot method was 1.19 acres. The difference for the polygons drawn from the unregistered photos was .45 acres.

	UAV (Unregistered)	UAV (Registered)	Natural Resource Manager's Allowable Error
Error of Commission	21%	4%	4%
Error of Omission	17%	18%	4%
Average Perimeter Difference (Meters)	11.4	9.9	3
Maximum Perimeter Difference (Meters)	38	68	10
Area Difference (Acres)	.45	1.19	.1

Table 4.1: UAV method polygon quality and the Natural Resource Manager's allowable error.

B. Cost Comparison

Table 4.2 breaks down the different parts of the UAV method to show how long each part took. The on foot method took about 35 minutes to walk around the weed perimeter. Differential correction of the on foot data and the exporting of it to a shapefile took about five minutes. Looking at the UAV method, setting up the aircraft for the UAV method took about five minutes. Flight three, which is the only flight that yielded usable data, took about seven minutes and it took another five minutes to put the aircraft away. **Step 1** of the four post-processing steps took about six minutes after going through the 116 photos acquired from flight three; 49 images were left. **Step 2** took just over a minute. **Step 3** took about fourteen minutes. **Step 4** took four hours and fourteen minutes. The time it took to digitize a weed perimeter was less than a minute. The total

Parts of the UAV Method	Time in Minutes
Set Up and Put Away Aircraft	10
Fly Aircraft	7
Step 1: Image Selection	6
Step 2: Georeferencing	<1
Step 3: Rotation	14
Step 4: Registration	254
Interpret Boundary	<1
Total	293

Table 4.2: Time in minutes for each part of the UAV method for flight three.

time after adding up the flight time and all the steps for the UAV method was about five hours for just one flight. Most of the fuel was used up during each flight so if we say imaging a weed patch requires one eight ounce tank of fuel then the fuel costs for flight three were eighteen cents. Table 4.3 contains the operating time (including post-processing) and total operating costs at study area one of the UAV method, on foot method with a Trimble GeoXt, and the on foot method if a Garmin Gecko 201 had been used. The operating cost for the on foot GeoXt method for study area one was $8 while for the on foot method if a Garmin had been used it would be $7.20. The difference in cost between the two on foot methods is because data from the Garmin cannot be differentially corrected, thus reducing the on foot method with a Garmin operating time. The UAV method through **Step 4** was $75.98 while the UAV method leaving out **Step 4** was $10.29 (if there had been a GIS technician performing the UAV method rather than a researcher).

	UAV (Unregistered)	UAV (Registered)	On Foot (Trimble)	On Foot (Simulated Garmin)
Time (Minutes)	39	293	40	36
Operating Costs	$10.29	$76.16	$8	$7.20

Table 4.3: Study area one operating times and costs.

The initial cost for the two methods is as follows: The UAV was approximately $1,125. Also part of the initial cost of the UAV is the time required to learn how to fly. If the pilot had been paid from Camp Williams as a GIS technician for the time it took to practice on the simulator it would have cost $467. This brings the total initial cost to $1,592. For the on foot method the Trimble GeoXT GPS receiver cost $4,295 and the TerraSync software (a Trimble Navigation product) costs $1,295. The total initial cost of the on foot method then was $5,590. The difference in initial cost between the two methods is $3,999 in favor of the UAV method. If the Garmin Gecko 201 were used instead of the Trimble GeoXT then the total initial cost of the on foot method would be $300 with an initial cost difference between the two methods at $1,292 in favor of the on foot method.

The purpose for the total cost comparison for 2006 between the two methods was to see if over the course of a summer the costs of the UAV method, both initial and operating, would be less than the costs of the on foot method. This comparison assumes that for every weed patch at Camp Williams one eight ounce tank of fuel would have been used for the aircraft. The results of predicting what the operating costs of the methods would have been if extrapolated to all noxious weeds at Camp Williams in 2006 are summarized in Table 4.4. Table 4.5 is a comparison of the cumulative growth of costs between the two methods over ten years at one year intervals. A one time initial cost is added to the operating cost for 2006. For every year thereafter up to ten years the operating costs for each year are lumped onto the accumulation of costs from previous years. Figure 4.4 is a graph of the same thing.

Method (Processing Step or Equipment Used)	**Rate Per Acre(UAV) or Kilometer of Perimeter(on foot)**	**Total Operating Costs for 2006**	**Sum of Operating and Initial Costs for 2006**
UAV (Unregistered)	$1.43	$614	$2,206
UAV (Registered)	$9.13	$2,184	$3,776
On Foot (Trimble GeoXT)	$8.59	$791	$6,381
On Foot (Simulated Garmin)	$7.73	$712	$1,021

Table 4.4: Predicted total costs in 2006 for the on foot and UAV methods (all rates and costs extrapolated and estimated).

Year (Beginning With 2006 as Year 1)	**UAV (Unregistered)**	**UAV (Registered)**	**On Foot (Trimble GeoXT)**	**On Foot (Garmin Gecko)**
Year 1	$2,206	$3,776	$6,381	$1,021
Year 2	$2,820	$5,960	$7,172	$1,733
Year 3	$3,434	$8,144	$7,963	$2,445
Year 4	$4,048	$10,328	$8,754	$3,157
Year 5	$4,662	$12,512	$9,545	$3,869
Year 6	$5,276	$14,696	$10,336	$4,581
Year 7	$5,890	$16,880	$11,127	$5,293
Year 8	$6,504	$19,064	$11,918	$6,005
Year 9	$7,118	$21,248	$12,709	$6,717
Year 10	$7,732	$23,432	$13,500	$7,429

Table4.5: Accumulation of total costs at one year intervals (assumes a one-time initial cost and a weed infestation that is exactly the same for each year).

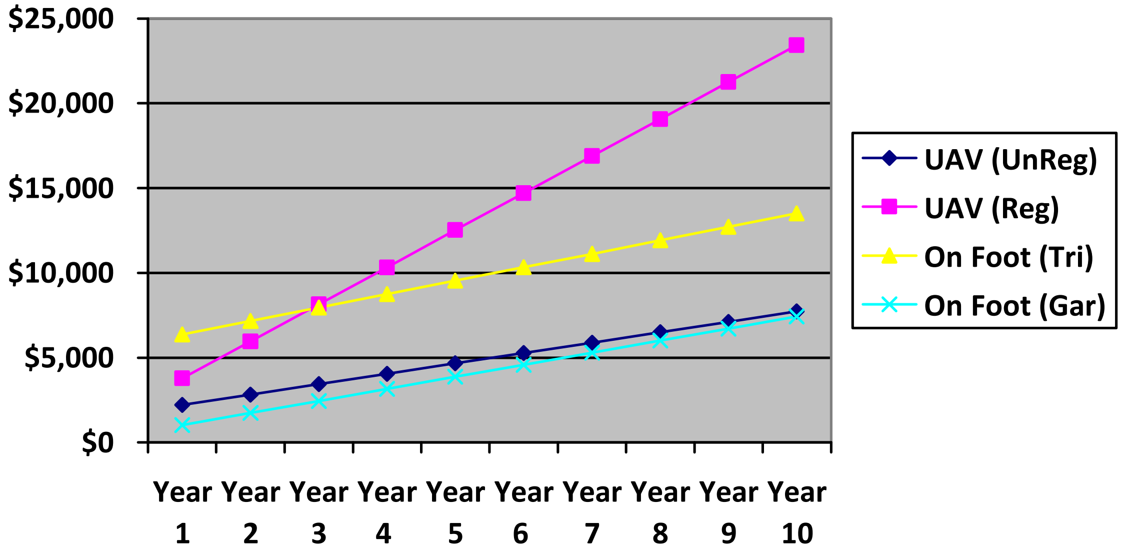

Figure 4.4: A graph displaying the information contained in Table 4.4.

C. Supervised Classification

The supervised classification produced errors too high to be able to distinguish weed areas from non-weed areas. Figures 4.5 and 4.6 have a line drawn in them depicting a boundary for each photo separating the weed area from the non-weed area. Figures 4.5 and 4.6 are individual photos which do not cover the entire weed patch at study area one. The boundaries being depicted in them represent internal boundaries within the two photos between weed and non-weed areas. This is not the same boundary created by the on foot or UAV methods which encompass the entire weed area in that part of Camp Williams. As can be seen in Figures 4.5 and 4.6, the error of commission is so high that if one were to look at the classification without showing where the classification was in error it would be impossible to tell where the boundary belonged. The errors for the classification of photo 101338 (Figure 4.5) were 71% commissional and 26% omissional.

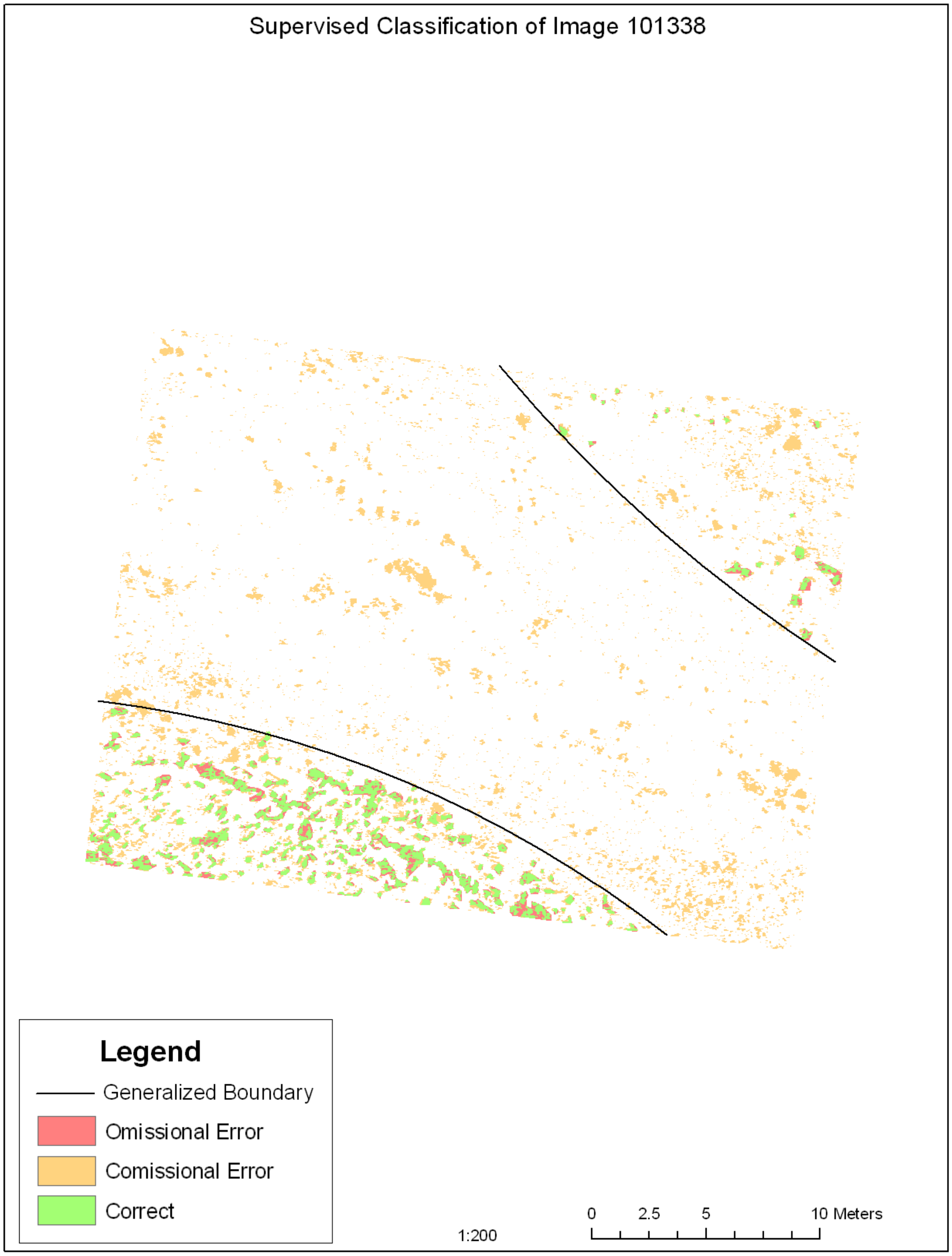

Figure 4.5: Error of supervised classification for image 101338.

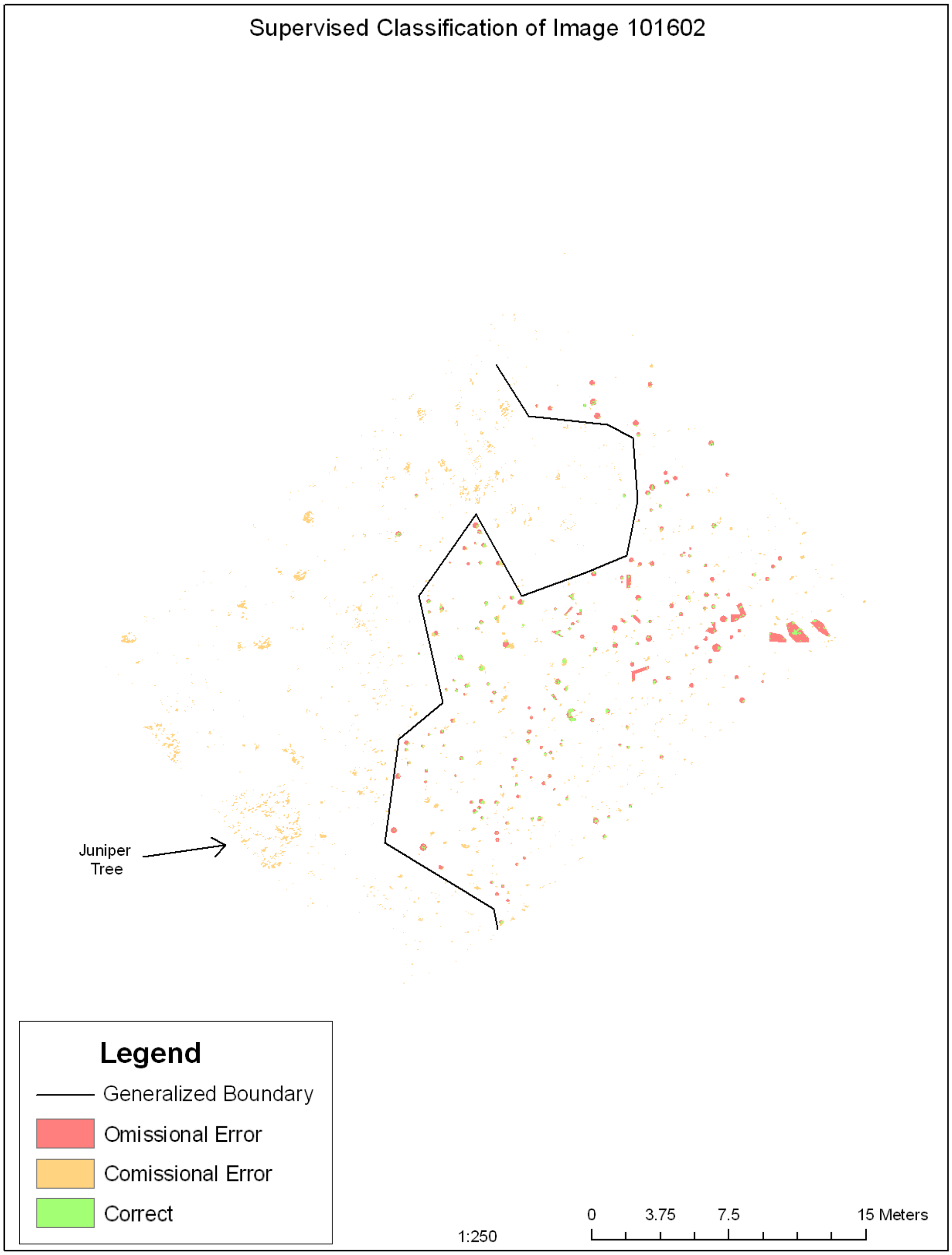

Figure 4.6: Error of supervised classification for image 101602.

The errors for the classification of photo 101602 (Figure 4.6) were 80% error of commission and 73% error of omission.

D. Study Area Two

Initial examination of the aerial photographs revealed that identifying the Dalmation Toadflax while among the Yellow Sweet Clover would not be possible. The red lines in Figure 4.7 encompass areas that were mapped with a GPS receiver on the ground by walking around the patches. It is clear that there is no difference between the look of the plants within the red perimeters and outside of those areas. This phenomenon was the same across the entire study area. For this reason no further research was performed at study area two.

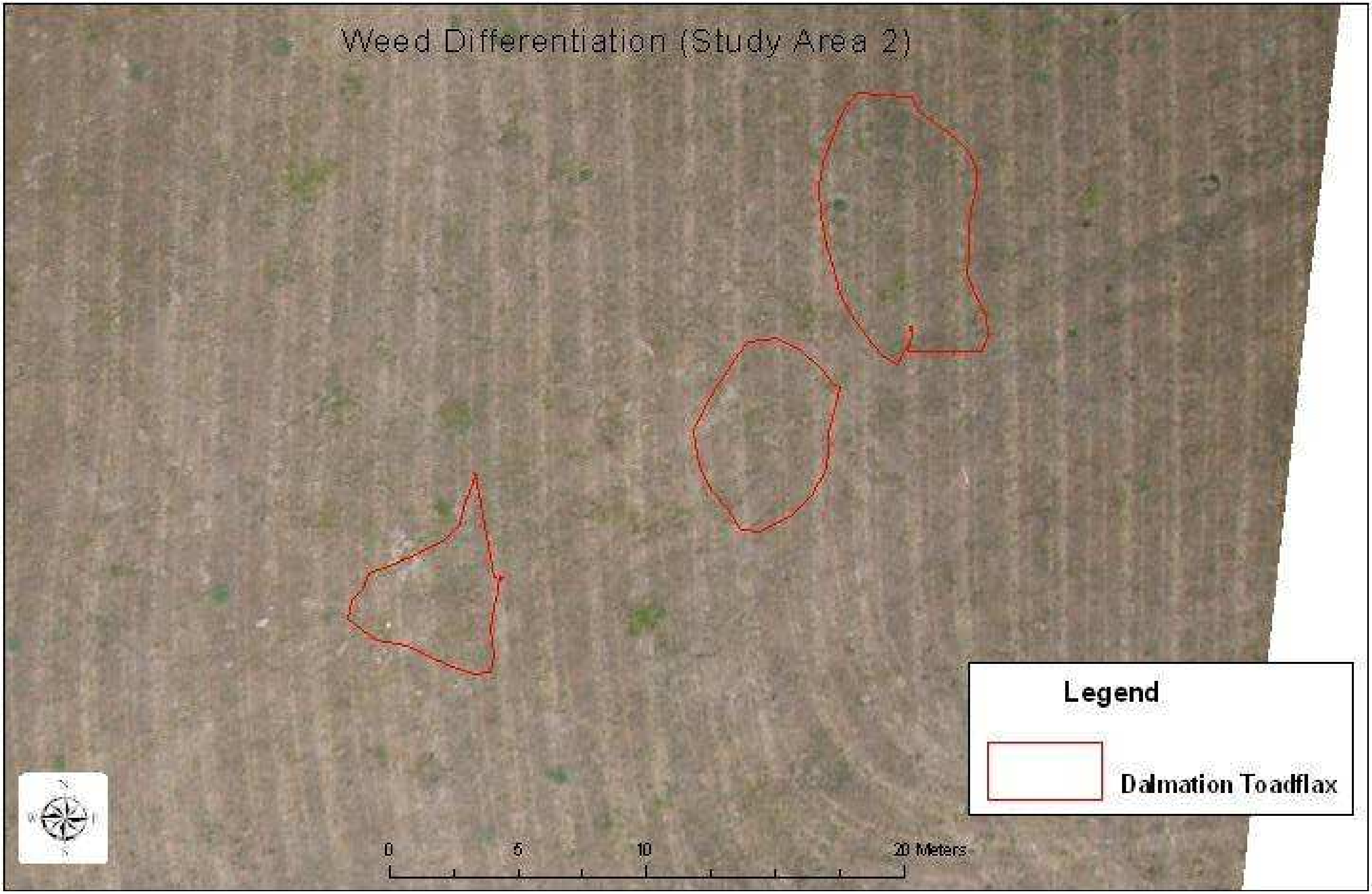

Figure 4.7: A map demonstrating that what's inside the polygons is indistinguishable from what is outside.

Chapter Five: Discussion

A. Positional Accuracy

After registration, the images had a positional accuracy of approximately 3 meters. The primary cause of post registration errors was distortion due to off nadir photography resulting in non-uniform scale across the images and non photo centered coordinates. This means that while some parts of the images were as accurate as the base image, the entire image was not. Theoretically the problem of tilt of the aircraft distorting the imagery could be fixed by including an Inertial Navigation System (INS). Combined with a GPS an INS could provide necessary information to remove the distortion. In 2000, Luethi *et al.* managed to put togethor an INS/GPS integrated system for less than $500 (does not take into account cost of labor). A quick browse on the internet shows that there is currently an abundance of commercial options for obtaining a light weight, small, and cost-effective INS.

Registration to a base image would not have been necessary had the position of the images not been so inaccurate. There are a number of possible explanations for the rotation being off by as much as 40° and the general position of the images being inaccurate to 53 meters. Likely part of the problem was the fact that the aircraft was traveling on average approximately 17 meters per second during flight three. Since both the camera and the GPS receiver counted time at the seconds level there was room, even after the two were synchronized by including an offset in Hardin’s (2005) program, for error at the sub-second level. This means that the GPS receiver may have recorded a point at one end of a second and the camera took a picture at the other end while the aircraft traveled 17 meters in between. The maximum airspeed for flight three was 34 meters per second. In that case alone 34 meters of the inaccuracy could be explained. To fix this both the GPS receiver and the camera would have to be able to measure time at the sub second level.

Another problem affecting the positional error and the rotation is the fact that the best accuracy of a WAAS enabled Garmin is three meters according to About GPS (2007). As well as affecting the positional accuracy of the center-point of each image this could significantly alter the rotation of the images up to 19° when traveling at the average speed for flight three (17 meters per second) and with the Garmin recording positions at an average accuracy of 3 meters (Figure 5.1). If the aircraft were slowed down to 8.5 meters per second with the same average GPS accuracy the rotation error could be as high as 35°. If the GPS accuracy were decreased to 10 meters while the aircraft were traveling 8.5 meters per second the rotation error could be as high as 67°. Being able to differential correct the data could reduce this error substantially.

One of the most likely other causes for the rotational error is the fact that the direction the aircraft is pointing is rarely exactly the direction the aircraft is heading. Hardin's (2005) program calculates the direction the aircraft is heading, not pointing. This is especially true when there are crosswinds. During flight three the terrain did not allow the pilot to fly perfectly into or with the wind. To reduce the rotational error flying into or with the wind would help substantially. Another way to reduce this error regardless of the wind direction in relation to the direction of travel of the aircraft could possibly be to

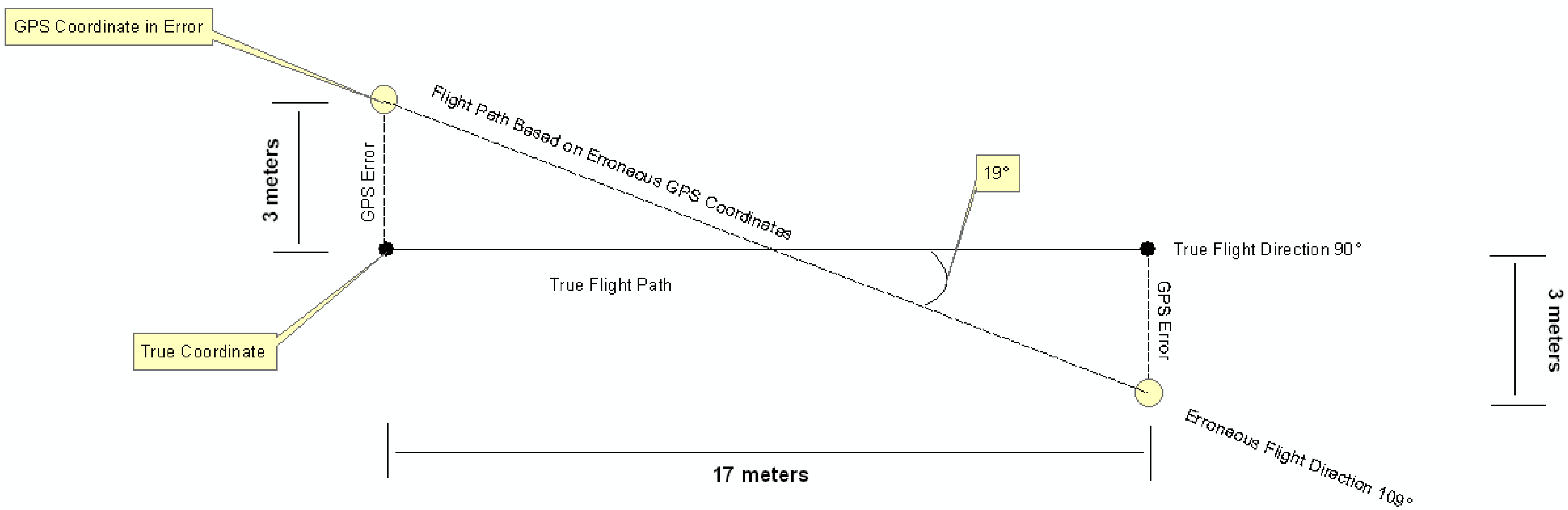

Figure 5.1: A diagram depicting how GPS error causes error in calculating direction of flight.

include a digital compass onboard the aircraft with the capability of recording readings at set intervals. Direction could also be recorded from an INS. Whatever the sources of information about the location and orientation of the aircraft, the ideal situation would be to use a computer onboard the aircraft that would, at each time a photo was taken, trigger all onboard measurement devices to record and then send that information to the computer where it would automatically calculate the location, scale, and orientation of the photos.

B. Method Comparison

Looking at Table 4.1 and comparing the UAV registered polygon with the unregistered polygon there were only two out of the seven categories that the registered UAV polygon performed better than the unregistered polygon. For all of the extra time it took to register the images, results do not show an increase in accuracy, and sometimes a decrease was observed. The main explanation for this is the fact that there was a large area on the east side of the patch in which the image interpreter was unable to identify any musk thistle (Figure 4.2). This was probably due to the weeds being less dense in that area. Despite that, the registered UAV polygon followed the on foot polygon boundary pretty closely with the on foot polygon for the rest of the weed patch. This does call into question the necessity of going through with the image registration when the unregistered imagery is, at least in this case, better. However, the unregistered photos could have been arranged differently bringing some photos in the viewer on top of others that they were not on top of before and others getting buried. Each different arrangement would have produced significantly different results in the unregistered polygon, so some arrangements could have been worse in every way when compared to the registered polygon.

There is a give and take between cost and accuracy. This study failed to show it, but it is theorized that with many samples the registered UAV method would prove to be more accurate than the unregistered UAV method. Whatever improvements that can be made to improve the accuracy of the automated georeferencing process, however, would help reduce the need to register to a base image and ultimately increase efficiency.

As is indicated in Table 4.1 the unregistered photos still cost more at study area one than the on foot method did, but at least the gap is not near as large as it is with the registered photos. This helps to show that if image registration was not necessary then the cost of the UAV method could be much more competitive with the on foot method. Table 4.5 and Figure 4.4 show that the unregistered UAV method would be cheaper than the on foot method (using the Trimble as they now do) even after ten years. This assumes that neither the aircraft nor any of its parts would have to be replaced in that time period due to a crash or malfunction. This is a very unrealistic assumption. In accordance to the desired accuracy of the Natural Resource Manager at Camp Williams, however, the .45 acre area difference metric puts the unregistered UAV method beyond the acceptable margin of error of .1 acres (Johnson 2007). Also, as Table 4.5 and Figure 4.4 show, if the Natural Resource Manager really wanted to cut costs he could purchase a Garmin instead of a Trimble and still generally get better accuracy than with the UAV method.

An interesting side note that came about in this study is the effect the shape of a patch can have on the cost comparison. This was not directly observed but was theorized as part of the way the operating costs for the two methods were measured. The UAV method cost measurement was determined in part by the size of the weed patch in acres. For the on foot method the cost was in part determined by the length of perimeter. It did not make sense to measure the two methods the same because the nature of mapping a weed patch on foot is to walk around the perimeter of the weed patch while the UAV method is not restricted to the perimeter but flies over the entire area. Because the on foot method follows the perimeter, its cost per acre increases exponentially, while holding the amount of area constant, as the shape becomes more elongated and the length of the perimeter therefore increases. This explains why the predicted operating cost for the unregistered UAV method for 2006 as shown in Table 4.4 was less than the predicted operating cost for the on foot method even though the cost for the unregistered UAV method for flight three as shown in Table 4.3 was more than the on foot method. It also explains why there are a substantial number of weed patches that were predicted to have cost more by doing the on foot method than the registered UAV method. However, because the data suggests that the cost of mapping weed patches with the registered UAV method increases at a much higher rate with the increase in size of a patch than the on foot method does, it is theorized that size and not shape has more influence, in the case of the registered UAV method, on the total costs. This would not be true with the unregistered UAV method as it had a much lower operating cost.

Another variable that could theoretically influence the cost of the UAV method would be the height above AGL that the aircraft was flown. The higher the aircraft the more ground area each image could cover reducing the number of images that would need to be processed. If no registration with a base image were necessary then this fact would not matter near as much. The trick would be to collect imagery at just the right height where the target weed could still be identifiable and yet each image could cover as much ground as possible. For this study, given the difficulty of identifying the weeds at the East side of the weed patch, the average height above AGL of 57 meters with a maximum of 126 meters may have been too high. A higher resolution camera could also compensate and, combined with a wide angle lens, could have reduced the number pictures needed to be taken.

C. Study Area Two

Because the dalmation toadflax was indistinguishable from the yellow sweet clover, efforts at study area two were not successful. One way to get around this problem might be to try and image the toadflax at a time when it has flowers and the sweet clover does not. According to Lajeunesse (1999), dalmation toadflax flowers from June to October. She also mentions that seed dispersal begins in July. The yellow sweet clover flowers from May to August (University of California 2006). This leaves a window of opportunity between September and October. The problem is that land managers would want to map and eradicate the toadflax well before this time to limit the amount of seed that is produced. Higher resolution imagery could help as well, but that would likely increase the costs. What differences there are between the toadflax and sweet clover (the shape of the leaves) would be identifiable at some higher resolution. This would require a more expensive camera or lower flight altitude which would increase the number of pictures required to be taken resulting in more time and ultimately more money.

D. Conclusion

Given the results of this study it can not be said that using a UAV to map weeds is a more efficient and effective method than the on foot method currently used at Camp Williams. This study also assumed that neither the aircraft nor any of the other devices like the camera had to be replaced at any point in time. The plane used in this study crashed on flight five due to the wing splitting in half and almost all onboard components were damaged beyond repair. The crash was likely due to the structure being weakened during previous rough landings and perhaps the extra weight of the equipment it was carrying. Crashing UAVs has also been experienced by other researchers like Jones *et al.* (2006). Having a more experienced pilot to pilot the aircraft could reduce the likelihood of damaging the aircraft but would likely increase the operating cost.

If it were not for the cost of fuel for the aircraft the unregistered UAV method would have surpassed the Garmin version of the on foot method after three years. This is significant enough that if perhaps an electric motor were used instead of a fuel powered motor and if the positional accuracy of the UAV photos without registration to a base image could be accurate to ten meters (about what you would get with a Garmin on the ground) then the UAV method could be the better choice.

The increase in cost of the on foot method as the shape of the weed patch becomes more elongated indicates that perhaps doing a combination of both the on foot and UAV method might be the best approach. In other words, for those weed patches that are elongated, use the UAV, while for those that are more circular, use the on foot method. There was a substantial number of elongated weed patches that formed along Camp Williams roads in 2006. In these cases, piloting the aircraft from a car or truck could be used to increase the efficiency of the method.

E. Low-Cost UAV Potential

If a video camera were put on the UAV and a live data link was established from the camera to be viewed in real time on the ground it may be possible to scout areas for noxious weeds. Given how difficult it can be to pick out noxious weeds in a still picture (e.g. differentiating between dalmation toadflax and yellow sweet clover or the inability to recognize the less dense musk thistle area at the East end of the weed patch at study area one) it would seem that trying to recognize plants in real time as a video is playing would be even more difficult. It was not tested in this study, but Hardin and Jackson (2005) claimed that they could fly their UAV at a lateral distance of 1 kilometer while still being able to keep it in sight and under manual control. If this is truly possible then it would make sense to use the UAV to scout locations that are far enough away from roads to inhibit the ability of a person to see and recognize noxious weeds.

Apart from imaging weeds this UAV system as used in this study could be useful for other applications. For instance, being able to map objects in dangerous areas like munitions impact areas on military training facilities where Unexploded Ordinances (UXO) may exist. The UAV could be used to do rapid re-imaging of a small site at high resolution for land impact monitoring and change detection. If a camera were used in the UAV that had the capability of imaging in the Near Infrared (NIR), plant health in a farmer's field could be monitored at a very small temporal resolution (theoretically the temporal resolution could be measured by hours or even minutes). There are likely many more applications for small low cost UAVs that have likely been thought of or will be thought of, which leaves the research community exciting, fresh ground to explore as useful components become lighter and less costly.

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