An Analysis of Radiocarbon Sampling Methods on Landslides in the North Fork Stillaguamish River Valley, Washington, USA

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Executive Summary

Tragedy in the North Fork Stillaguamish (NFS) River valley, Washington, USA has sparked an increase in landslide research in the Pacific Northwest. In 2014, the town of Oso, WA lost 43 lives to the deadliest landslide in North American history. The Oso Landslide (formally referred to as the State Route (SR) 530 Landslide) began as a rotational slide and became a debris flow when it reached the NFS River (Keaton et al., 2014). Since this devastating event, researchers have been trying to understand and, ultimately communicate, landslide hazard risk in this river valley.

The approach to assessing the hazard and associated risk of landsliding in this valley has been determining the frequency of slide events since the last glaciation about 16.4 k.y. ago (Porter and Swanson, 1998). The Fraser glaciation deposited permeable advance outwash sand and gravel over impermeable glaciolacustrine silt and clay layers. Heavy precipitation events in the winter months, a signature of western Washington climate, saturate the permeable sand units and weaken the cohesion of the steep hillslopes in the NFS River valley. In addition to lithology, climate, and topography, the NFS River meanders throughout the valley and interacts directly with the hillslopes. This occurs most commonly in the narrowest portion of the valley where the Oso Landslide is located (Keaton et al., 2014).

Recent studies have designated a surface roughness value, using standard deviation of slope, to these landslides. These surface roughness values are correlated with numerical ages of landslides based on radiocarbon dates of wood samples (LaHusen et al., 2016). These wood samples represent the time of the slide event, which would have presumably killed and entombed these trees. The more radiocarbon dates of landslides in the NFS River valley, the more accurate the age-roughness model is for estimating landslide ages.

In an effort to further calibrate the numerical age-roughness model, this project collected four new wood samples for radiocarbon dating and developed a protocol for determining best methods for sampling organic material from landslides. Wood samples for radiocarbon dating are found in gullies that carve into landslide deposits, fluvial terraces that cross cut landslides, and landslide ponds. In this project, I identify which methods of sampling suit different ages of landslides as well as the limitations of each method. I present here: (1) a protocol for determining which method to use to sample landslides for radiocarbon dating, (2) an explanation of how to remotely identify features, such as ponds, to support field work, and (3) an analysis of the accuracy of each method according to the four new radiocarbon dates that I obtained.

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Acknowledgements

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An integral part of this project was coring ponds. I was fortunate to be able to use both the equipment and expertise of Dr. Doug Clark from Western Washington University. Without his raft and coring equipment, I would not have been able to core into the Rowan Landslide pond or to attempt to core the Beaver Landslide pond. Thank you.

1. Introduction

In 2014, the United States witnessed geomorphology in action in the most tragic landslide incident in the nation's history. The Oso Landslide killed 43 people on March 22, 2014 in the North Fork Stillaguamish (NFS) River valley of Washington state, USA. The 2014 Oso Landslide event has since motivated new research on landslide susceptibility, impacts, and frequency. Incised river valleys, such as the NFS, that cut into glacial deposits have been experiencing landslides since the last glaciation about 16.4 k.y. ago (Porter and Swanson, 1998). Much attention has been paid to the high susceptibility of reactivation of old landslides in these valleys (Thorsen, 1989) and more recent studies have emphasized the importance in understanding the hazard and risk associated with both new failures and reactivations of older slides (Keaton et al., 2014).

One of the most revolutionary tools for identifying and analyzing landslides has been Light Detection and Ranging (LiDAR) technology. LiDAR is now regarded as essential in geomorphic work such as landslide hazard mapping and analysis, especially in heavily vegetated terrain such as in the Pacific Northwest. Commonly used in a Geographical Information System (GIS) such as ArcGIS, bare earth topography LiDAR allows for easier recognition of landforms. The high topographic resolution also provides a platform on which to create landform metrics such as surface roughness. LaHusen et al. (2016) used LiDAR, in combination with selective radiocarbon dating of tree wood samples, to establish a quantitative relationship between landslide age and landslide roughness. With numerical dates calibrating an age-roughness curve, the authors estimated the dates of landslides that have not been directly dated. Building on this earlier study, Booth et al. (*in press*) expanded the analysis to include over 200 landslides in the valley. These data are useful in assessing the frequency of landslides in the NFS River valley. Understanding frequency of landslides allows policy makers and scientists a way to communicate risk to the public and developers.

Dating landslides provides a means of understanding risk in a given landslide area. Data from both Booth et al. (*in press*) and LaHusen et al. (2016) suggest that the NFS River valley has had extensive landsliding since the last glaciation. In order to more fully calibrate the surface roughness dating method and ultimately, to understand the frequency and subsequent risk of these landslides, dates of landslides that run the range of the age spectrum must be known from radiocarbon analysis. However, while radiocarbon samples are ideal for providing absolute dates, obtaining and dating radiocarbon samples can be costly, access to samples can be difficult, and locating samples can be challenging. It has been especially difficult to obtain samples from older (>5000 years) landslides whose gullies and surfaces have diffused significantly and where the North Fork Stillaguamish River has not cut into and exposed the lower toes of the slides.

As part of the larger project assessing the frequency of landslides in the NFS River valley (LaHusen et al., 2016; Booth et al., *in press*), I aimed to provide more radiocarbon dates to calibrate the age-roughness curve. I focused on older landslides because few absolute ages exist for this part of the curve, but also tested a method on one younger landslide. In addition, my project focuses on comparing terrace, gully, and pond coring methods of sampling for radiocarbon dating and provides a protocol for determining the best approach to sampling organic material for landslide dating.

2. Background

2.1 Landslides in the North Fork Stillaguamish River Valley

This project site area is located in the North Fork Stillaguamish (NFS) River valley (Fig. 1), where glacial deposit hillslopes have experienced mass wasting since the last glaciation. After the 2014 Oso Landslide, immediate work was done to assess the characteristics and causes of the failure. The National Science Foundation-funded Geotechnical Extreme Events Reconnaissance (GEER) team created a geotechnical report that thoroughly explores the potential triggers for the failure (Keaton et al., 2014). While increased rainfall and potential logging effects may have contributed to the 2014 event, it is not an entirely unique event for the NFS River valley (LaHusen et al., 2016; Booth et al., *in press*). Glacial stratigraphy, heavy rainfall, and steep topography caused by river incision have contributed to mass failures in this region since the retreat of the last glaciation about 16.4 k.y. ago (Porter and Swanson, 1998; Dragovich et al., 2003; Keaton et al., 2014). In addition, the Oso Landslide and adjacent long-runout mass failures are located in the narrowest segment of the river valley, indicating that these hillslopes of ~200 m relief are affected by the increased interaction with the meandering river (Keaton et al., 2014; Booth et al., *in press*). Haugerud (2014) used cross-cutting relationships and roughness to create the first map that interprets relative ages of these landslide deposits in the Oso Landslide area. Since this initial interpretation, several additional studies have been conducted on the history of landslides in the NFS River valley using LiDAR (Booth et al., *in press*; LaHusen et al., 2016).

There are two primary ways to determine the timing of past landslides: relative (e.g., surface roughness and cross-cutting relationships) and absolute dating (e.g., radiocarbon). Cross-cutting relationships are used to determine the age of a landslide relative to adjacent geomorphic features such as landslides, rivers, or additional scarps within the given landslide. For instance, if one landslide's run-out is truncated by another landslide deposit, the latter landslide must be younger than the landslide whose run-out it is truncating. River terraces deposited either on top of or cut into landslide toes also provide maximum or minimum age brackets on landslide timing. These principles are useful for determining relative ages of

landslides in a complex and were the first analyses done in the NFS valley (Haugerud, 2014).

2.2 Surface Roughness Dating of Landslides

In addition to cross-cutting relationships, Booth et al. (*in press*) and LaHusen et al. (2016) have used surface roughness values from LiDAR calibrated with a subset of radiocarbon ages to predict ages of landslides in the NFS River valley. Using standard deviation of slope (SDS), LaHusen et al. (2016) assigned roughness values to landslides with radiocarbon dates for three landforms to create a surface-roughness curve. Booth et al. (*in press*) thus expanded this method to over 200 landslides (with consistent morphology) in the valley as a way to predict landslide ages based on surface roughness. Results from these studies suggest that long run-out landslides are not new to this river valley and hillslopes have been failing relatively regularly since the last glaciation. This surface-roughness curve, as with all models, is only as good as its calibration to known landslide ages. Therefore, obtaining numerical radiocarbon dates on landslides, especially representative slides from all parts of the curve, is essential to predicting frequency of landslides.

This study provided more radiocarbon dates for Booth et al. (*in press*) using two different sampling methods: pond coring and terrace sampling. As Pánek (2014) explains, multi-dating approaches are useful for verifying different dating methods. Given time and funding, it may also be appropriate to incorporate dating methods other than radiocarbon dating. In a comparison of dating techniques, Lang et al. (1999) found that techniques such as Accelerator Mass Spectrometry (AMS) and Thermal Ionising Mass Spectrometry (TIMS) can increase dating precision. Radiocarbon dating is still used as an effective method for gathering dates on landslides, however (Pánek, 2014). Therefore, in order to gather as many dates as funding allows, we committed to radiocarbon dating in this project.

3. Geologic Setting

The NFS River valley drains west from the crest of Washington's Cascade Range, which was formed in part as a result of the Juan de Fuca Plate subducting beneath the North American Plate. The region experiences rare deep intraplate earthquakes and Cascadia Megathrust earthquakes as well as more common crustal earthquakes (Pacific Northwest Seismic Network, 2017).

The study area covers a 25 km east-west stretch of the NFS River valley of Washington, USA. The site includes hillslopes, including the Oso Landslide, which sits on the southeast end of the Whitman Bench (Fig. 1). The NFS River flows westward toward the Puget Sound and meanders across the river valley where it interacts with the bottom of hillslopes. The NFS River has flowed from the northern Cascade Mountains in Washington since before the last glaciation, the Fraser

Glaciation (Porter and Swanson, 1998). However, when the Puget Lobe (Bretz, 1913) of the Cordilleran Ice Sheet advanced southward about 17.5 k.y. ago, it blocked the NFS and other rivers flowing from the western Cascades into the Puget Sound. Until the ice retreated about 16.4 k.y. ago (Porter and Swanson, 1998; Beechie et al., 2001), the NFS River valley filled with over 200 m of glacial sediment. Sediment includes till above advance outwash of medium-coarse sand to sandy gravel overlying glaciolacustrine sediments of silty find sand, silt, silty clay, and clay (Dragovich et al., 2003; Keaton et al., 2014). Following glacial retreat, the river incised directly into these sediments. Then, about 12.4 k.y. ago, a lahar from Glacier Peak volcano forced much of the NFS River headwaters into the Sauk River, and incision rates slowed down (Beget, 1982; Booth et al., 2003). The steep hillslopes of glacial sediments have since been prone to mass failure as water infiltrates the advance outwash, is blocked by glaciolacustrine fine sediment, and subsequently saturates the advance outwash (e.g. Tubbs, 1974). For the past few decades, smaller failures have occurred intermittently (Miller and Sias, 1998). However, the reality of the Oso Landslide and our knowledge of other historic mass failures such as the Rowan Landslide (LaHusen et al., 2016), show that these hillslopes are capable of an array of failure sizes (Booth et al., *in press*).

4. Methods

In order to achieve my goals of obtaining radiocarbon samples from older landslides, I tested sample collection from three geomorphic features on the landslides: gullies, terraces, and ponds. Ideal dating would include samples both from a river cutting directly into the toe of a landslide and from a gullies carving into the upslope reaches of landslide deposits. These samples would provide the most accurate bracket on numerical age of a landslide. However, landslide age and morphology (as well as proximity to a river) can make sampling difficult. In this study I found that dating ponds proves to be the most promising for sampling older (>5000 years) landslides. Therefore, in addition to assessing the three sampling methods, I also created a prototype for a protocol to remotely locate ponds for sampling.

4.1 Assumptions

When a landslide occurs, it may take down trees along with it. Once the trees die in the landslide debris, their ^{14}C begins to decay to ^{12}C with a half-life of about 5,370 years (Götte, 1953). In dating these wood samples, it is assumed that the radioactive decay of ^{14}C begins at the moment the tree dies, and that the trees were killed at the time of the landslide. One source of error in identifying wood samples is the potential to obtain samples that were not killed in the slide event. If wood samples are too shallow, they may instead be remnants of logging or are simply trees that died more recently than the landslide event. To avoid this error, I ensured that wood samples were well within the landslide or fluvial terrace deposits. In

addition, wood samples from the cores of tree may have a margin of error greater than a twig due to "inbuilt age". The concept of "inbuilt age" describes tree samples that produce radiocarbon ages that predate the landslide event, which we assume killed the tree (McFadgen, 1982). Short-lived materials, like twigs, address this issue and provide the best tool for dating landslide events. Furthermore, in dating landslides by sag pond cores, it is important to determine that the sag pond has likely been in place since the landslide event. The sag pond must be as old as the landslide to ensure the pond was created by the landslide rather than by modern influences such as beaver dams or anthropogenic changes to the landscape such as from logging.

4.2 Sample Collection and Dating

With knowledge of the regional and site geology as well as assistance in identifying landslide debris, I collected wood samples from various landscape features: a fluvial terrace carved into and deposited adjacent to a landslide toe, a pond at the surface of a landslide deposit, and gullies into landslides. With the assumption that trees were killed in the landslide, ideal wood samples were aligned parallel to the landslide (suggesting trees were knocked down by landslide) and were within the landslide debris thus, convincing me that the wood was killed in the slide event.

4.2.1 Gully Sampling

Gullies, defined here as ravines eroded by water, provide the clearest method for obtaining wood samples to radiocarbon date. Gullies expose a cross sectional view into the large landslide deposit and thus, an access point for finding buried wood samples. Ideally, gullies remove the laborious effort of shoveling through topsoil, blindly aiming for wood samples that are often no larger than a thumb. LaHusen et al. (2016) recovered two gully samples from the Rowan Landslide, dates from which were averaged with four additional samples from the toe of the landslide cut by the NFS River to yield a date for the Rowan Landslide of 518 calendar (cal) ^{14}C yr B.P. (LaHusen et al., 2016; Booth et al., *in press*).

4.2.2 Terrace Sampling

The NFS River meanders and cuts into the bottom of valley hillslopes; especially where the valley is the narrowest (Booth et al., *in press*). The resultant river terraces sometimes cut into the toes of landslide deposits. This relationship between river terrace and hillslope can provides a relative age: the landslide must be older than the terrace that has cut into it. Therefore, dating the wood samples from the terrace sediments gives a minimum age constraint on the landslide. I applied this method of relative dating to the C-Post Landslide, about a half mile east of the Oso Landslide (Fig. 2 and 3).

4.2.3 Pond Sampling

Rotational landslides, such as those that compose much of the NFS River valley landslide complex, contain uplifted blocks or "hummocks" that can disturb the water table and create sag ponds (Varnes, 1978). Collecting organic material in ponds can be used to place new age bounds on landslides in two ways: 1) Samples taken at the deepest part of the pond would provide a minimum age on the landslide or 2) samples of wood taken beneath the pond and within the underlying landslide deposit itself would provide a landslide event age proper assuming that the wood was killed during the slide event. In coring, we can either aim to recover the exact stratigraphy (including landslide debris) or, with knowledge of the site stratigraphy, we can simply recover sediment we believe contains landslide debris. In this study, we attempted to core into ponds on two different landslides: one with a known age (Rowan) and one with an unknown age (Beaver).

4.2.4 GIS Protocol for Remotely Identifying Ponds

Because sag ponds appeared more promising for older landslide radiocarbon samples, I wanted to identify more ponds in the site area. Scouting sag ponds created by landslides can be challenging and is time consuming to do solely in the field. Adam Booth (*in press*) created a gully shapefile to help scout best possible gullies on landslides. In this project, I aimed to provide a protocol for remotely identifying ponds on landslides using LiDAR, as well. Remotely identifying ponds is a method that may be refined and used to target ponds for field work in future research and sample collection.

5. Site Locations and Sample Collection

In this project, I searched for datable organic material in river terrace and pond sediments from three landslides adjacent to the Oso Landslide: the Rowan Landslide, the Beaver Landslide, and the C-Post Landslide. The Rowan Landslide is dated to be about 518 years old using both gully and terrace radiocarbon samples (LaHusen et al., 2016) and lies across the river, directly to the west of the Oso Landslide. The Rowan Landslide was significantly more voluminous than the Oso Landslide (Iverson et al., 2015). The Beaver Landslide is located on the south side of the NFS River from the Oso Landslide and is estimated, using surface roughness, to be 5,579 years old (Booth et al., *in press*). The C-Post Landslide is located about a half mile east of the Oso Landslide on the north side of the NFS River (Fig. 2). The modern Stillaguamish River cuts the toe of the C-Post Landslide and has deposited a small fluvial fill terrace directly adjacent to it.

5.1 Gully Sampling in the NFS River Valley

I attempted to find wood samples in gullies of old landslides including the C-Post Landslide and another landslide east of the Beaver Landslide, which is estimated to be about 5,579 years old. However, we determined the wood samples from these gullies were not suitable to date, because they were too close to the surface and may be remnants of trees that were logged within the last century. Ultimately, I did not obtain sample successfully from gullies, because I focused on the oldest landslides (more than 1ka.) whose gullies were too diffuse, and/or filled with sediment, to provide useful cross-sectional access into the landslide debris.

5.1.1 Gully Sampling Limitations

In practice, gullies are useful only for relatively young landslides. Landslides that have diffused, and/or filled with sediment, over their lifetime have overgrown and shallow gullies. These types of gullies do not provide a clear view into the landslide debris.

5.2 Terrace Sampling at C-Post landslide

The C-Post Landslide was estimated by the roughness model to be 2,557 +/- 874 years old based on the numerical model of age-roughness (Booth et al., *in press*). We obtained wood samples from a river terrace that cut into the toe of the C-Post Landslide east of the Oso Landslide (Fig. 3). I identified the toe of the landslide using LiDAR imagery and field investigation. This north side of the NFS River meanders and cuts into the toe of the landslide and has left behind a small fluvial deposit. The deposit is well exposed on the river bank and abundant wood samples were found entrained in the terrace deposit. We sampled this terrace with the understanding that numerical ages of the river terrace would provide a minimum age of the landslide (Fig. 4).

To collect the wood samples, I first identified the largest wood samples in the terrace. I then chose three samples that were vertically about half way up the ~4 m tall wall of the terrace thus, ensuring the samples were killed in the landslide debris (I submitted 16CPOST1C and 16CPOST1D for dating) (Fig. 5 and 6). I used a soil knife to pry the wood samples into aluminum foil, then foil wrapped and protected the samples from possible contamination with other wood, human fingers, or paper. I individually wrapped the samples in aluminum foil, labeled them, and placed them in separate quart-sized Ziploc plastic bags. In the lab, I used tweezers to gently remove any modern organics and soil from the samples before sending them to the DirectAMS Radiocarbon Dating lab in Bothell, WA.

5.2.1 Terrace Sampling Limitations

Collecting samples from either landslide toe deposits cut by the river or river terrace deposits is an easy method of dating landslides because of the high degree of exposed surface area and relative ease of working along the river bank in search of samples to date. However, not all landslides are currently being cut by a meandering river and terrace deposits are not everywhere along the channel margins. LaHusen et al. (2016) collected samples from the Rowan Landslide where the river directly cut into the toe. In this project, we were able to collect samples from the terrace truncating the toe of the C-Post Landslide. While this is an indirect date, this provides a valuable minimum age on a landslide of otherwise unknown age. In order to provide a more direct measure of landslide timing we would need to date samples from a gully or a pond as well.

5.3 Pond Coring at Rowan and Beaver landslides

We attempted to core ponds on two different landslides in the NFS River valley: the Rowan Landslide and the Beaver Landslide (Fig. 7, 13). We cored the Rowan Landslide (a known younger landslide) to test the coring method before attempting to core an older landslide with an unknown age (Beaver).

5.3.1 Rowan Landslide Pond Sampling

The Rowan Landslide has more than five sag ponds, and I sampled from the largest and most easily accessed pond (Fig. 7). The Rowan Landslide has more than six prior carbon dates obtained by dating wood samples from the landslide debris (LaHusen et al., 2016). I chose to core the Rowan Landslide, because we already had dates on other parts of the slide and it would be interesting to see how other samples compared. Therefore, I aimed to test this pond coring method to see how similar ages from the base of the pond and/or landslide deposit beneath the pond were to the other ages obtained previously.

To identify the deepest part of the pond, we used a high-precision Trimble Global Positioning System (GPS) device and a raft to paddle a transect across the Rowan Landslide pond and recorded depths with a depth meter at each location coordinate in the transect. This method of obtaining bathymetry may only be necessary for ponds that have a clear gradient from shallow shorelines to a deep center. However, we found that the depths across the Rowan Landslide pond only varied by a meter and the pond was only 3 meters at maximum depth. At the Beaver Landslide pond, we were able to walk into the pond using chest waders and determined that the depth was too shallow and not variable enough to choose a true deepest point for coring. Even with this information, however, it was challenging to determine the best places to core on the Beaver Landslide pond. For as far and wide as we could walk, we attempted to choose the deepest areas of the pond. Locating the deep areas of the pond will be easiest in mid-Winter when the pond has filled from the rainy season and is still relatively easy to bushwhack to before the growing season begins.

In each coring session, I used a Livingstone Core provided by Dr. Doug Clark of Western Washington University. The Livingston Core is used to manually penetrate organic layers and sediment. Coring with Livingston cores has been especially useful in gathering radiocarbon samples from glacier forefields (Menounos, 2009). In the United States, the Livingstone Core is the most common tool for gathering sediment cores from ponds (Wright, 1967). Cores extended onto the Livingston Core range from 1-2m and are used in accordance with the goals of the coring. For instance, if we suspect that landslide debris is below thick layers of root mass, top soil, and peat, then we would use longer cores. A casing, such as a 10 in. diameter PVC pipe can be used to stabilize the hole that is being cored. Once the casing is at least a few inches in the hole, one can core as deep as cores are available. The Livingstone Core uses a square rod, which is given a quarter twist when lifted before sampling (Wright, 1967). A piston is held in place at the top of the core by one person while another person drives the rod into the core. We used a coring raft, which is used to core ponds that are deeper than chest waders, on one of the ponds on the Rowan Landslide (Fig. 8 and 9). The raft structure is composed of two inflatable kayaks, which are set parallel to one another, and a wooden platform that sits on top of the kayaks. The wooden platform has an approximately 10 in^2 square hole through which the casing and/or core barrels are placed. In the lab, I cut the core samples in half, vertically, to inspect for wood samples (Fig. 10 and 11). Ideally, small twigs are used for radiocarbon dating. Twigs would not survive long unless entombed in landslide debris, which would hypothetically make them excellent for providing specific dates (Malick, G., *per comm.,* 2016). We obtained a twig in the field from the bottom of Core 3 (Fig. 12).

Once we successfully sampled cores from the pond, the samples were immediately duct-taped on both ends. It is important to remember to mark the push number (the number of core barrel pushes into the pond sediment) on each core barrel to indicate the depth at which the sample was taken. It is also helpful to mark the ends of the barrel that indicate the top and bottom of the push. On my field day on the Rowan Landslide pond, however, I neglected to indicate the push number as well as the top and bottom of each core barrel. Fortunately, the depth at which the samples were cored, or the orientation of the core, do not affect the dates of the landslides. Our goal was to simply gather wood samples from the landslide debris. However, it is helpful to know the relative depth of the wood samples in order to decide which samples are the most likely to produce representative dates of the landslide event. We determined that the core with the least amount of sediment was our third and final push, since we lost sediment from that core in the field. We did not successfully retrieve sediment from our first meter of pushing, so we figured the core with the most sediment must have been our second push (Fig. 10). The tops and bottoms of Push 2 and 3 were determined by comparing sediment. I designated the bottom of Push 3 by correlating it with the poorly graded, gray sand we sampled from the bottom of the core in the field (Fig. 11). In addition, the sediment at the top of Push 3 matched the sediment at the bottom of Push 2.

From the Rowan pond cores, I recovered two wood samples from Push 2 and one twig sample from the bottom third of Push 3. I avoided samples from the very top and very bottom of each core in case organics from the top of the coring (the bottom of the pond) fell in the hole between pushes. I decided to obtain radiocarbon dates on one wood sample from 74 cm deep in Push 2 (thus, 1.74 m below the bottom of the pond) and the twig sample from the bottom third of Push 3 (Fig. 11, 12).

5.3.2 Beaver Landslide Pond Sampling

The Beaver Landslide has a substantial sag pond, which is easily identified in LiDAR (DNR, 2016). The Beaver Landslide is estimated by the numerical model to be ~5500 years old. Dates on this landslide would provide useful ages to calibrate the numerical model. The sag pond is a promising target, because it is large, perennial, and likely contains organics that washed into the pond sediment following the landslide event. We attempted to hand core the Beaver Landslide pond (Figs. 13-15). This pond is seasonally full and should be attempted to auger around times of higher precipitation in order to determine the deepest point. I identified the deepest point as the northeastern most point of the pond, which was also filled during the dry season. This implies that the northeastern section of the pond is the deepest (Fig. 16). However, we were unable to manually push through a dense layer of logs in the bottom of the pond.

5.3.3 Pond Coring Limitations

In addition to dense log layers, coring ponds is limited by the amount of time and equipment required. The Rowan Landslide pond was deep enough that we needed a raft. This required the two kayaks, pumps, the wooden platform, the core barrels, the casings, the tool box, and personal gear. With the hands of seven people, we carried this gear from the Washington Department of Natural Resources (DNR) gate, a quarter mile down a dirt road, and then bushwhacked through dense brush for another quarter mile to the launch site. The preparation process took nearly four hours, while the coring itself took only an hour or two. We faced a similar dilemma with the Beaver Landslide pond having to carry coring gear from the DNR gate to the site a half mile away. With this time and labor commitment in mind, I suggest future coring endeavors should obtain a gate key from the Washington DNR if possible.

6. GIS and Aerial Imagery Pond Protocol

Using inspiration from Adam Booth's (*in press*) GIS gully-finding protocol, I developed the beginning phase of a protocol for remotely identifying ponds. I used LiDAR and a point return intensity analysis to locate bodies of water in the NFS River valley. Compared with aerial imagery, it is clear that this method needs to be refined, but shows promise as a useful reconnaissance tool.

6.1 LiDAR Scouting

An intuitive approach to identifying ponds is to determine flow direction and areas of accumulation using GIS hydrology tools. However, even when smoothed with curvature, LiDAR is often too high resolution for this method to be useful. Rather than obvious "sinks" being filled in the LiDAR's data elevation model (DEM), hydrology tools show no clear pattern of flow direction or accumulation (Fig. 17 and 18). First, in order to smooth out microtopographic features, I smoothed the LiDAR DEM (Slaughter, *per comm.,* 2016). Applying flow direction and accumulation to a smoothed LiDAR did make head scarps of landslides clear in the DEM, but it is not helpful for sag ponds. I also tried to use a standard deviation of slope to identify completely smooth areas, which would hypothetically be sag ponds. The standard deviation method was ineffective in identifying sag ponds; even sag ponds I had identified in the field. Finally, I attempted to use curvature as a way to identify concave "bowls", which would hypothetically be sag ponds. Assessing curvature effectively identified large head scarps, but did not successfully identify known ponds.

6.2 Point Return Analysis

I detected potential sag ponds by locating bodies of water with return points. In a USGS report on point density analysis, the authors used focal sum of point returns to identify bodies of water (Worstell et al., 2014). For instance, the highest intensity, or return points of LiDAR laser beams, are in areas of flat topography where beams hit the surface and return directly to the sensor. The intensity is moderate in areas of rougher topography and is the lowest in bodies of water where laser beams scatter instead of returning to the sensor (Worstell et al., 2014). This intensity layer can be grouped as a raster file with the LiDAR dataset, such as the 2014 Oso LiDAR from the Puget Sound LiDAR Consortium (PSLC). By conducting a Boolean analysis on the intensity layer, one can then designate the lowest return values in the intensity layer.

6.3 Point Return Analysis and Aerial Imagery

Finally, I combined the LiDAR point return analysis method with aerial imagery assessment. Even significant ponds will be missed on the 2014 LiDAR Data Elevation Model (DEM) if they were filled with water when the LiDAR was flown (PSLC, 2014). Standing water will appear "flat". National Agriculture Imagery Program NAIP imagery more clearly shows sparse vegetation as well as areas of standing water. In scouting for ponds on NAIP, I attempted to verify high density point returns with sparse vegetation and visible standing water on imagery.

7. Results

After attempting to gather radiocarbon samples from three different landforms (terraces, gullies, and ponds), I obtained four radiocarbon samples. I also determined the best landforms to target for different ages of landslides. Here, I will discuss my results from radiocarbon sampling as well as my remote analysis of sag pond locations. With three landforms used to date landslides, I obtained ages most successfully from terraces and ponds. Known landslide ages from gully samples help to understand and verify the pond core values and vice versa.

7.1 Rowan Landslide

Though I was unable to collect gully samples for dates, LaHusen et al. (2016) obtained gully dates on landslides that average the Rowan Landslide to be 518 cal ^{14}C yr B.P. I dated two samples from the Rowan pond cores. The pond cores date the Rowan Landslide to be between 91-358 cal ^{14}C yr B.P (Table 1). These dates are younger than the average of dates obtained elsewhere on the landslide. However, these new dates likely provide a minimum age and show that ponds are useful for providing age constraints. If we had recovered in-tact stratigraphy and were reasonably sure that we were in the landslide debris, these ages could be more trustworthy as the landslide age. However, because we did not maintain stratigraphy, these ages provide a minimum age. In addition, we also need to consider the possibility that we dated modern wood in the pond.

7.2 C-Post landslide

Two wood samples from the terrace that cross-cuts the C-Post landslide provided numerical dates that post-date the landslide event. DirectAMS radiocarbon dated the two samples, giving ages of 4,146-4,250 cal ^{14}C years B.P. and 4,021-4,125 cal ^{14}C years B.P (Table 2). These ages are the first dates providing any absolute age information on the C-Post Landslide, which the roughness model estimates to be 1,683-3,431 cal ^{14}C years B.P. years old (Table 3). The C-Post Landslide terrace dates are older than the estimated ages C-Post Landslide. We trust that these dates are a minimum age, because the terrace is directly adjacent to the erosional contact with the landslide toe. The terrace must post-date the landslide, because the river that laterally eroded the toe of the landslide would have also eroded the terrace (LaHusen, *per comm*., 2016).

7.3 GIS and NAIP Imagery Analysis for Pond Locations

Even with the best LiDAR data available, LiDAR data alone is unreliable for remotely sensing sag ponds. I determined that the most effective way to locate potential ponds is by using return LiDAR points, or intensity rasters, to point out bodies of water and verifying them with aerial imagery, such as NAIP.

A major limitation of both LiDAR and Google Earth is the time at which the data was collected: rainy season or dry season. LiDAR is able to shoot through vegetation, but not water, which makes standing water appear flat. Therefore, if LiDAR was flown during a rainy season, the flat standing water of perennial ponds does not provide an elevation drop large enough to distinguish as a potential pond. Google Earth can also be limited in its ability to show perennial sag ponds of landslides. All modern satellite imagery, for example, does not show water in the Beaver Landslide pond. However, my site reconnaissance showed that there was at least a half meter of standing water at the northern boundary of the pond. The inability to see this pond on aerial imagery could thus be because satellite imagery is taken in the summer. In the summer there is less cloud coverage, but there is also less standing water in the landscape. In addition, the growing season has peaked by the summer and can block the view of standing water in these ponds.

I applied the point return analysis in GIS method to the Oso 2014 data, which included a rasterized intensity layer of LiDAR point returns. I then identified the lowest values of point returns, and interpreted these to indicate water bodies (Fig. 19). While I have created a prototype for a protocol, this protocol must be refined before use as a practical tool. This method did not effectively locate the field-verified Rowan Landslide ponds (Fig. 20), but did identify the Beaver Landslide pond (Fig. 21). I also located a promising potential pond further upslope, which may be ground-truthed as well (Fig. 22).

8. Discussion

In my efforts to gather ages on historic landslides in the NFS River valley, I found that there are multiple approaches to gather radiocarbon samples from landslides; each with their own strengths and weaknesses. Comparing both the ages and methods to obtain these ages is useful for discerning which approach to take when dating landslides. In addition, I present here advice for determining the best approach to obtaining radiocarbon samples to date landslides.

8.1 Landslide Sampling Methods

In efforts to gather older landslide dates to better calibrate the age-roughness model, I quickly determined that sampling gullies was ineffective. In theory, gullies are the most direct feature into landslide debris. However, because older landslides are more diffuse, gullies are overgrown and subdued thus making obtaining wood samples challenging to nearly impossible.

The second sampling method of dating terraces proved useful for gathering date information on a landslide of unknown age: the C-Post Landslide. Radiocarbon ages from terraces define the age that the river cut into a toe or body of a landslide. These

are minimum ages and are not well-suited for use in the age-roughness curve, because they do not provide a numerical age of the landslide event. However, terrace dating can be used in conjunction with cross-cutting relationships to verify relative ages and importantly, to consider what parts of the calibrated curve need further adjustment. Hypothetically, if we can identify a cross-cutting relationship that shows the C-Post Landslide cutting across an older landslide of a known age, then we can use the older landslide as a maximum age.

Coring ponds has shown to be a useful method for dating landslides. I was able to gather dates that likely provide a minimum age constraint on known dates of the Rowan Landslide. If we had recovered in-tact stratigraphy, providing better assurance that we were in fact cored into the landslide debris proper, these ages could be more trustworthy as the landslide age. However, because we did not maintain stratigraphy, these ages provide a minimum age. We also cannot, at this time, rule out the possibility that they are modern wood.

Furthermore, the difference in ages may be attributed to the age of tree if the difference falls within the margin of error of the age ranges on the Rowan Landslide. If greater than the margin of error, then the dates from the pond may be representing either significantly older trees than those dated in the gullies, or trees younger than the age of the slide event. If the latter, then our pond core may be unreliable. If the former, then our pond cores provide useful dates for validating both the average age of the Rowan Landslide as well as the age-roughness curve. While coring the ponds of the Beaver landslide would provide viable dates of the event, we were physically unable to core into this pond because of a packed layer of logs. This observation is important to remember, because it is likely that most ponds on old landslides will have had time to gather a significant amount of fallen trees. For future work, this pond (and old landslide ponds alike) will need a power auger to break through the wood layer. For most ponds, it is helpful to identify the deepest part of the pond in order to minimize the layers needed to core through to reach the landslide sediment.

8.2 Advice for Determining Best Methods to Sample Landslides

To support future research, I recommend these steps for determining the best methods to sample landslides: Ensure that landslides are mapped in a given complex or site area. If the estimated ages are unknown, it is useful to first identify cross-cutting relationships to determine relative ages. To begin gathering dates, determine which landslides are a priority to date. If younger landslides are a higher priority, then the best method for sampling will likely be obtaining wood samples from gullies in the slide debris. GIS analysis of curvature, slope, and drainage can help remotely identify gullies prior to field work (Booth et al., *in press*). If older landslides (approx. >2000 years old) are a priority, coring ponds may be a more effective sampling method and can be used alone or in conjunction with terrace sampling. In developing an age-roughness curve with a wide range of ages, both

young and old landslides may be a priority. In this case, decisions should be made according to time and financial capabilities. For example, it may be the most efficient to begin efforts on dating gullies of relatively young landslides (<2000 years old) and any landslides that are post-dated by river terraces. For all landslides, each method should be considered if the primary method for a given landslide does not work.

I focused on first identifying promising site locations on public land. In the case of the NFS River valley, I had access to all Washington DNR land. Some of the most promising sites are on private land, thus, with more time, and in future studies, researchers should attempt to gain access to these private lands.

8.3 Advice for Identifying Ponds in a Landslide Complex

I was able to remotely identify two known ponds using the protocol, but did not remotely identify two other known ponds. While I am encouraged that the protocol devised for this study worked for a subset of ponds, this method needs to be refined for practical use in future research.

Coring ponds may be the most effective method for dating ancient landslides whose gullies are diffused and over vegetated, but it is crucial to first remotely identify as many ponds as possible on landslides. One should note that rotational and long runout landslides reliably contain long-term sag ponds that formed at the time of the slide event whereas shallow or translational failures rarely do. I discovered two main methods for identifying ponds on rotational, deep-seated, ancient landslides: point return density analysis and aerial imagery. The first and most time efficient attempt to identify ponds is to use aerial imagery such as NAIP. Some ponds, such as the Rowan Landslide ponds, are easily identified on aerial imagery (Fig. 7). However, some ponds, such as the Beaver Landslide pond, don't even appear to hold water on the aerial imagery (Fig. 13, 16). Therefore, it is useful to determine bodies of water using a LiDAR DEM intensity layer. The lowest intensity values correspond with bodies of water, which scatter LiDAR laser beams away from the sensor. By locating areas of high density low return values from the Boolean raster, one can find the same locations on aerial imagery. Then, depending on when the LiDAR was flown, one can determine if there could feasibly be a pond in that location even if there was not water present when the aerial imagery was taken. Once ponds (or gullies or terraces) are identified remotely, all features should be ground-truthed on a site reconnaissance prior to conducting field work.

I used this LiDAR and NAIP Imagery analysis to test this protocol. I discovered that using LiDAR return points to locate bodies of water does not always highlight sag ponds. For example, two known ponds (one on the Rowan Landslide and one on the Beaver Landslide) showed different LiDAR return signatures. In this method, the Beaver Landslide pond was lit up by a cluster of low value return points (Fig. 21). However, the Rowan pond did not contain low return points (Fig. 20). This could be

because the Rowan Landslide pond had less water than the Beaver Landslide pond at the time the LiDAR was gathered. Low return values that do not signify ponds, may be identifying relatively small sinks on the surface where surface water accumulates.

Using point return analysis, I did, however, identify a potential pond location on the Beaver Landslide (Fig. 22). I used point return analysis to locate potential bodies of water. Then, I compared the site on NAIP imagery with that of the Beaver Landslide pond, which I had previously attempted to core. I believe this site may be a promising location to core, because it looks similar to that of the Beaver Landslide pond both on NAIP imagery (short, light green vegetation) and on point return analysis (sag pond depression with light blue clusters of low point return). However, because I was unable to manually core the original Beaver Landslide pond, this pond may also be resistant to manual coring. I also tested this protocol on the Rowan Landslide ponds, which I had field verified. While point return analysis showed points of water, there was not a significant cluster to easily identify a body of water. Therefore, this protocol is not yet practically useful. However, I am encouraged that, with refinement, this tool can be used to remotely identify ponds for field work.

9. Conclusions and Future Work Recommendations

In this project, I explored the different methods of gully, terrace, and pond core sampling of landslides. In an effort to understand the frequency and subsequent risk of landslides in the NFS River valley, I used these methods to contribute two new numerical ages to the age-roughness curve and two numerical minimum ages to the C-Post Landslide (LaHusen et al., 2016; Booth et al., *in press*). I applied the method of pond coring, which was a new approach in the NFS, to the Rowan and Beaver Landslides. While pond coring was successful on the Rowan Landslide pond and showed the feasibility of the method in this valley, I was unable to manually core into the Beaver Landslide pond. I presented a method of remotely identifying sag ponds by analyzing point return density on LiDAR in conjunction with aerial imagery. It is my recommendation that this method be further developed and used as a means to remotely locate and prioritize sag ponds on ancient landslides. Future research should consider focusing on the oldest landslides in the NFS River valley in order to calibrate the age-roughness curve and, ultimately, communicate precise risk to the landowners and county managers.

Determining the frequency of landslides in the NFS River valley is a significant undertaking and will require more radiocarbon dates on landslides to refine and/or validate the age-roughness curve. There are a few next steps that will support this ongoing research. First, I recommend that older (>5000 years) landslides continue to be a focus in the NFS River valley. I have identified an example of a pond that could potentially be ground-truthed (Fig. 22). However, to further refine this

technique I suggest future researchers develop a stronger method for remotely identifying ponds. At the least, future research can continue to use both aerial imagery and LiDAR point return to locate ponds. In addition to remotely identifying and ground-truthing ancient pond locations, I recommend future research to identify all fluvial terraces adjacent to landslide deposits. This approach has already been taken on the landslides immediately near the Oso Landslide, which is where the valley is the narrowest and the NFS River interacts with the hillslope the most (Booth et al., *in press*).

In this project, we provided minimum dates of the C-Post Landslide from a terrace, but it would be more valuable to obtain a numerical date from the landslide debris. There is a large gully on the C-Post Landslide that lies within private land (Fig. 23). This gully appears large on a gully shapefile (Booth, *per comm*., 2016) and may be useful for locating wood samples on this landslide. Future research should consider contacting the landowner for access to this gully, because it is estimated to be an older landslide and would help validate the age-roughness curve (Booth et al., *in press*) and place tighter limits on landslide frequency.

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Figures

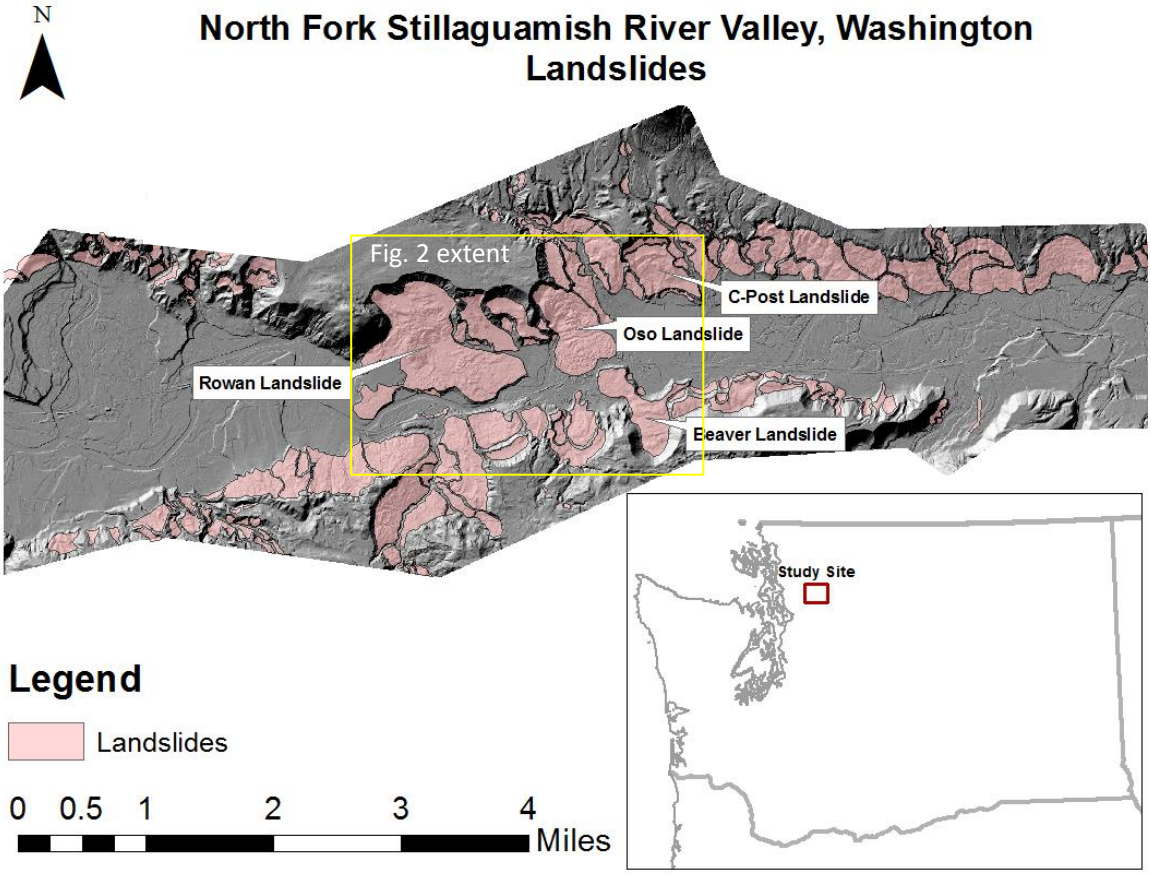

Figure 1. Map of landslides in the North Fork Stillaguamish (NFS) River, Washington, USA, using 2014 Oso Lidar (PSLC, 2014) (Booth et al., *in press*). Insert map shows valley location in Washington State.

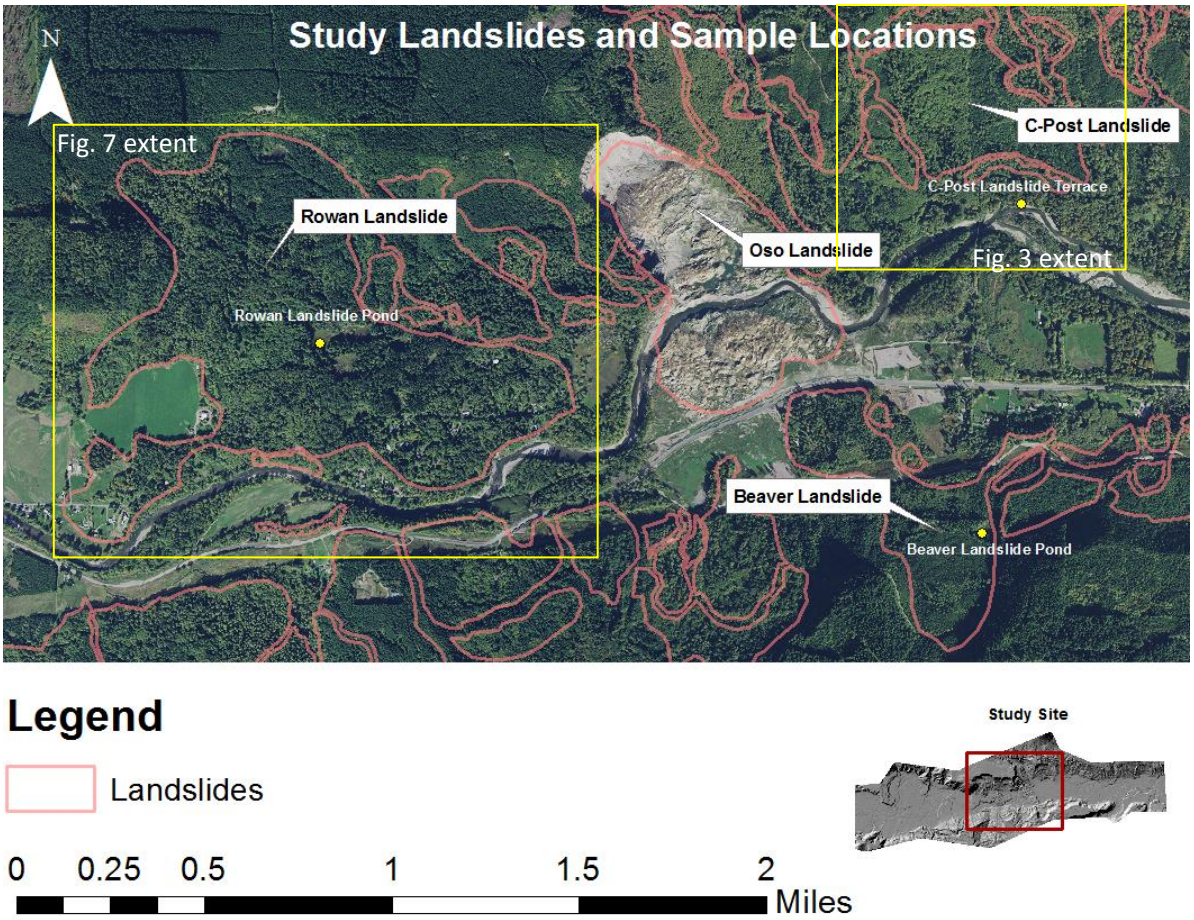

Figure 2. Site map of the three study landslides and their sample attempt locations. Landslide shapefile by Booth et al. (*in press*). Base map is the 2015 NAIP aerial imagery.

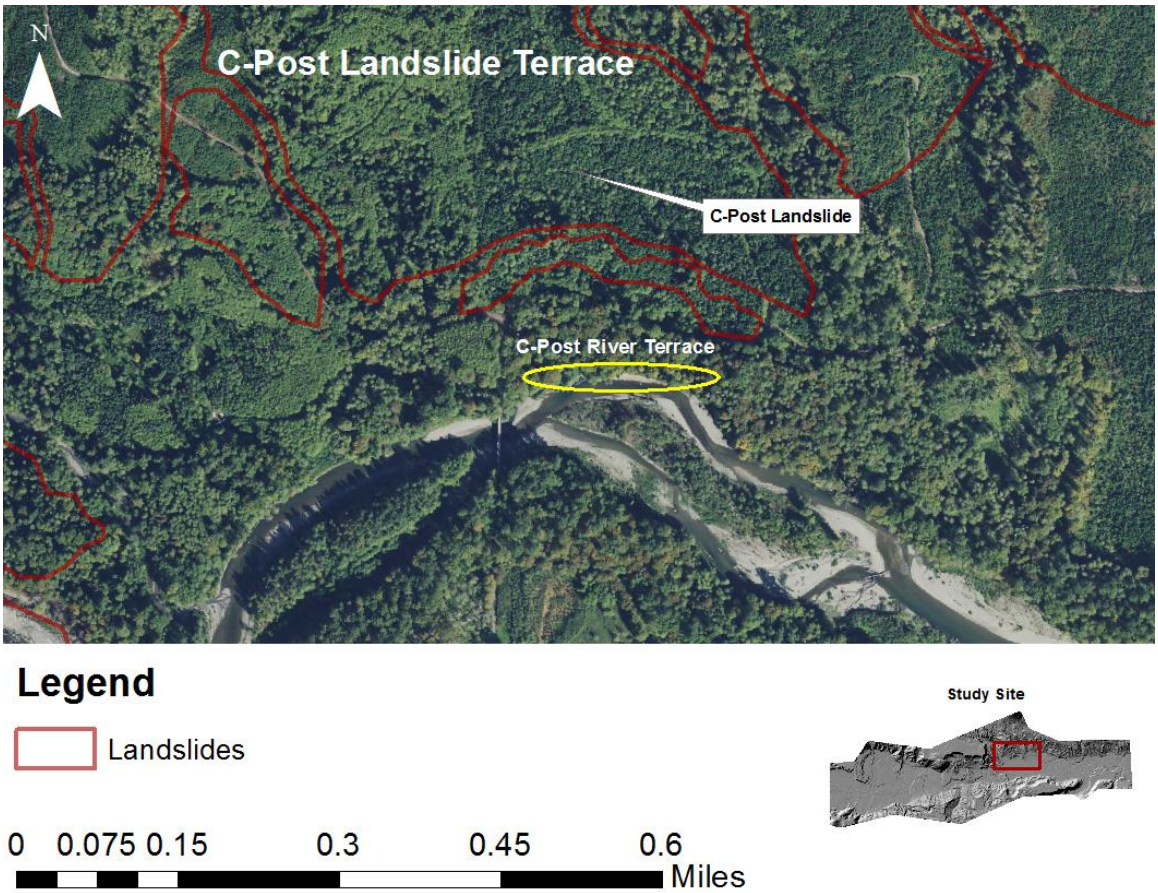

Figure 3. C-Post Landslide Terrace location on 2015 NAIP imagery.

Figure 4. Terrace along NFS River carved into C-Post Landslide. View facing North from the NFS River of the C-Post Terrace. Graduate student Sean LaHusen for scale.

Figure 5. Professor Alison Duvall, University of Washington, standing beside the C-Post Terrace.

Figure 6. Graduate Sean LaHusen holding beverage can for scale at in situ wood samples from the C-Post Terrace (sample: 16CPOST1D).

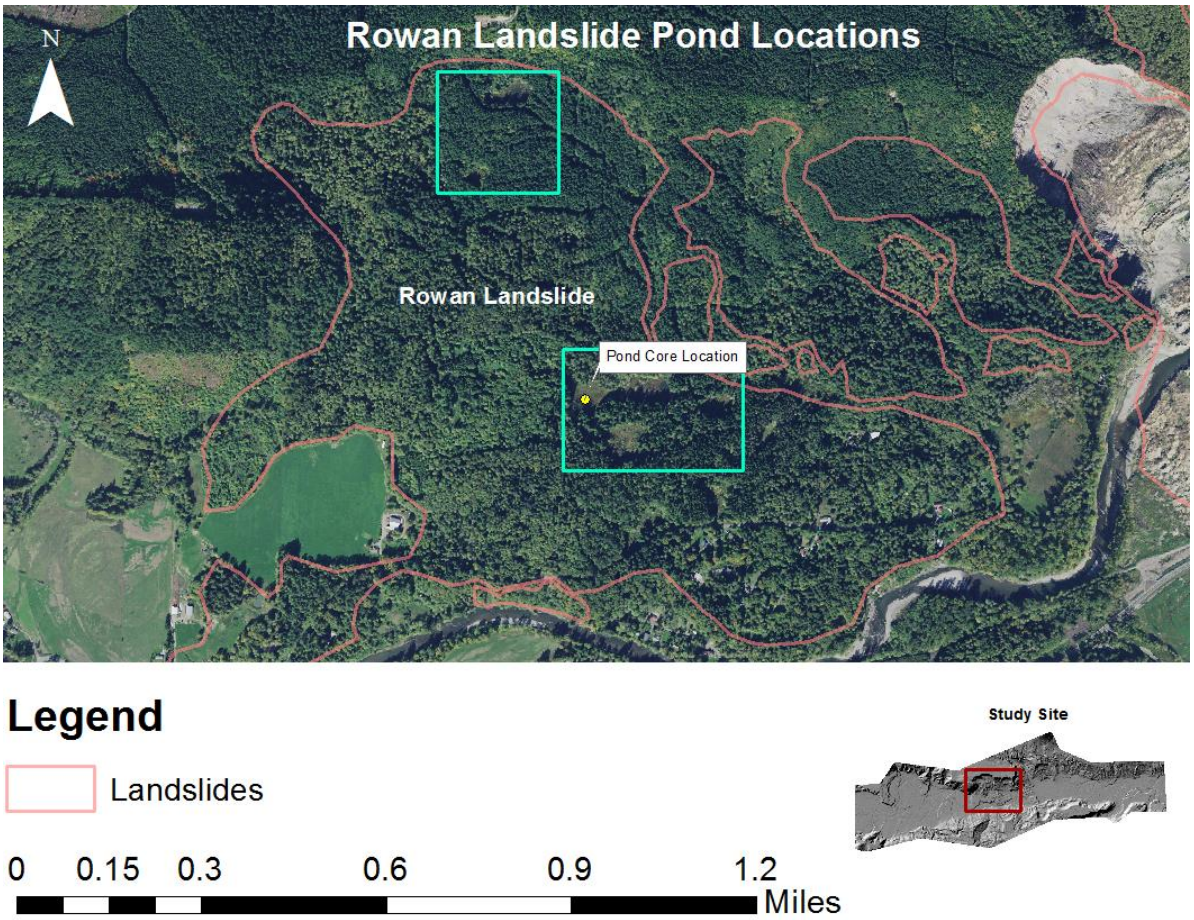

Figure 7. Site map of the Rowan Landslide and the pond core location. Boxes surround five ponds that are visible on aerial imagery. Landslide shapefile by Booth et al. (*in press*). Base map is the 2015 NAIP aerial imagery.

Figure 8. Pond coring raft setup (courtesy of Doug Clark) on the Rowan Landslide pond. Photo by Hannah Letinich.

Figure 9. Coring raft on the Rowan Landslide pond. Pictured: Geoffrey Malick, Western Washington University, Dr. Doug Clark, and the author, Susan Wisehart. Geoffrey Malick is holding the core barrel, Dr. Clark is holding the casing in the core hole, and Susan Wisehart is holding the piston wire. Photo by Hannah Letinich.

Figure 10. Push 2 Core from the Rowan Pond. Depth is from 1 - 2 meters below the bottom of the pond.

Location of wood sample RP2.2

Figure 11. Push 3 Core from the Rowan Pond. Depth is from 2 - 3 meters below the bottom of the pond.

Location of twig sample RPTWIG1

Figure 12. Dr. Doug Clark on the Rowan Landslide pond holding the bottom of Push 3, which contained an ideal twig (sample: “RPTWIG1”) for radiocarbon dating. Photo by Hannah Letinich.

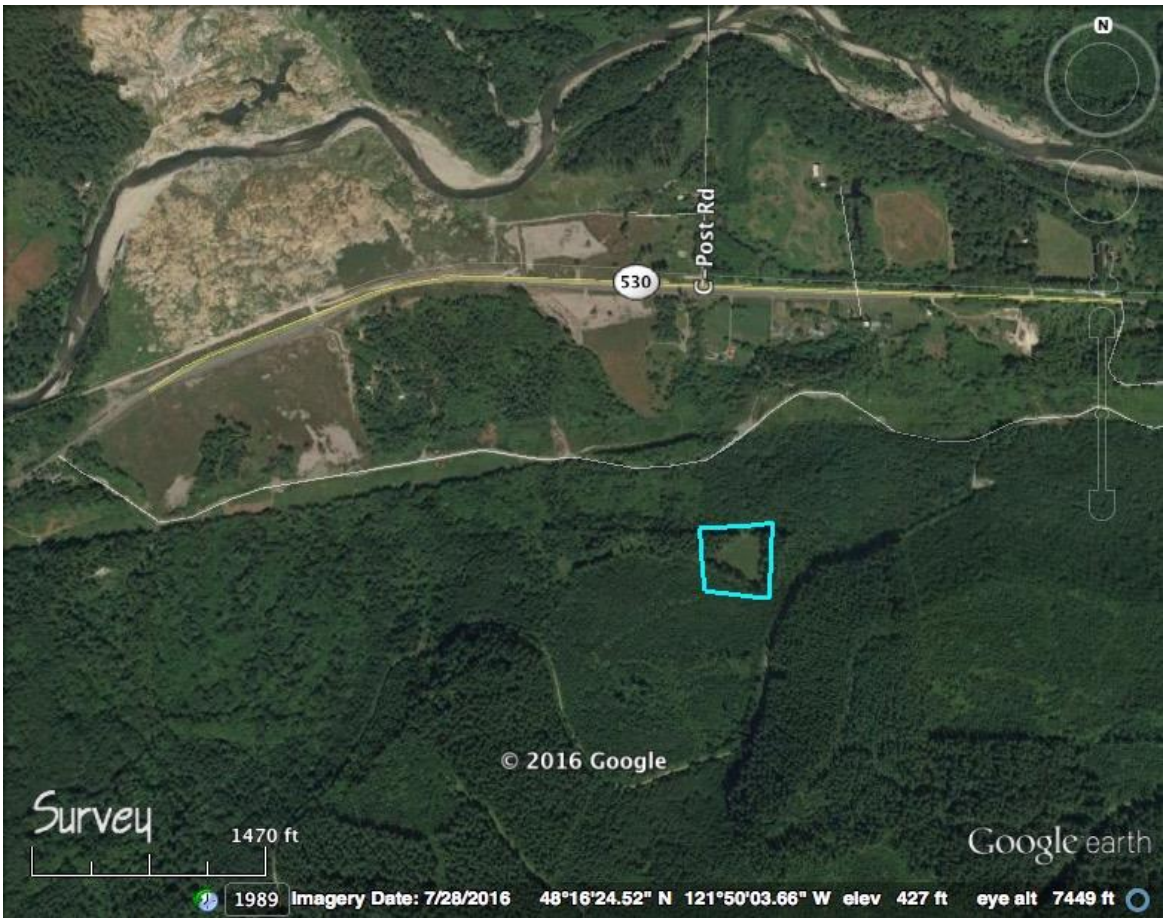

Figure 13. Site location for the Beaver Landslide pond.

Figure 14. Field work on the Beaver Landslide pond. Pictured is Geoffrey Malick and Susan Wisehart about to attempt a manual pond core with chest waders. Photo was taken on December 2, 2016 and shows the pond filled with water from recent precipitation. Photo by Valerie Bright.

Figure 15. Geoffrey Malick and Susan Wisehart attempting a pond core on the Beaver Landslide pond. Wire is connecting top of the core to the piston, which is held taught to vacuum seal sediment into the core barrel. Black pipe is the casing for the barrels. Photo by Valerie Bright.

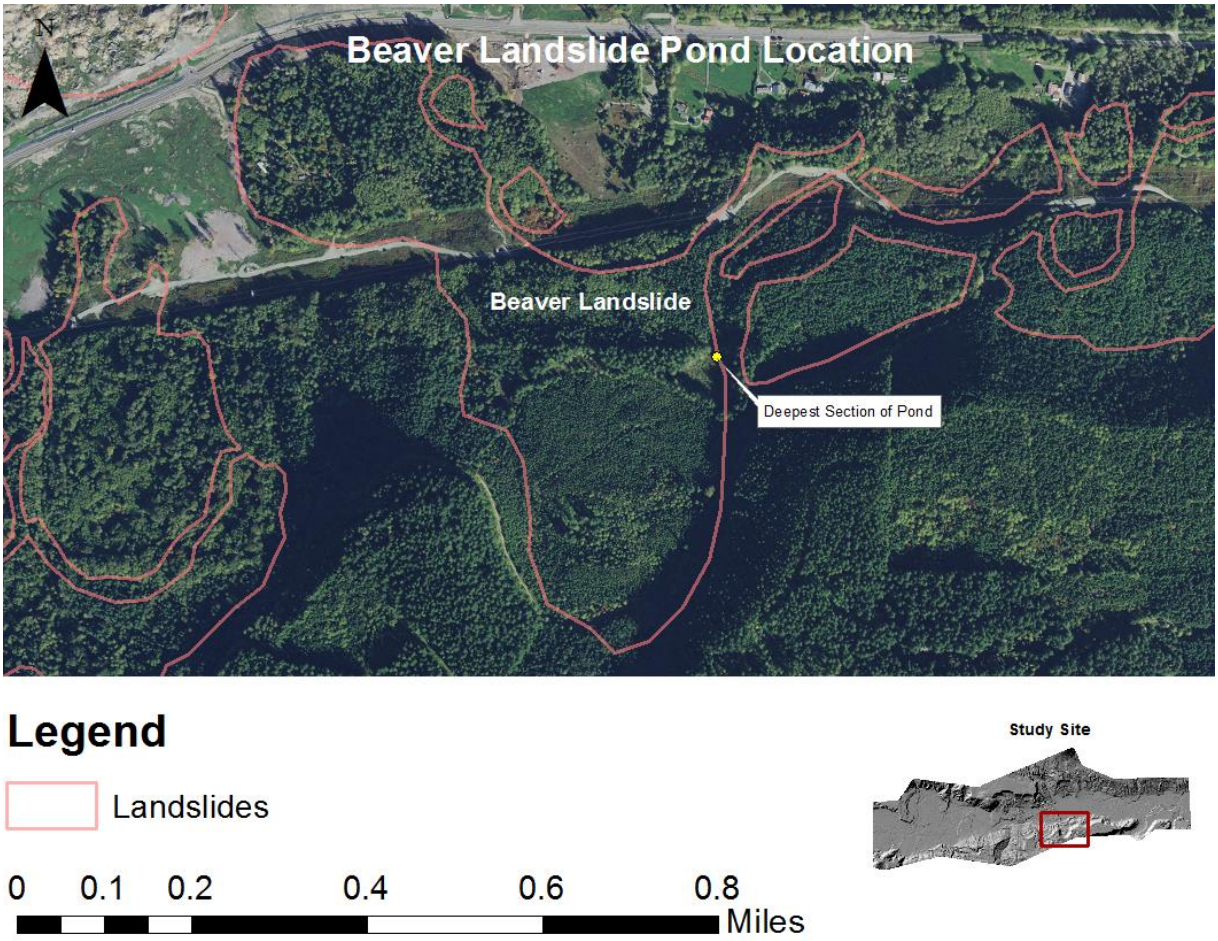

Figure 16. Site map of the Beaver Landslide, pond location, and approximate deepest part of pond. Landslide shapefile by Booth et al. (*in press*). Base map is the 2015 NAIP aerial imagery.

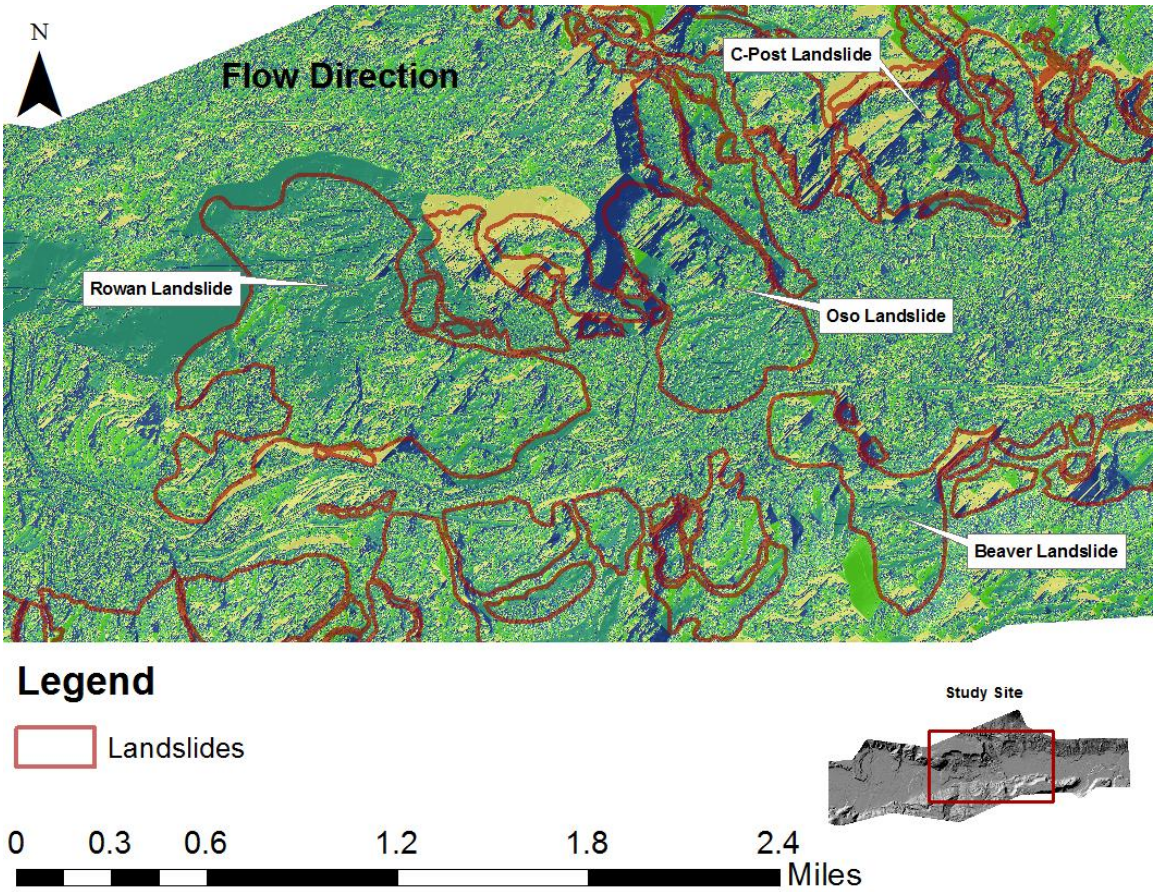

Figure 17. Flow Direction map, using 2014 Oso Lidar (PSLC, 2014). Colors indicate varying directions of flow.

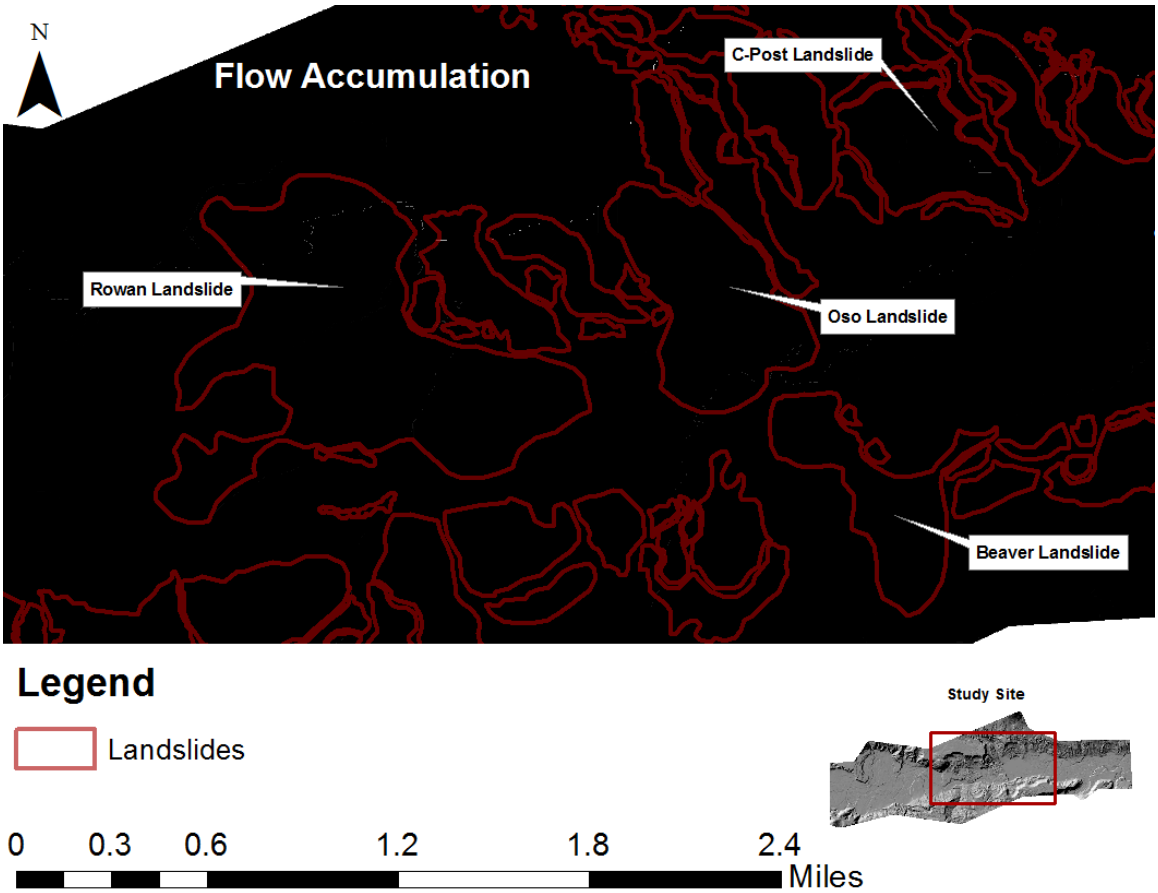

Figure 18. Flow Accumulation map, using 2014 Oso Lidar (PSLC, 2014). Accumulation on high resolution LiDAR results in this single color map, which is not useful to locating potential ponds.

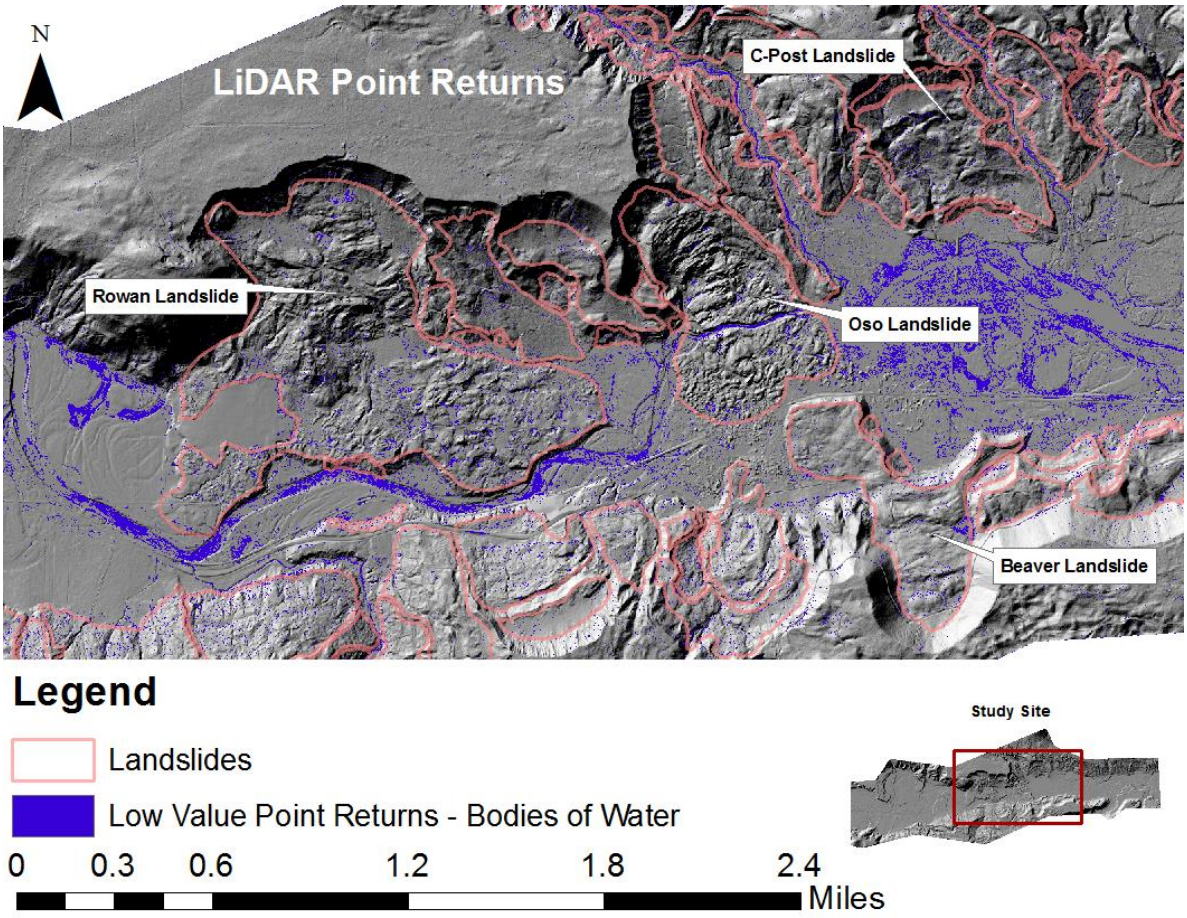

Figure 19. Point returns locating bodies of water, using 2014 Oso Lidar (PSLC, 2014).

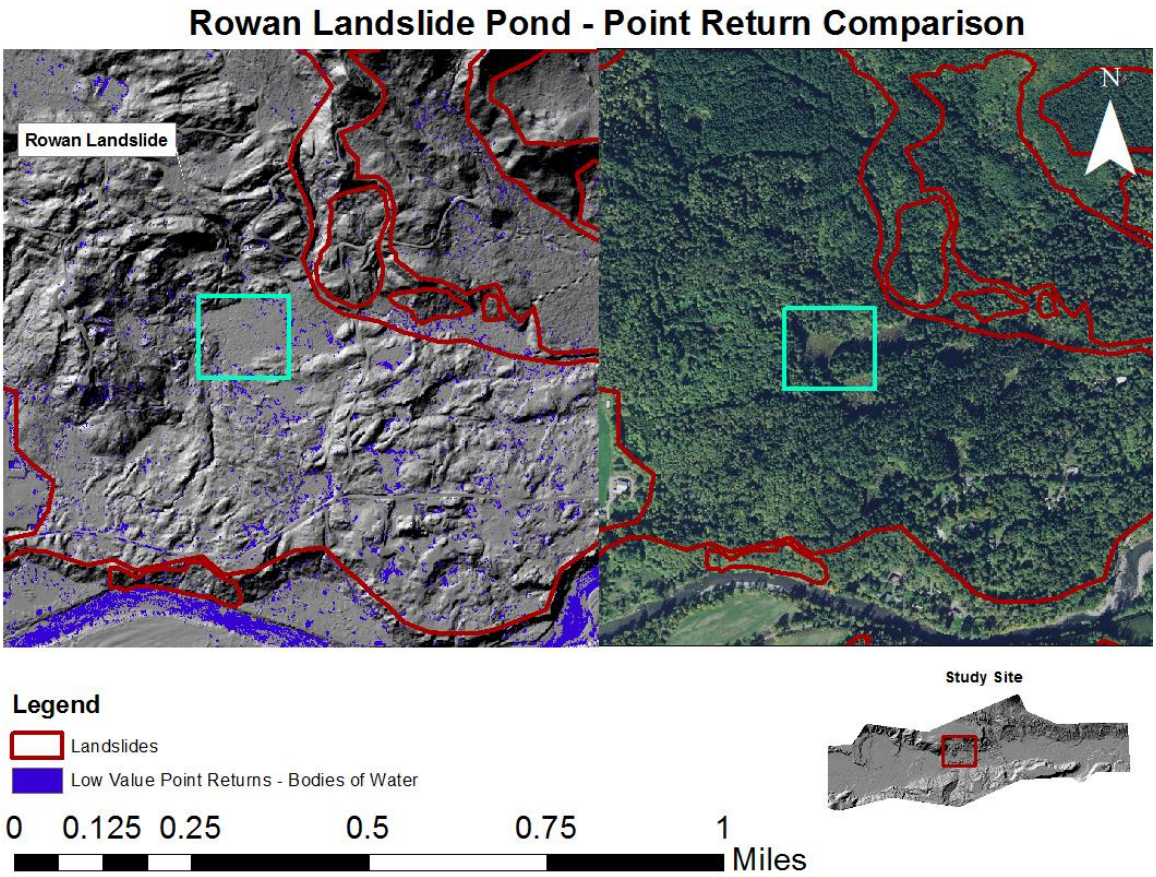

Figure 20. Attempted coring pond location on Rowan Landslide, using 2014 Oso Lidar (PSLC, 2014) and 2015 NAIP imagery. Aerial imagery indicates bodies of water while return points do not.

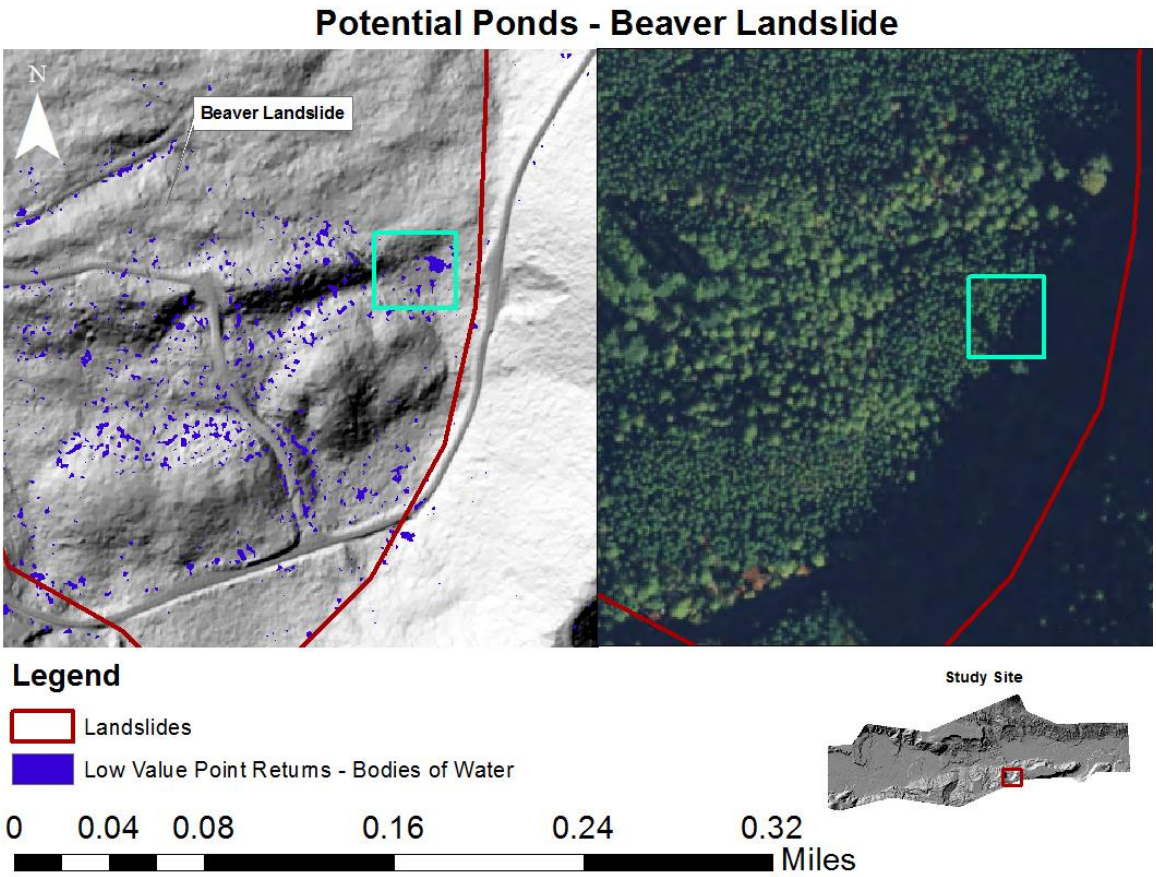

Figure 21. Potential coring pond location on Beaver Landslide, using 2014 Oso Lidar (PSLC, 2014) and 2015 NAIP imagery. This shows a comparison of blue specks (low point return values) in the left image to the location of a known pond: The Beaver Landslide Pond. Point return analysis verifies water presence, but does not usefully identify bodies of water on its own.

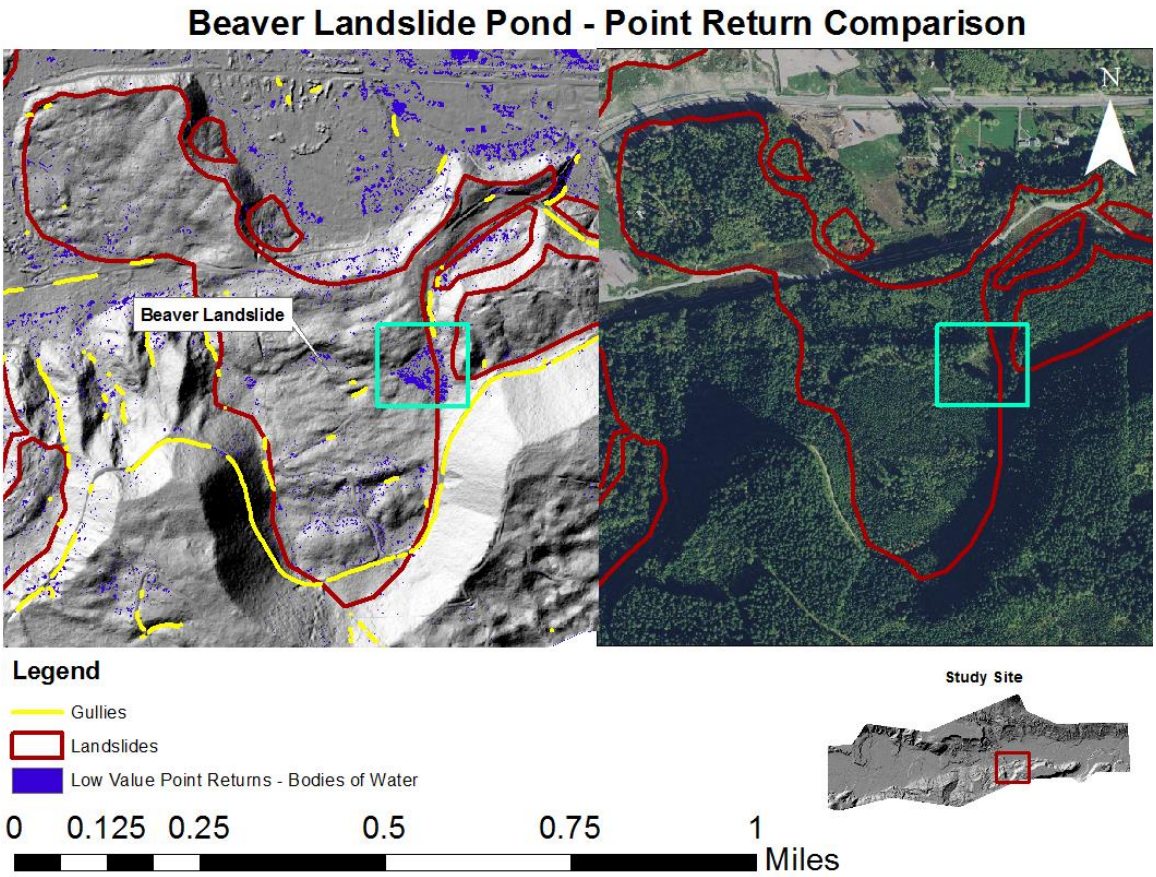

Figure 22. Attempted coring pond location on Beaver Landslide, using 2014 Oso Lidar (PSLC, 2014) and 2015 NAIP imagery. Return points indicate body of water while aerial imagery does not.

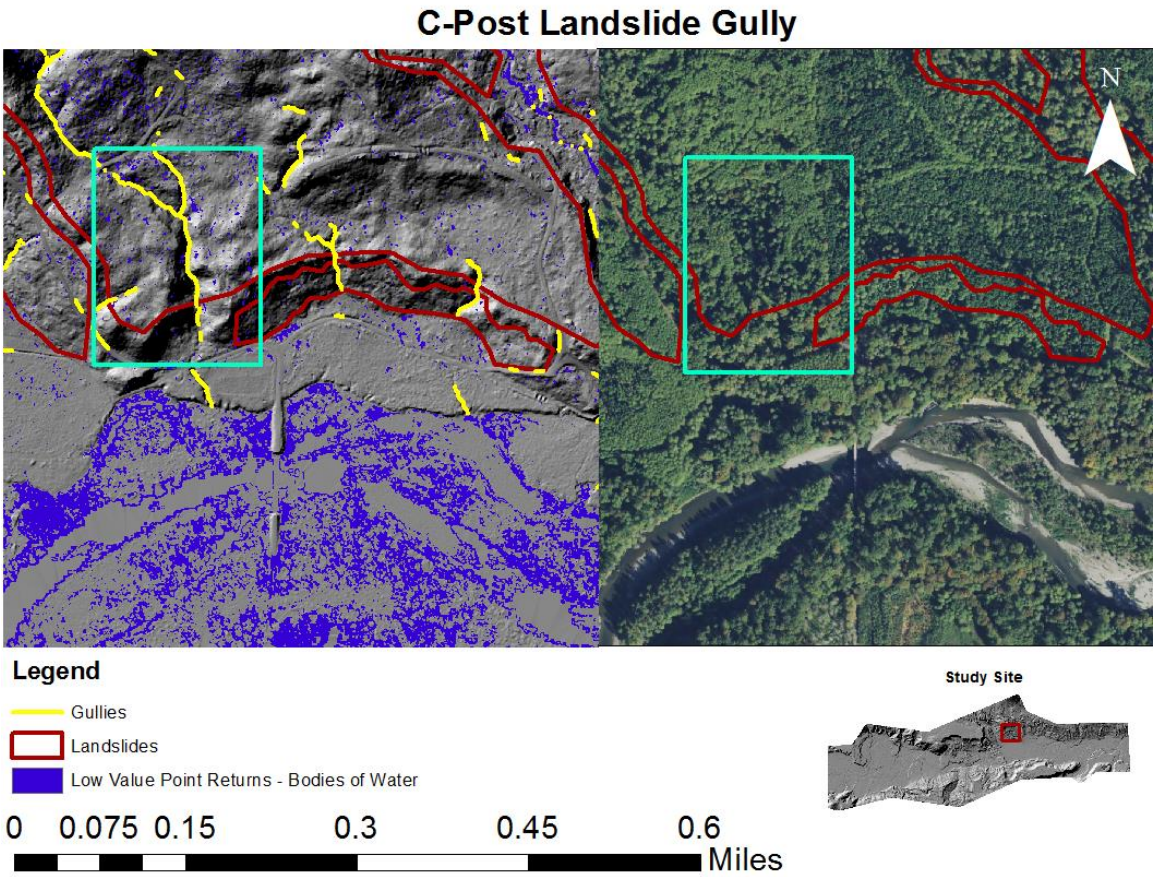

Figure 23. C-Post Landslide gully location that sits within private land, but could be promising site for obtaining wood samples (PSLC, 2014; NAIP, 2015).

Table 1. Radiocarbon and Calendar Ages for the Rowan Landslide Pond. Note that these ages are difficult age to date in carbon record. Around 100 years is high uncertainty.

Sample Location	**Sample Name**	**Radiocarbon Years (^{14}C years B.P.)**	**Calibrated Age Range(cal ^{14} years B.P.)**	**Certainty (%)**
Rowan Pond	RP2.2	179	203-358	95.4
Rowan Pond	RPTWIG1	65	91-325	95.4

Table 2. Radiocarbon and Calendar Ages for the C-Post Landslide terrace.

Sample Location	**Sample Name**	**Radiocarbon Years (^{14}C years B.P.)**	**Calibrated Age (cal ^{14} years B.P.)**	**Uncertainty (years)**
C-Post Terrace	16CPOST1C	3,727	4,073	+/- 52
C-Post Terrace	16CPOST1D	3,812	4,198	+/- 52

Table 3. Predicted landslide ages from the age-roughness curve (Booth et al., *in press*). Rowan Landslide was averaged to be 518 cal ^{14}C years B.P. (LaHusen et al., 2016).

Landslide Name	**Predicted Age**	**Uncertainty**
C-Post Landslide	2,557	874
Beaver Landslide	5,579	1900