Developing an Impact Assessment of Local Air Quality as a Result of Biomass Burns

Waste to Wisdom: Subtask 4.4.1

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October 2017

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

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C I N T R A F O R

Working Paper

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CINTRAFOR
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This Working Paper is based upon a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, University of Washington 2016. This research work was supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative (BRDI) program. Award Number: DE-EE0006297. Opinions, findings, conclusions, or recommendations expressed in publication are those of the author(s) and do not necessarily reflect the view of the funding agencies.

Executive Summary

Monitoring air quality and estimating future air conditions is a challenging task due to the many influencing components. Weather conditions, geography, natural and human caused chemical input are various factors affecting the air quality locally and often great distances away. Human caused sources of emissions such as vehicle use, industry emissions, and forest management practices such as slash pile burning and prescribed burns are primary sources of pollution. Examining the impacts and pollution behavior is essential in order to manage the airshed better. Therefore, then needs for air quality assessments and forecasts include:

- Monitoring current air quality for awareness of possible high level of harmful chemicals
- Determine the sources of air pollution such as industrial plants or high traffic areas
- Examine poor air quality areas for trends and use data to project bad air quality timeframes
- Adapt current management plans such as forest and fire management, urban transportation and emission management strategies
- Adjust and revise air quality standards in order have less of an impact to humans and the environment

This study focuses on the estimating trajectory and concentration of particulate matter (PM) from burning residual slash piles left over after forest management practices and estimating PM respiration intake from the underlying human populations.

In order to catalog various slash piling methods, pile assessments were conducted across Washington state in 2014 on federal, state, and tribal lands. Piling scenarios were processed through a chemical transport modeling system and results were analyzed using GIS methods.

The analysis showed that the human intake of particulate matter as a result of residual biomass burning is heavily influenced by weather and pile burning locations. On days of large pile burning in the same locations, PM can impact less than 100 people and on a different day, PM from pile burning can impact more than 200,000 people. These findings display the need for thorough pre-burn smoke modeling to make better decisions for burn dates.

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1.1 Prescribed burn in response to increased wildfires

1.1.1 Wildfire in the western United States

In 2014-2015, Washington State experienced the largest wildfires in its history. Record setting burned area was first set in the fire season of 2014 with about 386,000 acres, only to be almost tripled in 2015 with over 1 million acres burned (National Interagency Fire Center 2014). Current research predicts an increase in wildfires with much of this to the changing climate (Little *et al.* 2010; Westerling *et al*. 2006). Earlier spring snowmelts create drier summer/fall forest conditions and drought-induced tree stress leads to favorable fire conditions. In addition to changing climate stresses, historical fire suppression has led to overgrown-stressed forest conditions. Human-caused change of the natural fire regime in the past has led to overgrown western forest systems (Agee 1993). The combination of changing climate and past forest management practices has created the wildfire conditions of the present. Changing climate with earlier spring snow melt, warmer summer days and historical wildfire suppression has led to western forests being prone to more large scale fires (Little *et al.* 2010; Westerling *et al.* 2006).

1.1.2 Forest management in responses to increased wildfire

In order to reduce the impacts from future large-scale fires, various forest management techniques have been implemented. One common forest management technique includes "thinning" to remove understory ladder fuels and reduce tree competition (Agee *et al.* 2005). While this is an effective method, it requires a sizeable work force and offers little initial financial (assuming no tree harvest) return besides reducing the risk of catastrophic wildfire damage to the area. Thinning is often performed in areas of major concern such as near towns and areas where thinning could be beneficial in creating fire breaks areas such as around roads. This technique is often more successful when implemented in tandem with other methods (Loudermilk *et al.* 2014). Prescribed burning is another tool that is used by forest managers to reduce ladder fuels and mimic a more natural occurring, beneficial, small-scale fire. Prescribed burning can be ecologically beneficial and create a more natural environment where fire suppression has altered the natural forest structure (Clewell *et al.* 2013). Timber harvesting is another effective management technique that can also offer significant financial gain. Removal and harvest of trees in an overgrown forest can reduce tree competition for resources. Although there are some controversial harvest techniques such as clear-cutting that can have detrimental habitat impacts, responsible and sustainable harvest techniques can improve overall forest health.

Timber harvest can generate significant revenue in some cases. For example, various Tribes in the Western United States partially rely on the revenue brought in from natural resource products such as timber. Not only do forest management techniques provide financial benefits for these tribes but it also reduces the risk of catastrophic wild fire that can impact future generations that rely on the forests.

1.1.3 Slash piles collection and burning

Current approaches used to mitigate large-scale wildfires include forest management techniques such as thinning or timber harvesting in order to reduce fuel loads (Agee 1996; Agee *et al*. 2005). These operations result in residual biomass being left in the forest or at the landing site as slash piles. There has been much research related to slash piles as a result of harvest or forest management operations. Piling of biomass is a common practice and occurs in several situations such as when material that is non-merchantable arrives at a harvest landing area and it is piled for burning, collection or decomposition. Creation of piles by hand as opposed to machinery often occurs when thinning techniques are utilized within a forest where a fire management plan is used to reduce fuel loads (Agee 1996). The residual slash piles can contain various types of biomass, depending on what is usable for sale and transport. Slash piles can vary in size and composition depending on the harvest techniques such as skidder or cable yarding. The residual slash piles can be composed of bark, stumps, tops, limbs, or logs. Some piles can contain soil which is introduced with the type of piling method such as mechanical which can have more soil or hand piling which can contain less soil (Hardy 1996). These variables influence how much smoke and other chemicals are released when the slash piles are burned.

Piles that are left in the forest without being burned deteriorate and decompose over time. In a wildfire scenario, if these slash piles are engulfed in a wildfire, piles can become ignition sources that can start additional wildfires by emitting embers. If slash piles are caught in a wildfires' path, overall smoke emissions are then increased because of the addition of large piles to the burn. Piles are often burned during low fire activity seasons to reduce the amount of smoke and possibility of igniting wildfires. Common residual pile burning occurs in the wetter months, often in winter to reduce the chance of uncontrolled spreading of fire. In some states, it is required to burn the piled residual slash material at some point in time in order to remove the piles from the area.

Improvement of the current systems that are in place for choosing burn time frames is essential in order to adapt to the changing air quality. For example, if a date is chosen for pile burning that coincides with a poor air quality day, either from anthropogenic or non-anthropogenic sources, then the impacts can be extremely detrimental. A better decision system tool may need to be created and implemented in order to avoid these types of poor air quality situations. The results of creating an impact assessment of biomass pile burning could inform policy makers of the potential impacts and assist in creating a better regulation system to improve air quality and lower impacts.

1.2 Environmental issues of slash pile burning

While residual pile burning is a popular method for disposing of slash material left in the forest, prescribed burning of woody biomass in forests is a major contributing source of air pollution. Slash pile burning can be a controlled process and reduce large-scale wildfires, but burning the piles also emits chemicals and particulate matter into the atmosphere, which can adversely affect local and regional air quality with acute negative impacts on human health at the local levels (Schwartz 1991; Pope 1989, 1991).

Burning biomass releases many chemicals into the air but the main harmful pollutants produced include particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), non-methane organic compounds (NMOC) (Reisen *et al*. 2015). Human health impacts are a major concern when discussing biomass smoke emissions. Exposure to air pollution has been found to have an adverse impact on human health (Durán *et al.* 2015; Schwartz 1991; Pope 1989, 1991) and varies depending on current health, the exposure timeframe, and particulate concentration levels (Dockery *et al.* 1994). Sensitive populations are the most impacted and include people with asthma or lung related ailments, the elderly, pregnant women, and children. Short-term exposures can cause difficulty breathing and contribute to decrease in lung function (Hope 2005). It can also aggravate existing health issues such as asthma and chronic obstructive pulmonary disease (COPD). Long-term exposure can lead to an increase in hospital visits and possible death. Poor air quality has been a rising concern with growing populations and increased large-scale wildfires.

1.2.1 Air quality regulation

The Clean Air Act was passed in 1970, last amended in 1990, required the Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS). These include primary standards that were created to protect "sensitive" populations including the elderly, children, and those with respiratory illness. Secondary standards were set for general public welfare and the environment (EPA 2012).

Densely populated regions around the world have updated their air quality standards over the years in order to reflect new research and to address worsening air quality. The Environmental Protection Agency (EPA) has updated air quality standards several times due to advances in research since 1971, Table 1.

Table 1. Table of Historical PM NAAQS by EPA

History of the National Ambient Air Quality Standards for Particulate Matter
During the Period 1971–2012

Final Rule	Primary/ Secondary	Indicator	Averaging Time	Level [1]	Form
1971 36 FR 8186 30-Apr-71	Primary	TSP[2]	24-hour	260 μg/m³	Not to be exceeded more than once per year
			Annual	75 μg/m³	Annual geometric mean
	Secondary	TSP	24-hour	150μg/m³	Not to be exceeded more than once per year
			Annual	60 μg/m³	Annual geometric mean
1987 52 FR 24634 1-Jul-87	Primary and Secondary	PM10	24-hour	150 μg/m³	Not to be exceeded more than once per year on average over a 3-year period
			Annual	50 μg/m³	Annual arithmetic mean, averaged over 3 years
1997 62 FR 38652 18-Jul-97	Primary and Secondary	PM2.5	24-hour	65 μg/m³	98th percentile, averaged over 3 years
			Annual	15.0 μg/m³	Annual arithmetic mean, averaged over 3 years
		PM10	24-hour	150 μg/m³	Initially promulgated 99th percentile, averaged over 3 years; when 1997 standards for PM10 were vacated, the form of 1987 standards remained in place (not to be exceeded more than once per year on average over a 3-year period)
			Annual	50 μg/m³	Annual arithmetic mean, averaged over 3 years
2006 71 FR 61144 17-Oct-06	Primary and Secondary	PM2.5	24-hour	35 μg/m³	98th percentile, averaged over 3 years
			Annual	15.0 μg/m³	Annual arithmetic mean, averaged over 3 years
		PM10	24-hour (8)	150 μg/m³	Not to be exceeded more than once per year on average over a 3-year period
2012 78 FR 3086 15-Jan-13	Primary	PM2.5	Annual	12.0 μg/m³	Annual arithmetic mean, averaged over 3 years
	Secondary		Annual	15.0 μg/m³	Annual arithmetic mean, averaged over 3 years
	Primary and Secondary		24-hour	35 μg/m³	98th percentile, averaged over 3 years
	Primary and Secondary	PM10	24-hour (8)	150 μg/m³	Not to be exceeded more than once per year on average over a 3-year period

(1) Units of measure are micrograms per cubic meter of air (μg/m³).
(2) TSP = total suspended particles.
(Source: http://www3.epa.gov/ttn/naaqs/standards/pm/s_pm_history.html)

1.3 Alternative use of woody biomass

Residual biomass that is the result of forest management activities often gets burned during the later wet months of the year or is left in the management area until the resources are available to burn which can often take years. An alternative to burning is to collect the residual biomass and utilize it to create products or energy. Most of the products created are related to heat or fuel uses due to the combustible properties of the dried woody debris. Products such as wood pellets are often a viable option for heating uses and this is a common option for woody biomass utilization. Within some industries that process wood, residuals are often used as “hog fuel” to be burnt for heat or energy generation as opposed to using coal or electricity from the grid. Unfortunately, due to the current cost and structure, much of the available biomass in the forest is not collected for industry use and is left to be burnt in piles within the forest management areas.

Other utilization of residual biomass would be extremely beneficial and using the material as a bioenergy source would decrease the emissions associated with pile burning while providing an alternative to fossil fuels (Oneil *et al.* 2010). Offsetting fossil fuels with residual biomass that is otherwise burnt and/or wasted can greatly reduce emissions (Lippke *et al.* 2012). The Northwest Advanced Renewables Alliance (NARA) https://nararenewables.org/ is a group of universities, government and private organizations that are conducting research related to the use of residual biomass for aviation bio-fuel and other useful co-products. Residual slash that is commonly burnt and wasted, emitting harmful chemicals, can be an attractive source if it is retrieved and then converted into a profitable fuel product created from a renewable resource. Retrieval and conversion to bio-fuel can be an alternative to slash pile burning that will avoid emissions while reducing the impact on global warming and human health. NARA affiliates are conducting research in many fields related to the creation of bio-jet fuel. The NARA research includes conducting a detailed Life Cycle Assessment (LCA) to evaluate the environmental impacts from utilizing residual biomass to create bio-jet fuel. LCA has become an accepted method for assessing the environmental impacts of product creation (Puettmann *et al.* 2010). The proposed methods of bio-jet fuel creation from residual biomass will carry their own environmental impacts as defined by the LCA research such as emissions from fuel use in transportation or energy use in production. This research fits into the related NARA LCA research as it describes an avoided impact of residual slash pile burning when the biomass is collected and used for bio-jet fuel production. For this project, 3 timbersheds in Southwestern Washington state were designated as harvest areas where the biomass volume was estimated. Five years of biomass from timber harvesting was modeled although 1 year was chosen for the air pollution analysis which amounted to a volume of ~800,000 tons of biomass harvested from the 3 specified timbersheds.

1.4 Literature review

1.4.1 Biomass supply

There are numerous forest inventory models and databases available, each with their respective strengths towards a specific application. The Washington Department of Natural Resources' (DNR) Forest Biomass Supply Assessment project (Perez-Garcia *et al.* 2012) is a database for estimating biomass in Washington State using market research, FVS, and GIS methods. The biomass supply estimate is produced by classifying the forest biomass by aspects such as land ownership, ecosystem types and then applying cost considerations to the estimations. The project team used an existing forest inventory, created land stratifications, and then applied harvest simulation methods to estimate biomass. Harvest modeling was conducted using the Forest Vegetation Simulator (FVS) and existing plot inventory. This assessment created a biomass availability database based on existing inventory, FVS and GIS methods, and economic variables. While the research interest was not focused on the use of the biomass after collection, the biomass availability projection model served as a primary tool for the current study research.

Adams *et al.* (2002) methods yield projections for privately owned lands in Oregon using data from the Forest Inventory and Analysis (FIA) program. The FIA study was conducted on private lands due to the large reduction in harvest volume on public lands. In comparison to earlier studies, a marketing simulation was included to project market demands. The inventory data utilized was based on 1995-1997 surveys. Current forest management techniques are assessed in order to fit future practices into projections. Additionally, modeling for growth and harvest are needed to project future availability and collection regimes for biomass. The findings of the study reveal that there is not a large variation in projections from previous work conducted. While this study is very involved with marketing dynamics and modeling forest inventory, residual biomass and the use of biomass was not a focus and residual burning or emissions were not considered in FIA research. Additionally, the research primarily focused on parts of Oregon as opposed to an inventory that is targeted towards Washington State.

The Gray *et al.* (2005) inventory report includes statistics for Washington state forested areas updated from the 1990 inventory data. According to the study, a volume decrease of 2.6 billion cubic feet can mostly be attributed to land use changes. Updates to the inventory from past inventory include spatial land and water acreage as well as land definitions. Again, residual biomass was not a focus and therefore the use of the biomass, whether burned or collected, was not assessed.

Additional related inventory work conducted by Adams *et al.* (2007) is similar in inventory modeling and methods. The study included the private lands in the states of Washington and Oregon. Similar to the past study, inventory data for the sites, forest management practices, land ownership changes, and models for projections of forest growth and harvest scenarios were essential. Yields were created using a variation of the Forest Vegetation Simulator (FVS) (Dixon 2002). The inventory data used was updated to the base year of 2003 by projecting up to that point from previous inventory data. The change in forest area was projected by using the same trends as the past except at a lower rate. The trend resulting in a decrease in area was attributed to development and private ownership sale. Similar to past studies conducted (Gray *et al.* 2005; Adams *et al.* 2002) the projections do not result in large differences compared to past study projections. Similar to the past studies, residual biomass was not a focus and therefore the use of the biomass was not a part of the research goals.

Wright *et al.* (2010) introduced methods for estimating biomass volume similar to Hardy (1996) although hand piles were assessed directly. The study measured 121 hand piles and included measurements for weight, size, and shape of the piles. Building from the upon the research of Hardy (1996), the researchers created additional steps in order to combine the guidelines for the machine piling as well as their method obtaining hand piling measurements. This approach resulted in a more accurate modeling due to being able to directly weigh the smaller hand piles as opposed to Hardy's (1996) estimation methods. This approach was focused more on the detailed small-scale residual biomass volume estimation. This research proves useful when estimating pile sizes and shapes including hand piles although it did not include creating an inventory or assessing the use of the biomass piles.

Hardy (1996) displays guidelines for estimating slash pile burn emissions based on several pile attributes. Burn emissions can be affected by pile dynamics such as pile shape, soil content in the pile, source species, and packing ratio (Hardy 1996). Larkin *et al*. (2009) displayed a modeling framework in which several models were utilized to create a system to assist in estimating burning emissions and plume trajectory. This system enables a user to use wildfire information as well as point source input such as pile information for residual pile burns. The information supplied to the framework allows the models to run analysis and supply trajectories and dispersion. The model framework allows for flexible substitutions of different model integrations such as varied fuel loading models, (CONSUME, FCCS, etc.) or trajectory models (HYSPLIT, CALPUFF, etc.), and supports side-by-side comparisons that can be tailored to the user's specifications or needs. While the framework is important when assessing airshed quality during wildfires, the BLUESKY "Playground" tool also allows for manual input of prescribed fire scenarios (Larkin *et al.* 2009; O'Neill *et al*. 2008). This research and tool development is focused on the emissions from biomass burning but does not include an initial biomass inventory nor does it assess human impacts from the emission dispersion.

This research fits the current research need of calculating emissions from a biomass burn and Bluesky is used as an input for the current research project.

Modeling smoke from wildfire can be done by using several methods and modeling systems. Goodrick *et al.* (2012) reviews the available modeling systems that are currently being utilized. The research points out that there are four categories or components that are involved when creating projections. These components are similar to those considered in the afore mentioned study by Larkin *et al.* (2009), including burn information inputs, smoke plume activity, and interactions within the atmosphere. The review examines 4 main models that are used within this type of assessment including Gaussian distribution and puff models. Goodrick *et al*. (2012) goes into detail explaining the Larkin *et al.* (2009) Bluesky modeling framework and its ability to be flexible with model choices although the modeling framework does not include residual biomass inventory or assess the impacts of the emissions after dispersion.

Wiedinmyer *et al.* (2006) compiles a methodology of emission projections at a regional scale. The study uses fire activity as a source for emissions by way of MODIS satellite thermal detection.. Fire or burned biomass was approximated by the fuel source such as forested tree cover or grassland. Percent burned was estimated by how much of each land cover classification was designated. Nine chemical compounds were compiled for 2002-2004 on a daily scale for North America as well as part of Central America. Although in part of 2002, a satellite was not providing data and had an influence on the fires detected. This study presents a method that results in acceptable fire detection and emission calculation with less time spent collecting fire and forest inventory. While the research calculates emissions and dispersion, initial biomass inventory or human impacts was not included.

Akagi *et al*. (2011) evaluated and calculated emission factors in order to improve past estimates and improve current methods. The authors state that biomass burning is the largest fine particulate contribution across the globe. This can be attributed to all types of biomass burning from crop burning (such as oil palm plantations in Southeast Asia) to wildfires (Akagi *et al.* 2011). The study goes into detail in assessing different types of landcover across the globe (e.g. boreal, tropical) in order to calculate chemical outputs specific to each region using past research as reference. In comparison to other related research, this study assessed many species of chemicals but does not include an initial biomass inventory or assess the human impacts after dispersion.

1.4.2 Pile emissions calculator – Bluesky Playground

Hardy (1996) displays guidelines for estimating slash pile burn emissions based on several pile attributes. Burn emissions can be affected by pile dynamics such as pile shape, soil content in the pile, source species, and packing ratio (Hardy 1996). Larkin *et al*. (2009) displayed a modeling framework in which several models were utilized to create a system to assist in estimating burning emissions and plume trajectory. This system enables a user to use wildfire information as well as point source input such as pile information for residual pile burns. The information supplied to the framework allows the models to run analysis and supply trajectories and dispersion. The model framework allows for flexible substitutions of different model integrations such as varied fuel loading models, (CONSUME, FCCS, etc.) or trajectory models (HYSPLIT, CALPUFF, etc.), and supports side-by-side comparisons that can be tailored to the user's specifications or needs. While the framework is important when assessing airshed quality during wildfires, the BLUESKY "Playground" tool also allows for manual input of prescribed fire scenarios (Larkin *et al.* 2009; O'Neill *et al*. 2008). This research and tool development is focused on the emissions from biomass burning but does not include an initial biomass inventory nor does it assess human impacts from the emission dispersion. This research fits the current research need of calculating emissions from a biomass burn and Bluesky is used as an input for the current research project.

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1.4.3 Chemical transport and interaction – AIRPACT

Vaughan *et al.* (2004) introduced a daily air quality monitoring system for the Pacific Northwest using several computer models (www.airpact.wsu.edu). The development of the modeling framework was focused on creating an air quality monitoring system capable of supplying information year-round on a daily basis.   The system creates hourly PM, ozone, and other pollution predictions including major point sources (such as power plants) and accounts for emissions from vehicles, biogenic and other human caused emissions. This expansive air quality monitoring system is an important tool that assesses many sources of pollution and concentration prediction. Additional AIRPACT development is continued in later research, adding other important updates including Bluesky (Larkin *et al.* 2009).   This initial research did not include residual pile burning input or incorporate the impact of each chemical to humans and environments into the system.   Figure 1 displays the major components of the initial AIRPACT system including wind, weather, and pollution models.

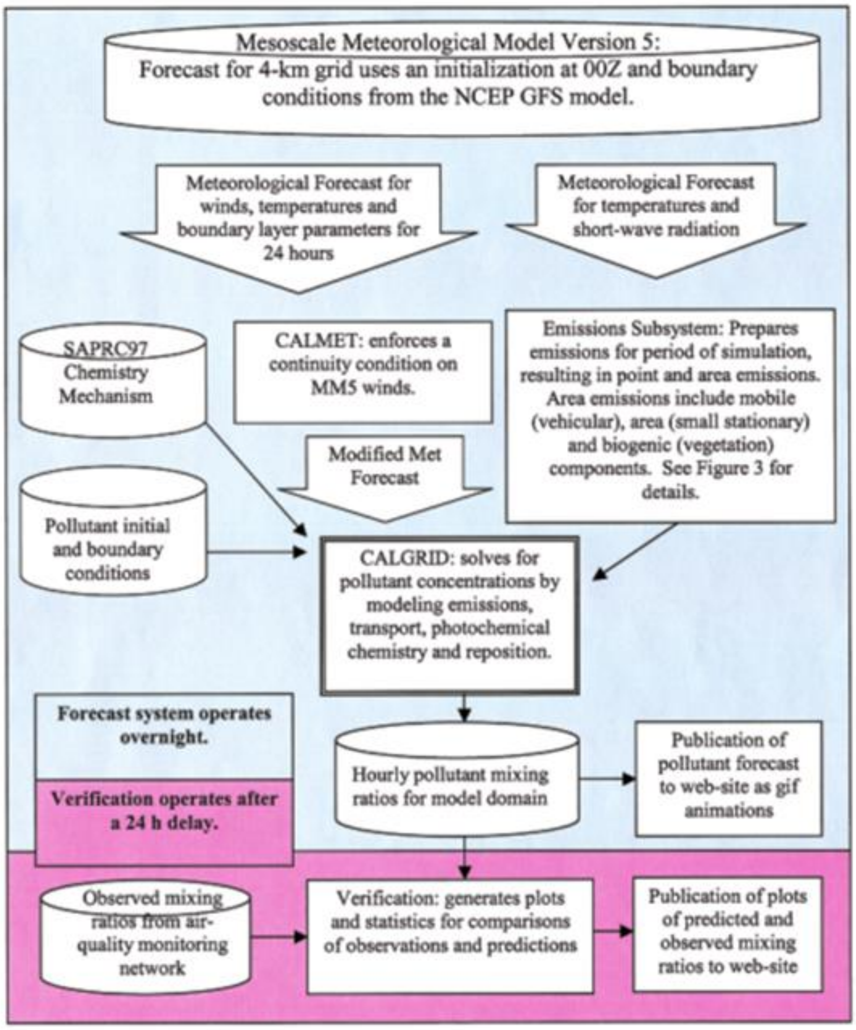

Figure 1. Major components of AIRPACT; Vaughan et al. 2005. Pg. 552.

Lamb *et al.* (2007) reviewed the AIRPACT-3 air quality forecast system, updated from AIRPACT-2. This updated system incorporated the Forest Service Bluesky fire emission model (Larkin *et al.* 2006; O'Neill *et al*. 2005). The addition of the Bluesky model enhanced the capabilities and emission predictions of AIRPACT-3. Data from the US-EPA National Emissions Inventory 2002 in conjunction with SMOKE was used to model other emission sources such as anthropogenic caused. Twelve-kilometer grid cells were used and the study noted that variable vertical layers were available. The Bluesky addition is able to provide daily fire activity through the National Interagency Fire Center. According to the study, Bluesky can output PM, CO, NOx, and other emissions which AIRPACT utilizes within its CMAQ. The study points out that combining these two modeling systems yields an emission complex that gives a better understanding of wildfire emissions impact to air quality. The study shows that NO_2 addition from wildfire emissions to the model has a significant effect on ozone calculations compared to leaving out the wildfire emissions. While this research accounts for chemical interaction in the atmosphere, it did not include a biomass inventory input. This research-modeling framework was utilized as a part of the current research project due to the geographic focus and dispersion modeling value.

Chen *et al.* (2008) provided an evaluation of the AIRPACT system mentioned in the previous study. Updates to the previous version and evaluated at version 3 for AIRPACT, this study confirmed that the newer version had significant benefits and sensitivity compared to previous version 2 of AIRPACT. CMAQ chemical transport (CCTM 4.6) is used within the AIRPACT 3 system to calculate the chemical interactions in the atmosphere. The resolution of the domain is a 12 km grid with 21 layers going vertically into the atmosphere. Meteorological information is provided by the MM5 v. 3.7.3 Mesoscale Meteorological Model and can provide data at a scale of 4km but for this study, the resolution was kept at 12 km. Emission modeling SMOKE was modified to provide the specific categorical emissions such as anthropogenic and biogenic. Bluesky modeling provided wildfire emissions and ClearSky provided data for agriculture related emissions. The results of the study showed that the system performed well in estimating emissions and incorporation of Bluesky burn emission modeling provided improved performance over past versions. This research utilizes the AIRPACT system but does not include initial biomass inventory for burning or specific human impacts from the emissions.

Clinton *et al.* (2015) research study utilized GIS software and fire models to create an estimation system tool. The author emphasized that the tool should be flexible and able to be modified for future analysis or data updates. GIS interface was the basis of the system and this provides the user the ability to completely access the different parts of the system. The system outputs emissions based on vegetation type and references past research done on emissions from certain types of vegetation. This tool provides a flexible input possibility and fuel source input although the tool does not input residual slash pile amounts or create a human impact assessment.

1.5 Motivation of the study and research objectives

While useful for removing slash material, pile burning releases chemicals and emissions into the atmosphere and the task requires attention from personnel in the forest to reduce the risk of having the fire spread to surrounding areas. Removing the slash material from the forest requires a cost-benefit analysis that reflects current market prices. Current research being conducted by the Northwest Advanced Renewables Alliance (NARA) is investigating the use of residual biomass left over after forest operations to create biofuel. This project integrates with NARA project by developing a method for spatially mapping human impacts from burning residual slash piles.

The literature review on slash pile burning and emissions modeling has indicated that there are various methods in which previous research has spatially mapped burn emissions, atmospheric chemical interaction/transport and assessed pile burning. Although previous research shows promise in creating the necessary tools, currently there needs to be more research conducted in the area of spatially calculating slash pile burn emissions/chemical interactions in the atmosphere and the detailed health impacts from biomass burnings. While there are methods of estimating the health impacts from burning biomass in piles, there could be improvement with finer population detail, plume projection, and potential health impacts.

Therefore the objectives of the study are:

- Estimate residual biomass inventory for the selected areas in Southwestern Washington State using the Washington State Biomass Calculator.
- Use the Bluesky Playground online tool to estimate emissions from burning biomass piles totaling ~800,000 tons of biomass based on the results of the Biomass Calculator.
- Model the pile burn emissions trajectory and atmospheric interactions using AIRPACT.
- Use chemical concentration results of AIRPACT to calculate the human intake of the emissions, categorize concentrations based on air quality standards, and estimate impacted populations.

This study focuses on assessing where particulates from pile burning can travel locally and deposit in the surrounding areas of the Pacific Northwest Region utilizing GIS and computer modeling systems. This approach catalogs the residual pile burn areas and uses a forest inventory model to project slash amounts for 2011. Pile burning and chemical transport models are utilized to project plume directions and chemical concentrations.

2 Methods

2.1 Workflow of methodologies

In order to estimate the available residual biomass for an area, model burning emissions, model pollution air interaction, calculated human intake, categorize concentrations, and estimate impacted populations, several tools and methodologies were integrated. Figure 2 displays the general workflow for this research where each method result is used as an input for the next method.

There are several tools available for estimating forest inventory but for this project, the Washington State Biomass Calculator (http://wabiomass.cfr.washington.edu/ (Perez-Garcia *et al*. 2012) was used. The biomass pile burn emissions were calculated using the BlueSky Playground web tool (Larkin *et al*. 2009). The chemical transport/interaction and plume dispersion were products of the Air Indicator Report for Public Access and Community Tracking (AIRPACT) http://lar.wsu.edu/airpact/ (Vaughan *et al*. 2004).

2.2 Biomass supply assessment – Washington State Biomass Calculator

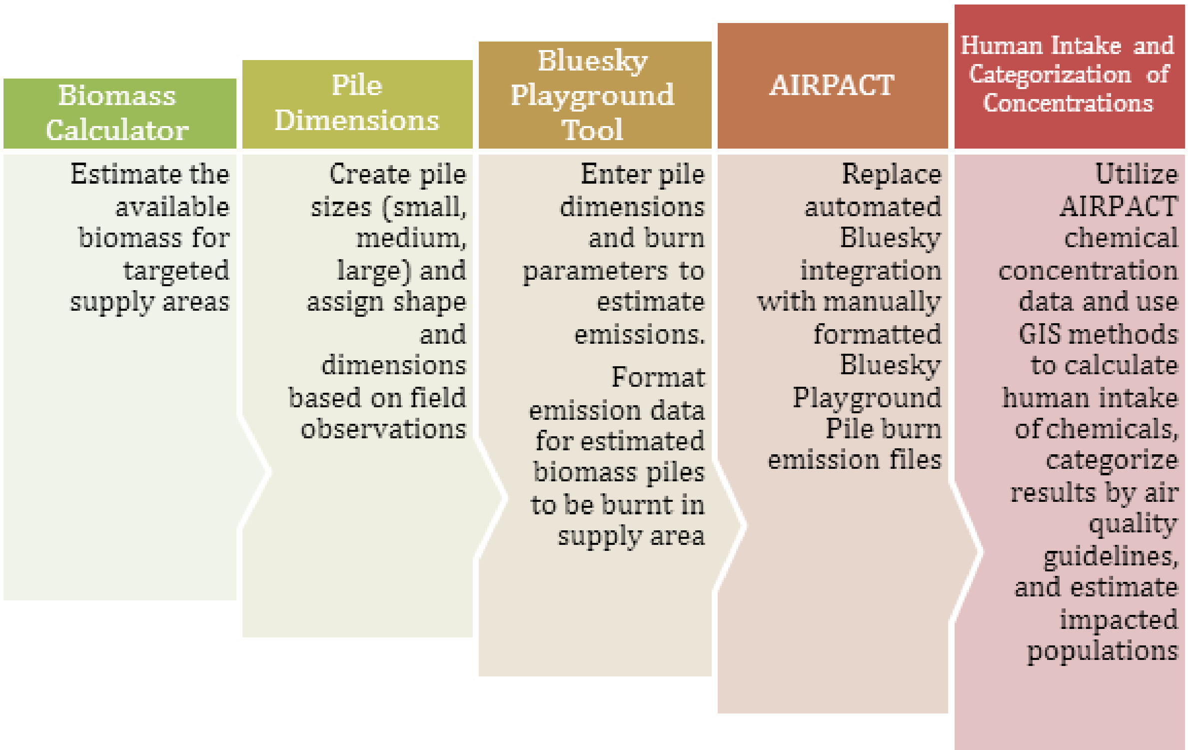

Figure 2. Methodology workflow.

2.2.1 Area of study

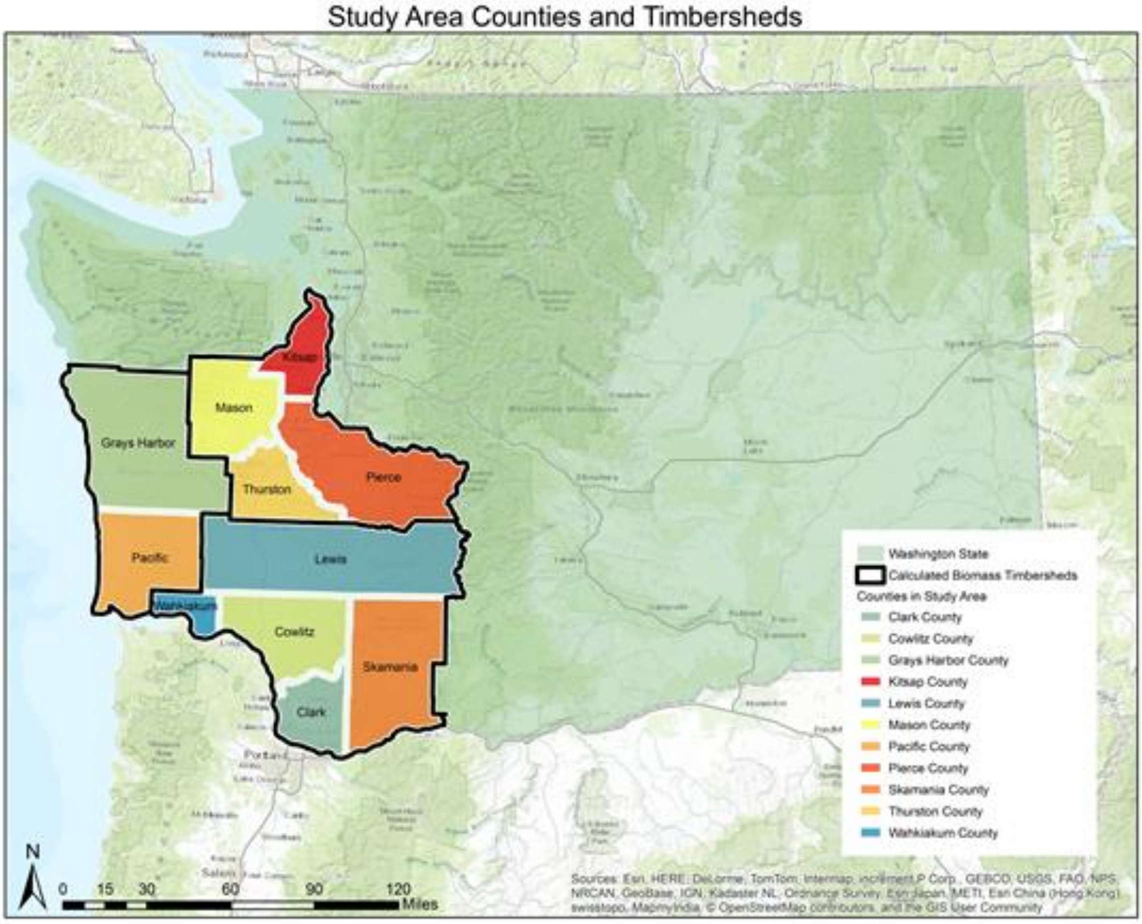

Figure 3. Washington State study area with county outlines.

The study area included 11 counties in the Western Washington State region. These counties are located within 3 timbersheds that are used with the biomass calculator and where the project burn pile scenarios were created. Figure 3 displays the 11 counties in various colors and the 3 timbersheds outlined in black. Data is available statewide and ranges from a small parcel level to the state level. For the purposes of this study, the 3 timbersheds were chosen because each timbershed contains multiple counties (county boundaries follow timbershed boundaries) and comparisons between counties can be communicated/interpreted easier as opposed to comparing watersheds or parcels. Additionally, there are also numerous facilities that process wood products in that region that can be used with the biomass scenario. The AIRPACT output grid of 4km x 4km (~2.5 miles x ~2.5 miles) was a better fit when spatially layered over a county level, as compared to a parcel which an AIRPACT grid cell covered many parcels.

2.2.2 Biomass calculation

The forest biomass inventory for this project was calculated using the Washington State Biomass Calculator that was developed as part of the Washington State Department of Natural Resources' (DNR) Forest Biomass Supply Assessment project (Perez-Garcia et al. 2012). Classifying the forest by aspects such as land ownership and ecosystem types produces the biomass supply estimates. FVS methods are administered and cost considerations (market considerations for biomass) can be applied to the volume estimates to create an available biomass supply based on user-applied market conditions.

The biomass calculator can be accessed online http://wabiomass.cfr.washington.edu/ and is available to the public with customizable parameters. Parameters such as location, management style, costs, and facilities can be adjusted to provide a flexible user interface. This inventory was chosen because the inventory data focus on the selected geographical area of Washington State and it provides specific estimates (such as percentage of cable or ground yarding) needed for this study. Figure 4 displays a window at the beginning of using the Biomass Calculator, starting with choosing a harvest model and then continuing on to choosing other parameters.

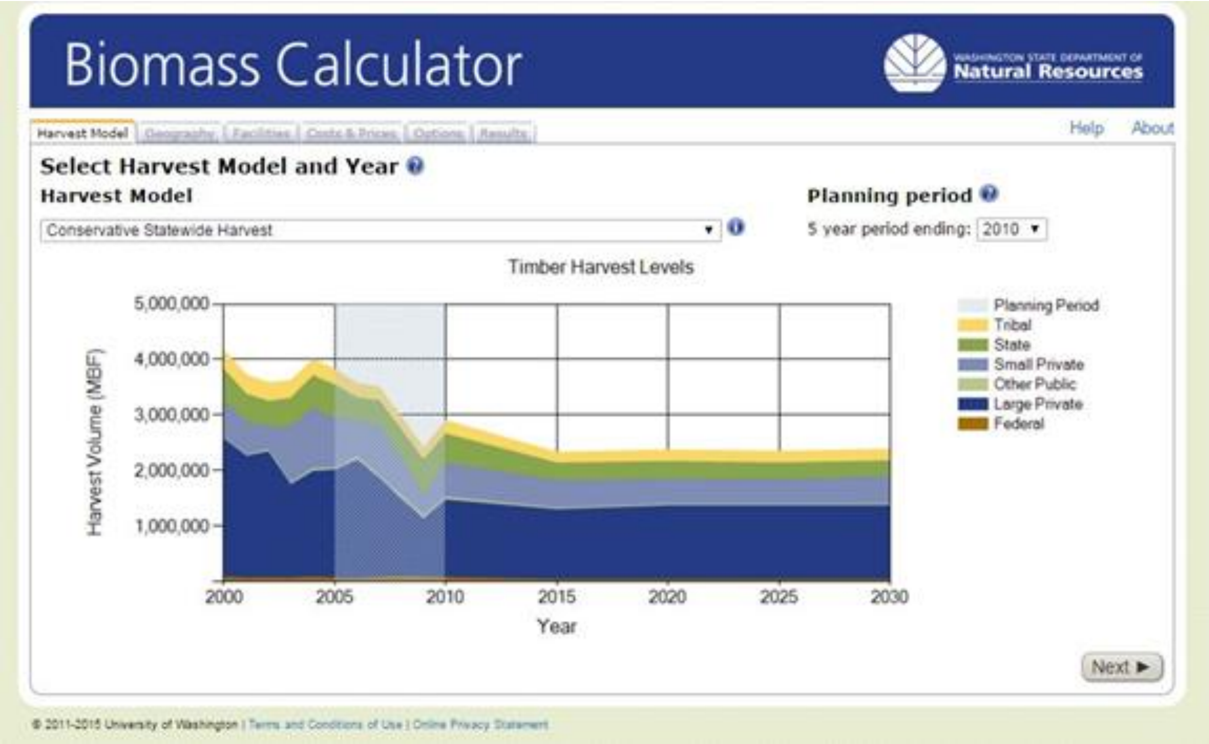

Figure 4. The Washington State Biomass Calculator online public tool. http://wabiomass.cfr.washington.edu/.

The inventory target area includes three timbersheds located in Western Washington State. Figure 5 displays the chosen timbersheds; the San Juan, Lower Skagit/Samish, and Stillaguamish. These timbersheds are identified within the Biomass Calculator as South Puget Sound, South Coast, and Southwest and were chosen because they are located within the projects target scope range of Southwestern Washington.

Figure 5. Washington State timbersheds used for analysis.

The project area timbersheds include the 214 Watershed Administrative Units (WAU), Figure 6. The WAU's were defined by the Washington State Department of Natural Resources (DNR) in coordination with other departments including Ecology, Fish and Wildlife, and Indian tribes. WA State is made up of a total of 846 WAU's with an approximated size of about 40,000 acres. These WAUs are utilized for natural resource management and watershed scale studies.

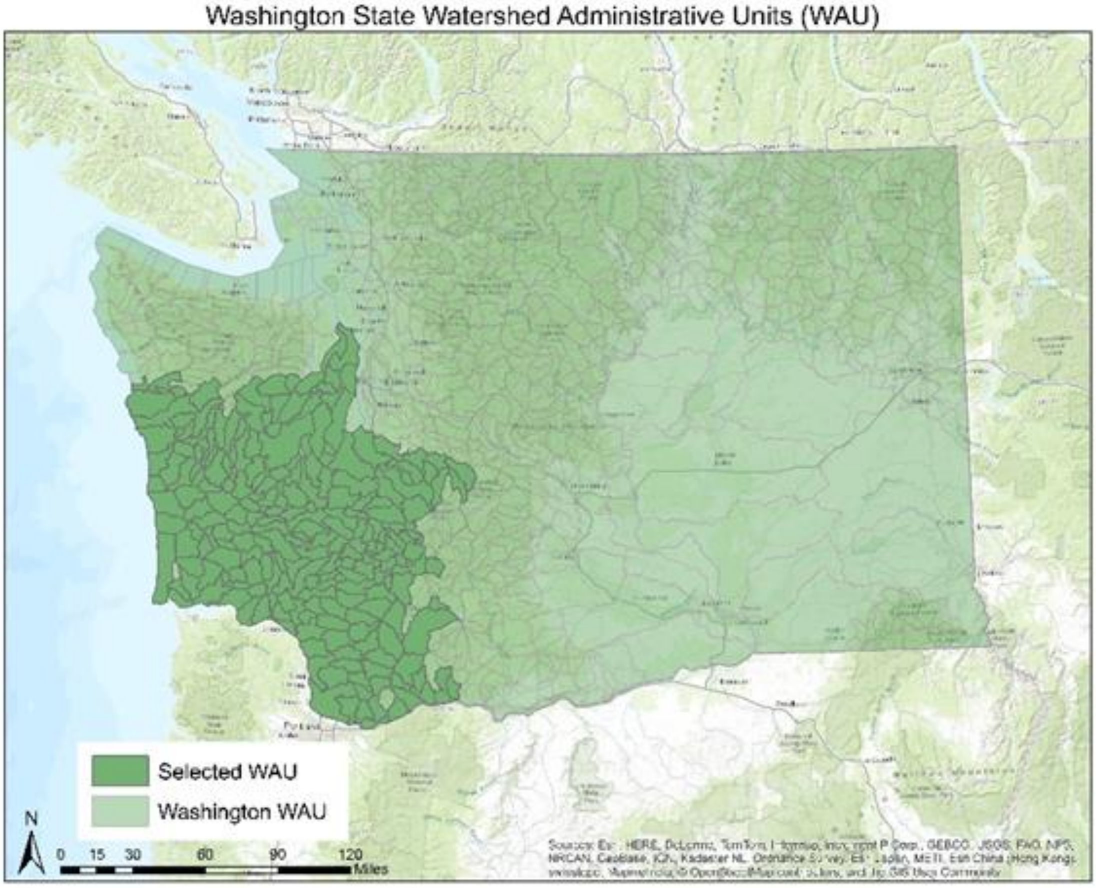

Figure 6. Watershed Administrative Units (WAU) chosen for the analysis.

The mean acreage size of the 214 WAUs included in this study is 38,903 acres and a standard deviation of 24,454 acres. The calculated output was on a smaller parcel level, which consisted of single 9582 parcels. Ownership of the parcels consisted of 84% private, 10% state, 3% tribal, 2% municipal, and 1% federal, Figure 7.

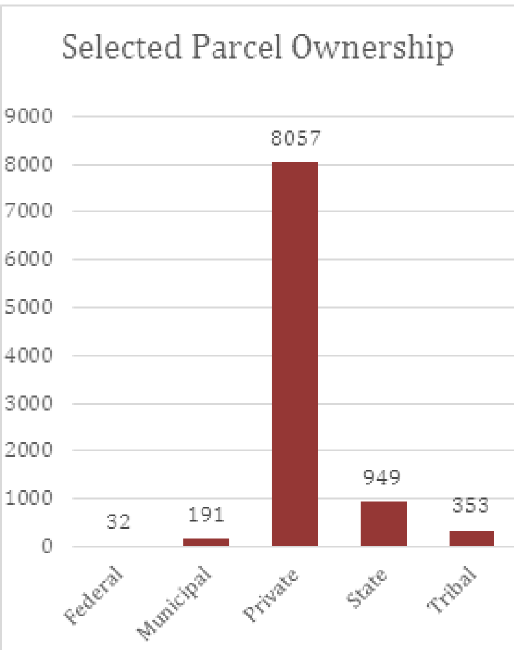

Figure 7. Selected parcel ownership totals.

2.2.3 Calculator parameters

The Biomass Calculator parameters were chosen to represent this projects target years and geography, Table 2. It is important to note that these parameters were set to describe a non-specific biomass scenario. This study was designed to develop a method for calculating the local impacts from biomass burning in which the parameters could be adjusted to reflect a specific project scenario. The biomass estimated in this project is defined as treetops, branches, needles, and bark. The parameters used included the type of harvest model (e.g. conservative, average, and aggressive). These harvest models have been computed using historical harvest information from the Washington State Department of Natural Resources (Perez-Garcia et al., 2012). An "average" harvest model was used for this project, which means that the state harvest levels were projected to be 3 billion board feet by 2015. The "Average" harvest model was chosen in order to provide a common or average harvest scenario as opposed to a more aggressive harvest model. This model computes estimates that cover a 5 year span (ex. 2010-2015). The 5-year span for the 2010-2015 biomass totals were then divided by 5 in order to obtain a one year of biomass volume with the scenario burn time-frame being November 2011. The geography parameters previously described consisted of 3 timbersheds, located within the NARA supply region. The facilities parameter included all existing processing facilities in the state. "Existing facilities" were chosen because of the goal of obtaining a generalized scenario without considering potential facilities. The biomass harvest cost model, which was set to "low", included costs for harvesting, grinding, loading, transporting, and unloading the biomass. This "Low" cost is represented as $96 per hour for mobilization cost, $21 per ton load/unload cost, $76 per hour for haul cost, $30 per ton for timber harvest cost ("Washington State Biomass Calculator User Manual," 2012). "Low" costs were chosen in the scenario in order to model a case where biomass collection was applied and costs would be low. The Biomass Calculator states "harvest costs for biomass are assumed to be $0 for all commercial timber harvests as the collection of biomass at the roadside is a side-effect of the timber harvest". The "Price" parameter is the biomass price paid at collection facility and was set at a value of $65. This value was set in order to model a generic price and could be adjusted to a specific application. Adjusting this value would increase or decrease the amount of biomass being collected. For example, if the value were set at $100, more biomass would be collected because of the increased market value. The "Max Haul Time to Facility" was set at 120 minutes (2 hours). This value represents the trucking travel time going one way between the biomass collection location and the processing facility. A 2-hour haul time was chosen to model a common haul time and represents an average haul time. The other parameters "Field options" and "Reporting Fields" are not important in this study as the final data received included those options available and was provided on a parcel size level.

Table 2. Biomass calculator parameters.

Run: Average Statewide Harvest
Year: 2010-2015
Geography: Timbershed
Geographies: San Juan (2), Lower Skagit / Samish (3), Stillaguamish (5)
Facilities: Bingen: Existing, Camas: Existing, Cosmopolis: Existing, Everett: Existing, Hoquiam: Existing, Longview: Existing, Mount Vernon: Existing, Port Angeles: Existing, Port Townsend: Existing, Tacoma: Existing, Wallula: Existing, Winton: Existing
Cost: Low
Price: $65
Max Haul Time To Facility: 120 minutes
Reporting Fields: Timbershed
Field Options: Names

2.2.4 Biomass calculator results

The biomass calculator output was imported as a spreadsheet, where each parcel row included the year, price, facility info, WAU id, owner, percent cable and ground yarding, and the biomass amounts available (tons). The calculator provides the scattered biomass, roadside biomass, and marketable biomass, where 100% of the marketable biomass and 20 % of the roadside biomass. In this study, we are assuming that future forestry research and equipment efficiency improvement could make 20% of the roadside marketable. The scattered biomass was not utilized in this study because emissions being calculated are the avoided emissions of what a biomass project would be collecting and not the total available biomass emissions. The explanation of how the inventory data was managed is further described in the "Inventory pile calculations" section.

2.3 Piles modeling

2.3.1 Field data collection

Field observations were conducted at various forest harvest and residual piling sites across Washington State. Figure 8 shows a large pile that was collected using a bulldozer in the Naches, Washington area. The purpose for the field measurements was to catalog the different types of piles for reference when creating the pile scenarios. Sites included land owned by WA State DNR, the US Forest Service, and Tribal forests. During the field trips, measurements of pile size were taken as well as the type of forest management method used and GPS locations were noted. Depending on the harvest method used and the terrain, pile specifics such as size and shape varied. Burnt piles were also evaluated to determine what percentage of the biomass was burned, Figure 9. Hand piling sites were also visited and recorded. These smaller sized piles were often the results of thinning practices as a part of forest management plans. The hand piles were recorded and a single pile burn emission was calculated although the final emissions results for the study did not include hand piles. On the following page, Figure 10 displays an example of a hand pile that was located near Naches, Washington. The study was focused on the mechanical pile emissions and impacts but future work could be easily designed to include hand piles.

Figure 8. Machine large pile 22m x 15m near Naches, WA 46° 48' 4" N 120° 58' 59'' W

Figure 9. Large burned pile near Cle Elum, WA 47° 19' 26.55" N 120° 42' 22.47" W.

Figure 10. Thinning small hand pile 1.25m x 1.25m near Naches, WA 46° 39' 25.18" N 121° 9' 26.87'' W.

While observing the various types of burn piles, it was apparent that certain characteristics were common among the types of harvest operations. Cable yarding operations often produced larger sized piles, because the material was brought or "funneled" to a central point or landing. Cable yarding is used for high slope harvest areas. A ground-based harvest operation often has less slope and it is easier to maneuver equipment around the harvest area. How the piles were made influenced the amount of soil that was introduced. Piles created by mechanical equipment are often contaminated with more soil due to the act of pushing the residual material into piles. The amount of soil contained in a burn pile (% in Bluesky Playground) is important as it affects the burn characteristics. It is important to note that the pile information gathered from the site visits was meant to act as a reference when preparing the pile burn scenarios.

2.3.2 Definition of pile categories

Residual pile shapes and sizes vary across the state of Washington. In order to develop a scenario that would be able to cover the broad range of piles, categories of pile shapes and sizes were created. The Forest Service Bluesky Playground (Larkin et al., 2009) integrated burn pile calculator was utilized to input specific pile parameters. The outputs include biomass weight per pile, emissions generated from burning, and PM2.5 spatial dispersion modeling. Based on the weight per pile output, different pile categories and amounts can be chosen in order to reach the desired biomass burn for target area. Figure 11 displays initial research by Hardy (1996) displaying various burn pile shapes that occur during piling procedures. These pile shapes form the basis of the shapes decided for this research project.

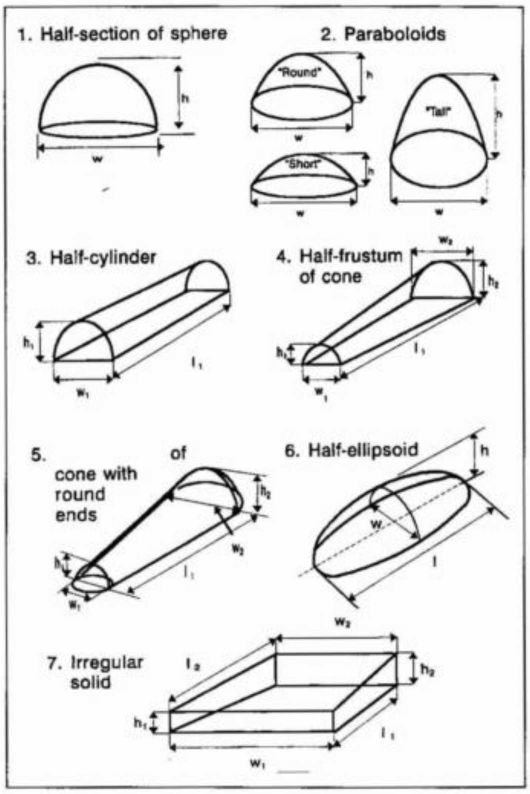

Figure 11. Pile shapes from Hardy (1996).

The burn pile size and shape categories were chosen in order to cover the broad range of residual pile scenarios encountered across the Pacific Northwest landscape. Residual pile research was conducted during the summer of 2014 and included visits to the Cle Elum Forest District, the Naches District, and the Yakama Reservation. The areas visited included different types of residual piles of varying sizes including both machine and hand piles. The piles assessed ranged from small hand piles (~6ft diameter) to large machine piles (~60ft diameter). Different shapes of piles were also evaluated. The shapes of the residual piles were paired with the size of the pile and the type of harvest/treatment. The varying pile sizes were used to create different pile groups and weights estimated by the integrated Bluesky pile calculator; 2 large (~50-60 tons/pile), 3 medium (~20 tons/pile), 2 small (10 tons/pile) and 1 small hand pile size (~.05 tons/pile). An additional pile size was added with the characteristics of a small hand pile often seen with thinning treatments.

Pile size and shape can be greatly influenced by the type of harvest or forest treatment method. Cable yarding is often used where slope is too great for wheeled or tracked machines to navigate safely. If there is a substantial amount of slope in the area, cable yarding may be the method of choice. In a cable yarding scenario, there may be little room for maneuvering residual biomass due to limited landing space. This often results in piles that are more oval or elongated in shape. The chosen shape of half ellipsoid was a common shape seen in the varying pile sizes during the site visits.

In the study, emissions of other shapes in the size categories were created with Bluesky Playground tool (Cone rounded ends, paraboloid, and half sphere) but the biomass inventory distribution only utilized the half ellipsoid shape. A half ellipsoid shape was observed during fieldwork as the most common shape for the slash piles. A small pile size was added in the pile categories to simulate a forest management practice such as thinning. It is important to note that the pile parameters were set to describe a generalized pile scenario that could be adjusted to represent a certain application. This study is designed to develop a method for calculating the local impacts from biomass burning in which these pile dimensions could be adjusted to a specific project scenario. Table 3 displays each pile category and size along with the dimensions and other parameters that are required by the Bluesky Playground online tool.

Table 3. Pile categories with their dimensions, dates of run, coordinates, and shapes as entered in Bluesky Playground tool.

Category	Large	Large	Medium	Medium	Medium	Small
Shape						
	Half Ellipsoid	Cone w/ Rounded	Half Ellipsoid	Cone w/ Rounded	Paraboloid	Half Sphere
Size (ft)	W=50 H=25 I	W1= 20 L=65 W	W=30 H=20 L=40	W1= 20 L=45 W2=25	W=40 H=20	H=15
tons/pile	62.5 tons/pile	52.91 tons/pile	20 tons/pile	19.22 tons/pile	20 tons/pile	11.25 tons/pile
Lat	46.801111	46.67	46.82	46.75	46.67	46.43
Long	-120.98306	-122.61	-123.51	-123.53	-123.34	-123.7
File Name	LargeHEpile	LargeCRpile	MediumHEpile	MediumCRpile	MediumPbpile	SmallHSpile
Date of Dispersion Run	10_01_2015	10_02_2015	10_04_2015	10_04_2015	10_04_2015	10_04_2015
Date of Run Creation	10_01_2015	10_04_2015	10_04_2015	10_04_2015	10_04_2015	10_04_2015

2.4 Pile emissions calculation – Bluesky Playground online tool

The BlueSky Playground web tool http://playground.airfire.org (Larkin *et al*. 2009) is a web-based tool that provides the ability to calculate emissions and plume trajectory for wildfire, broadcast burns, and pile burns. This online tool provides basic customizations and is a smaller, publicly accessible application version of the full Bluesky system. For burning a pile, the fuels, consumption, and emissions are calculated using the Consume model. Within the Bluesky Playground online tool, emissions were calculated using the default pile burn emission model FEPS (Fire Emission Production Simulator). FEPS model that is utilized by Bluesky calculates the emissions CO, CO2, CH4, and PM2.5.

2.4.1 Slash piles emissions calculation using Bluesky Playground tool

While there are numerous models available to simulate smoke emissions, a special tool was needed in order to simulate emissions from different pile shapes. Pile burning varies from other types of biomass burning in that mechanically created piles can have dense biomass compaction compared to a broadcast burn or a wildfire. Another characteristic that makes residual biomass pile burning emissions unique is that a pile may contain soil that was a result of the piling method. The Bluesky Playground" tool http://www.airfire.org/data/playground/ (Larkin et al. 2009) was used in this study to determine pile-burning emissions, Figure 12.

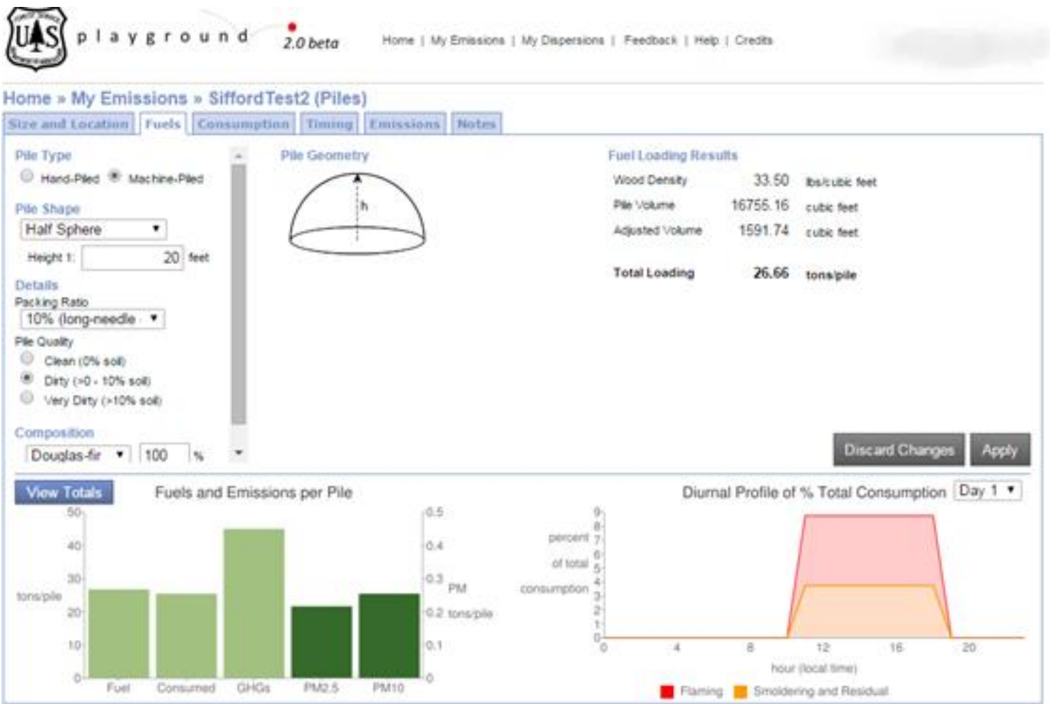

Figure 12. Forest Service Bluesky Playground web tool. http://www.airfire.org/data/playground/

The purpose of this was to calculate the emissions from burning one pile of each of the designated pile categories. The results produce the estimated pile emissions from burning each type of pile. The parameters input into the tool were based on the pile site observations and a literature review. The web tool allowed for user tailored pile specifics such as shape, packing ratio, soil content and composition. These pile specifics were determined based on field observations and the forest inventory information for the area. The consumption rate was also chosen based upon the field observations and common practice. The Playground online tool, by default, generated the emissions results for the following chemicals, carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), greenhouse gases (GHGs), particulate matter (PM), particulate matter <2.5 micrometer (PM2.5), particulate matter <10 micrometer (PM10), and non-methane hydrocarbon (NMHC). Figure 13 displays the online tool tabs and an example of the emission results for one pile burn.

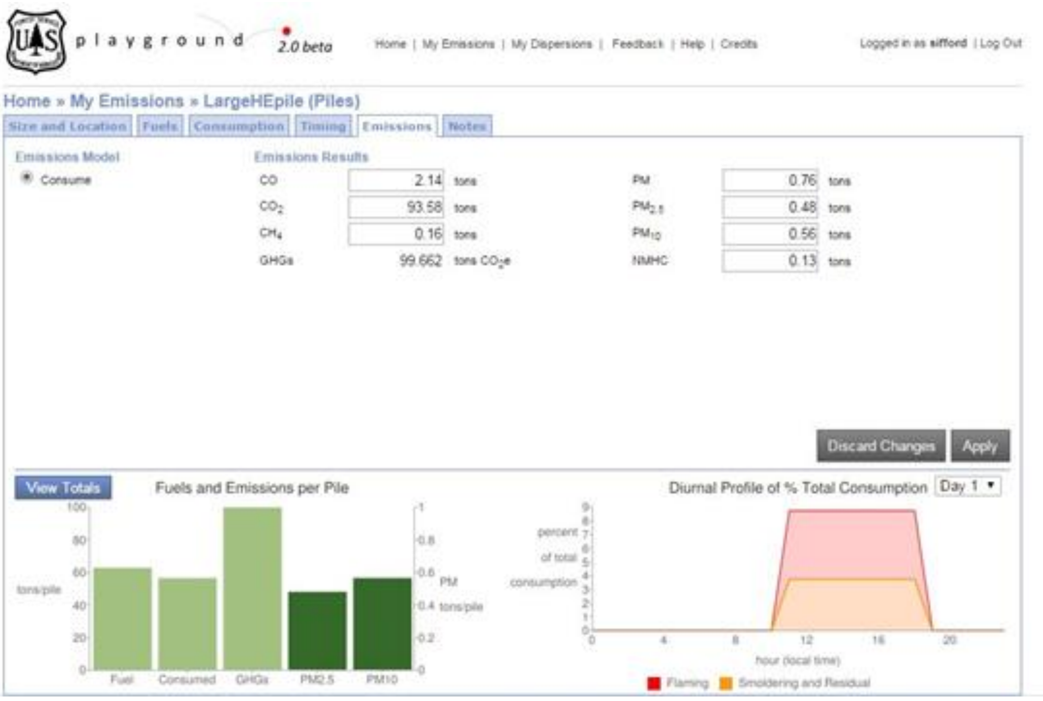

Figure 13. Bluesky Playground online tool emissions page.

The Playground web tool provides results for emissions calculations and also PM2.5 dispersion plumes. The particulate matter dispersion is output as a KMZ file that can be uploaded to Google Earth. For this analysis, the tools plume dispersion data was not utilized because the atmospheric interactions were modeled later using AIRPACT.

A pile from each pile category was separately input into the Bluesky Playground tool to compute the emissions per pile. Each pile was assigned a latitude and longitude that as its descriptor because the Bluesky Playground tool does not store user added file names. In order to distinguish the pile burns from each run, the coordinates were used to locate each pile burn even though these coordinates were not used in the analysis. The parameters chosen in the playground tool were kept the same for all the pile burns (except their size/shape). Parameters chosen include machined a piled category of emissions as well as hand pile category. The packing ratio was set at 10% and pile quality was set at “Dirty” (0-10%) soil. The soil parameter was set at “dirty” because the machine piles visited in the field often contained substantial amounts of soil due to the machine piling method. The species composition was listed as Douglas-fir. During the fieldwork, it was commonly seen that some amount of slash material was left over after a pile burn so the consumption was set at 90%.

2.4.2 Bluesky Playground tool emissions results

The different pile categories and sizes were "burnt" in the Bluesky Playground online web tool. Personnel at the Pacific Wildland Fire Sciences Laboratory provided the raw output files as spreadsheets. Each pile burn was provided with an "emissions" file and a "locations" file. The emissions file contains hourly emissions for different kinds of burning stages such as flaming and smoldering. The "locations" file contained the spatial coordinates and total emissions for each burn. These files were manually formatted to contain all of the burns in the scenario so that a single AIRPACT computer model run could be initiated instead of numerous single pile burn runs. Each of the results within the ladder of methods was used as an input for the last files for AIRPACT.

2.4.3 Inventory pile locations

The pile burn scenarios were modeled within 3 timbersheds and each biomass pile burn was placed within a Watershed Administrative Unit (WAU). Bluesky Playground tool and AIRPACT require location coordinates for the pile burns. The project scenarios are not of actual burns but of modeled burns, so locations for the inputs were created in ArcMap from the center of each WAU area.

Within ArcMap, each of the WAU polygon shape files were converted to a point by using the "Feature to Point" tool with the "inside" option checked. This tool uses a center of gravity-based algorithm to compute points inside a polygon. The resulting layer is the centroids of the WAUs layer as point features. The centroid points are then used with the "calculate geometry" function to generate the X and Y coordinates of the points. Figure 14 shows a map with the newly created centroid points. The resulting layer has the state WAU units with the centroid points and the corresponding XY coordinates in the attribute table.

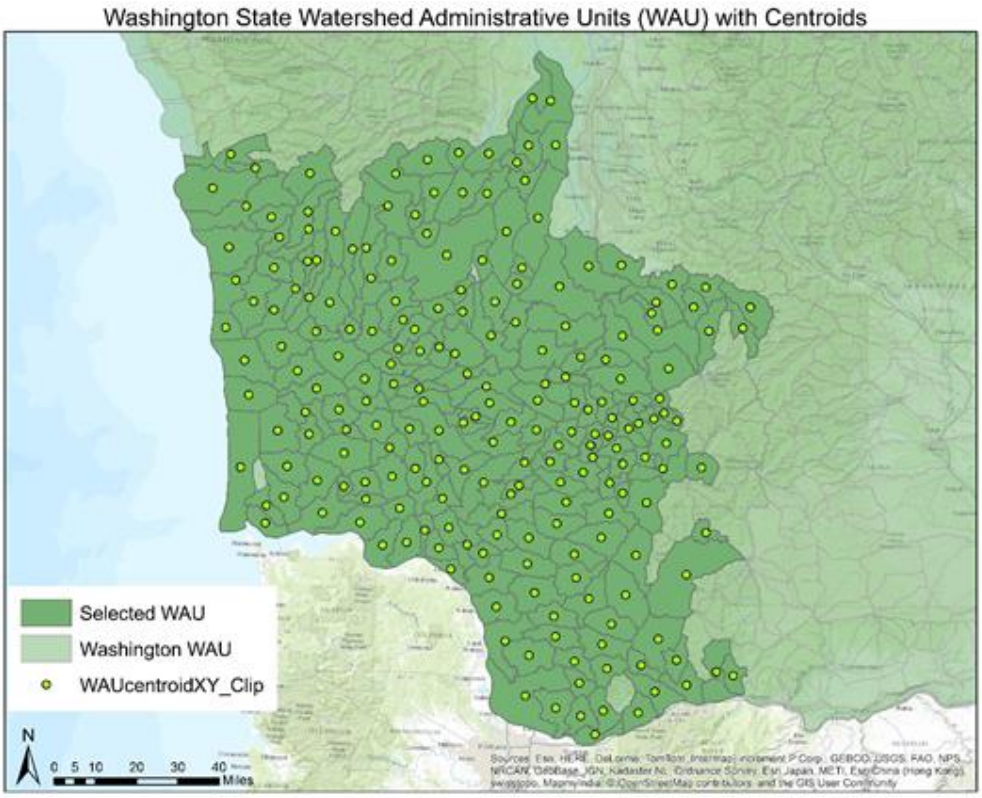

Figure 14. Map showing polygon centroid points.

Using the methods previously described in the methods section, the WAU shapefile layer was converted to a point by using the "Feature to Point" tool. The resulting layer has the state WAU units with the centroid points and the corresponding XY coordinates in the attribute table. Table 4 displays the WAU attribute file with the resulting centroid latitude and longitude points that are used as the burn locations for each WAU. The layers attribute table now displays the XY coordinate for each of the WAUs. The layer attributes are exported as a dbf table and manually added to the locations file that is to be input into the Bluesky files. These coordinates are assigned to the corresponding WAU burns in the Bluesky Playground locations file.

Table 4. ArcMap exported table displaying example WAUs and centroid coordinates in latitude and longitude.

WAU_ID	WAU_NM	WAU_CD	Latitude	Longitude	WAU_ACRES	WAU_UPLAND
169	UPPER WHITE	100106	47.01668	-121.5302	29942.50	29942.50
171	WF WHITE	100108	47.00407	-121.7027	42390.90	42390.90
173	MUD MTN	100203	47.16578	-121.8967	34149.10	34149.10
174	MIDDLE WHITE	100204	47.15817	-121.7228	28676.80	28676.80
175	GREENWATER	100205	47.08987	-121.4921	49586.40	49586.40
176	CLEARWATER	100209	47.08762	-121.7838	24801.90	24801.90

2.5 Chemical concentration and atmospheric interaction- AIRPACT

In order to mitigate air shed regulations and reduce human health impacts from biomass burning, assessment tools that can be tailored for a specific scenario are needed. Slash pile burning requires pre-burning emission estimates and scheduling that reduce the risk of sparking wildfires and overloading an air shed with smoke. Several air quality-monitoring systems are available to assess appropriate burning timeframes and emission estimating.

AIRPACT 4 is a model framework was used to evaluate the chemical transport and interaction (Vaughan et al. 2004; Lamb et al. 2007). The system creates regional air quality forecasts combining multiple models. Meteorological, emission, and chemical grid models are included in the modeling framework and are built into the system. Estimations of emissions are created from AIRPACT based on the source of the emissions (e.g. point or area sources). The system provides a large list of chemical species related to human activity related emissions as well as other sources.

2.5.1 Data formatting

The current AIRPACT system utilizes Bluesky for burn information but in order to input the customized pile burns, all of the previous methods tool and model results have to be formatted for AIRPACT. Each of the initial results had to be formatted and organized in order to achieve the project goals of estimating available residual biomass for a single year, modeling the emissions if it is burnt in piles of various sizes/shapes, and then input that formatted data into AIRPACT for final analysis.

The Biomass Calculator estimated residual biomass inventory for the 214 watershed administrative unit on a 5-year time scale, so the total was divided by 5 in order to obtain one year of biomass amounts. This data was provided on a parcel level spatial scale, which is a very fine scale. The type of harvest, which is a value of percent of cable and ground yarding, is provided with the data as well as estimates of the roadside and marketable biomass. The calculated biomass for each parcel was the marketable biomass plus 20% of the roadside. The volume of biomass available from each parcel varies and in reality, large amounts of biomass would not be burnt in a single day, either because of emission regulations or lack of labor. To assess this issue, we decided that a maximum of 200 tons per parcel was the maximum amount of biomass that could be burnt daily. This decision was based on an estimate of the average biomass of each parcel that occurs in a WAU. If the average amount of biomass per parcel in a WAU was more than 200 tons, then additional burn days would be needed. So 1 day of burn is ≤ 200 tons per parcel, 2 days of burn ≤ 400 per parcel, 3 days of burn ≤ 600 tons per parcel. For example, if a single WAU contained 20 parcels and had a total of 5000 tons of biomass, then the average biomass per parcel is 250 tons. Therefore 2 burn days would be required for that WAU. Using this method means that WAUs with parcels that produced more biomass required more burn days.

Our estimates showed that there were 24 WAUs that required 2 burn days and 13 WAUs that required 3 burn days. As a result, for the WAUs that required 2 burn days, the total biomass was divided in half while for WAUs that required 3 burn days, the total biomass was divided by 3. The amount of biomass to be burnt in each WAU is based on how many burn days the WAU needs.

Each parcel biomass amount was then divided by the percentage of cable yarding and ground yarding (estimated by the biomass calculator) that occurred. The resulting estimates were tons of biomass by cable yarding and tons of biomass by ground yarding. The biomass totals were then distributed by how many tons of each pile size category. Based on our field observations, the biomass from cable yarding was separated into; 75% into the "LargeHE" pile category and 25% into the "MedHE" pile category. The biomass from ground yarding was separated into; 75% into the "MedHE" pile category and 25% into the "SmallHE" pile category. This result suggests that cable yarding sites contain large/medium piles and ground yarding sites contain medium/small piles. Thus, if the area is cable yarded, then a majority of the piles will have "LargeHE" pile characteristics (large sized and half-elliptical shaped). While, if it is mostly ground yarded, then a majority of the piles will have "MedHE" pile characteristics (medium sized and half-elliptical). The pile percentages could be adjusted to a specific scenario for application although for the purpose of this project, these percentages were meant to represent a commonly seen scenario. The results of this method produce the amount of biomass for "LargeHe", "MedHE", and "SmallHE" piles per WAU burn day. Table 5 displays an example total amount of biomass allocated to each pile size (labeled large, med, and small) and the amount of biomass to be burnt in a WAU for day 1, 2, and 3.

Table 5. Results example of the tons of biomass allocated for each pile size.

fire_id	Count	Total_NARA	Large	Medium	Small	Avg_per_parcel	day_1	day_2	day_3
270303	1	432	191	197	44	432	144	144	144
100106	4	887	442	371	74	222	444	444	
100108	5	2081	645	1131	305	416	694	694	694
260332	6	1496	264	946	286	249	748	748	
270406	7	2041	852	963	226	292	1021	1021	
260316	10	2345	906	1155	284	235	1173	1173	
110114	5	3543	2494	995	54	709	1181	1181	1181
110112	8	3892	1588	1861	444	487	1297	1297	1297

The estimated emissions produced from Bluesky Playground simulation are reported on a per pile basis. The different pile category emissions were then divided by the pile tons of biomass in order to produce the emissions-per-ton of biomass burnt. This emission result was then multiplied by the corresponding pile category size amount of biomass that was previously calculated. Those 3 different emissions totals are then summed to provide an estimate of the total emissions produced by the 3 pile types, by WAU. These are the final pile burn emissions to be used with the AIRPACT model.

AIRPACT utilizes data produced by Bluesky but the fire data is fetched fairly automatically by the model, so raw Bluesky Playground output files have to be manually formatted to produce an input file for AIRPACT model. AIRPACT needs specific information about the fires so that it can generate a chemical transport profile. This information includes fire location, fire identification number, emissions from the burn, heat produced, and the area. The location coordinates were produced using ArcMap as previously explained. These coordinates were entered in the Bluesky Playground output file along with the corresponding WAU identification number (ID). Therefore, each WAU has a center point coordinate that represents the fire location or burn area. The "fire_id" variable was edited to contain the WAU ID number and the day of the burn. This means that if a WAU ID was 100 and it was the 1st day of burn for that WAU, the "fire_id" was 1001. If there is a second burn day, the "fire_id" was 1002. Labeling each fire that way made it easier to keep track of the WAU and burn day.

The heat content value was also entered in as an input for the burns in the AIRPACT model. Since individual values were not possible, an average heat value was assigned to the WAU pile burns. This value was the average of the heat content of the small, medium, and large pile burns created in Bluesky Playground.

2.5.2 Burn day distribution

The burn dates were chosen from a burn period window of 29 days in November 2011. The burn month November was chosen due to the large number of pile burns that were conducted statewide by various departments during this month. The year 2011 was chosen based on the project goals and the data availability. As previously stated, there can be multiple burn days for each WAU. The burn dates started on the 1st of the month and continued until the 29th day. To generate a random date for each WAU burn, a random number generator assigned a day from 0-29. For each WAU that had more than one burn day, the subsequent burn days were assigned the next consecutive days. For example, if a WAU was assigned the 15th and it had 2 burn days, the next burn day was assigned to the 16th. On burn days that were assigned at the end of the month, the next burn day was assigned immediately before the first day. For example, if the WAU was assigned the 29th of the month, then the next burn day would be the 28th.

2.5.3 AIRPACT NetCDF formatting

AIRPACT emission files were received in the NetCDF format shown in the ArcMap window, Figure 15. This file format can be projected in ArcMap but the raw data arrives with no spatial reference information due to the AIRPACT data extraction methods. Before the emissions data can be analyzed and computed with other project GIS layers, the data needs to be projected correctly. Initially, a manual method was utilized by importing the NETCDF files into ArcMap and then the "Raster to ASCII" tool was utilized. This converts the NETCDF to an ASCII tile to which the projection information can be linked. The correct spatial reference information was then linked to the ASCII file by adding the ".prj" projection file. Additionally, the ASCII file is manually edited to include the spatial reference info such as rows, columns, cell size, and corners. The ASCII file can now be added as a normal raster layer in ArcMap, complete with spatial reference information that projects correctly.

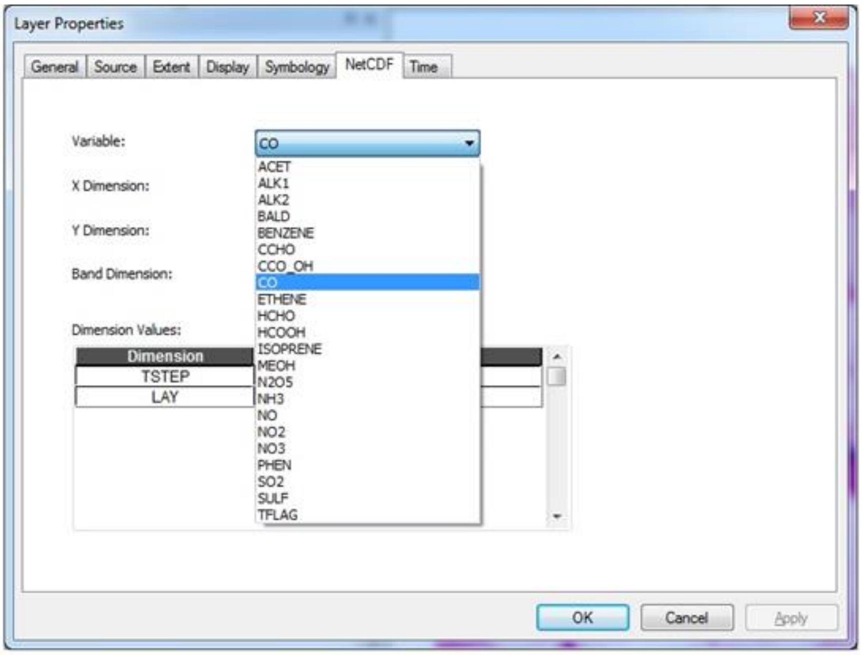

Figure 15. ArcMap properties window for the AIRPACT NetCDF layer file.

2.5.4 AIRPACT formatting results

The initial AIRPACT output data in a NetCDF format was not spatially referenced. Using the previously described methods and assigning spatial reference system the projection is achieved.

Figure 16 displays an example of a NetCDF dispersion of NO2 concentration that has been correctly spatially referenced and is projected across the Pacific Northwest region. The high NO2 concentration in the Northern areas in red-yellow over the Seattle-Tacoma area. The southern high NO2 concentration area is the Portland region. The NetCDF files were then manually separated into chemical species and trimmed down to the state scale using the “mask” tool within ArcMap. Figure 16 displays an AIRPACT NetCDF raster file that has been spatially referenced and is ready for analysis.

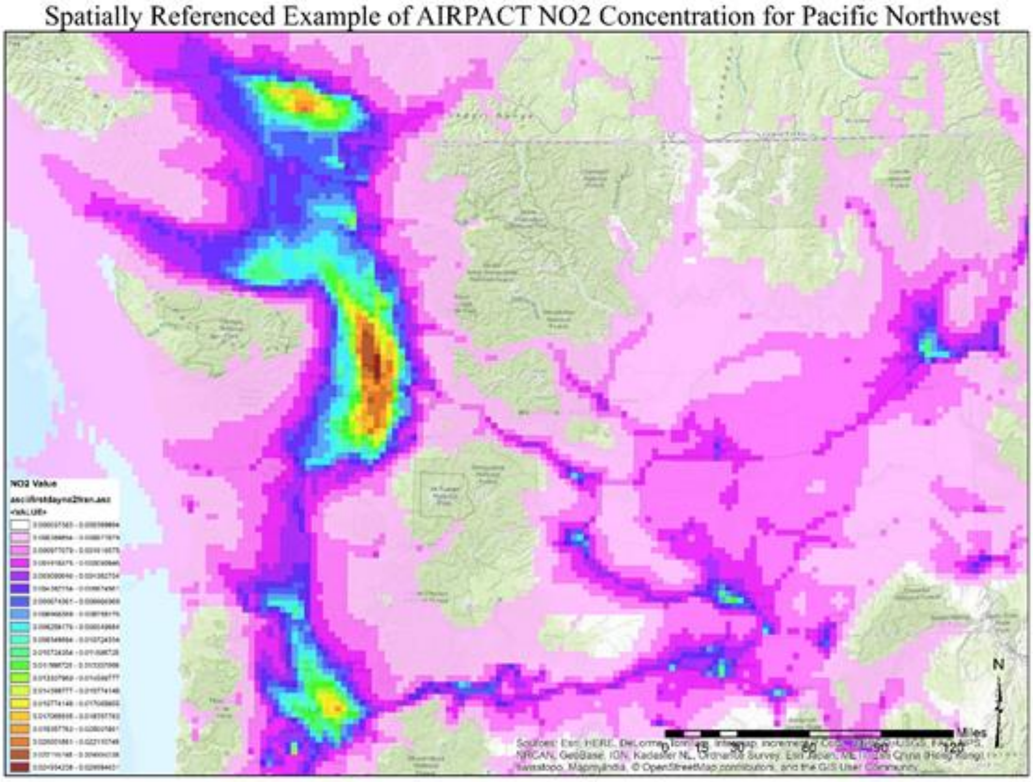

Figure 16. AIRPACT spatially referenced result example.

2.6 Human intake and categorization of concentrations

2.6.1 Producing various types of population layers

Human population densities for the study area were collected from the 2010 Census data (http://www.ofm.wa.gov/pop/geographic/tiger.asp). The population data can be represented on different spatial scales such as county level (Figure 17) or a more detailed level. To get a detailed representation of population in WA, census block level data was utilized.

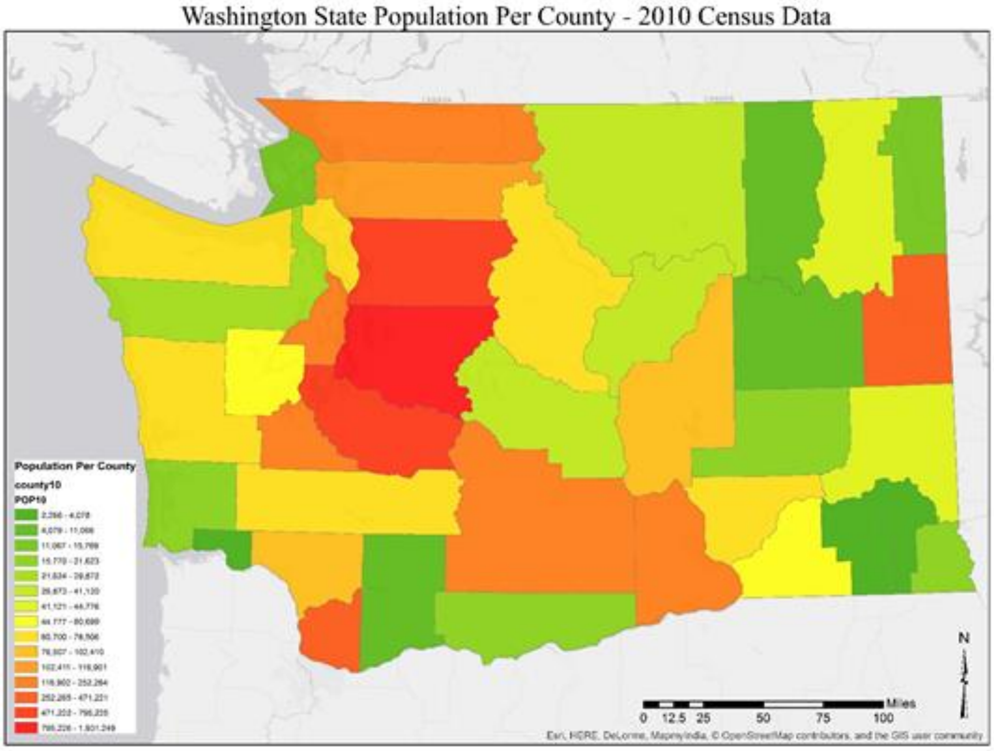

Figure 17. Population by county for Washington State.

In order to calculate emission impacts for a population using ArcMap, it was determined that the population data should be converted to the same scale and file type as the incoming AIRPACT 4 raster files. The higher detailed census block data was chosen for this analysis because AIRPACT 4 output resolution is at a 4km scale and the population data can be represented at the 4km scale also. Census blocks are often much smaller than 4x4km scale, especially in highly populated urban areas (e.g. downtown Seattle). Figure 18 displays the census blocks in the downtown Seattle area in reference to the AIRPACT grid. The figure shows there can be numerous census blocks within a single AIRPACT pixel grid cell in the Seattle downtown area. Although this is a unique, densely populated area, it demonstrates the size difference when city census blocks are compared to the AIRPACT 4km cell size.

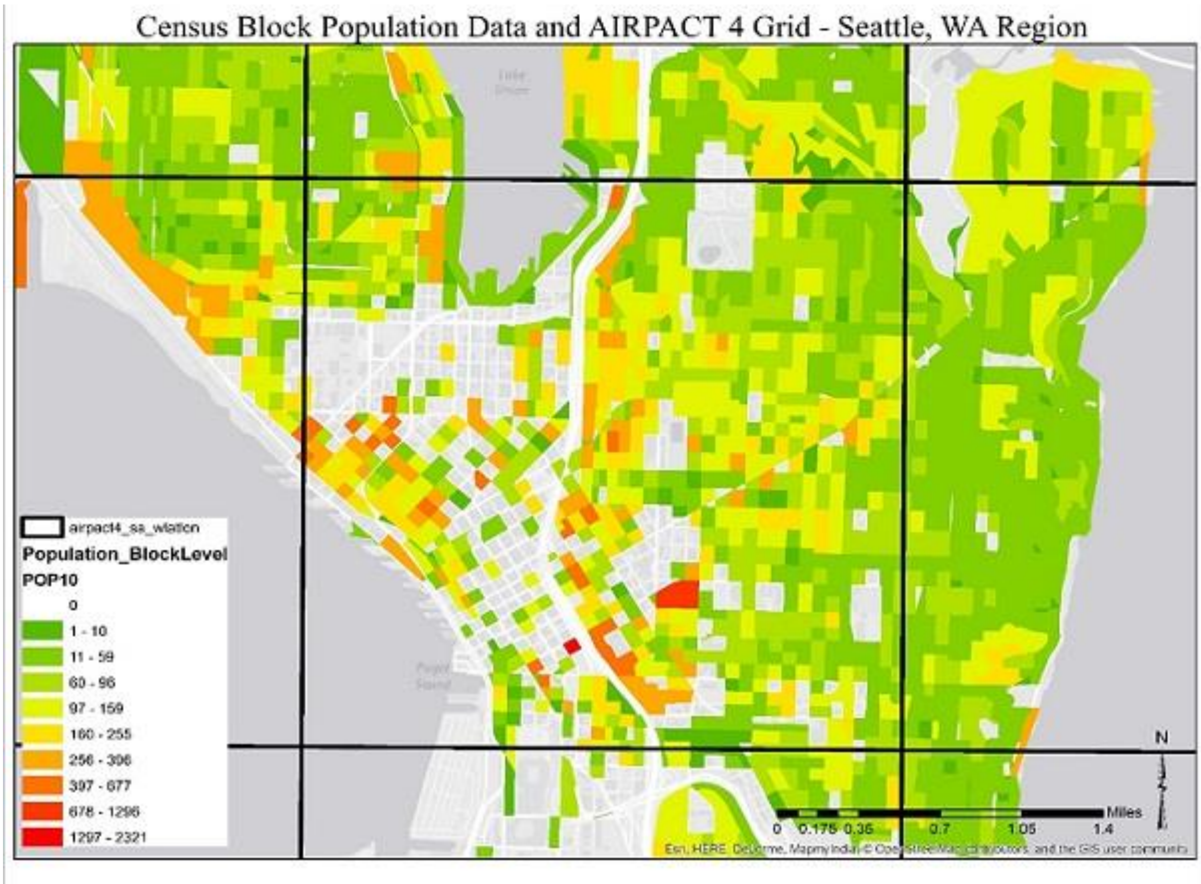

Figure 18. Downtown Seattle WA AIRPACT grid blocks overlayed census blocks.

The county level data was initially rasterized to the 4km AIRPACT spatial scale, although after reviewing the layer, the county level rasterization loses population density accuracy within a county polygon. For example, a large county may have a large population density on one half, but the other half may be sparsely populated. In that case, averaging population over the entire county polygon would create error in areas that actually contain few people.

Census block level data was chosen for this project due to the level of detail the data offers compared to county scale level. The final data output is on a 4km grid scale (AIRPACT output detail quality) so the detailed census block data was rasterized to a 4km grid. To accomplish this, the census block polygon data was converted to point data by creating center points for each polygon. The census points have the same attributes as the source data including the needed population values. The point data was used to create multiple types of population layers using different ArcMap tools. The “Points to Raster” tool was also used to create a layer that produced results directly from census point’s layer. This tool was then configured to sum the population attribute of each census point into one value for each pixel that the points fall in, creating a layer with the total population per pixel.

2.6.2 Population rasterizing results

Figure 19 displays the results after rasterizing the census points and summing the data. This analysis provides information that is unaffected by smoothing functions where each pixel is a direct result of the underlying census point data. The resulting raster is created on a person-per-pixel basis. Every block point census value that fell within each pixel was summed and creates a total population per pixel raster layer. The western high-density area in red-yellow represents the Seattle-Tacoma region while the eastern high-density area represents the Spokane region.

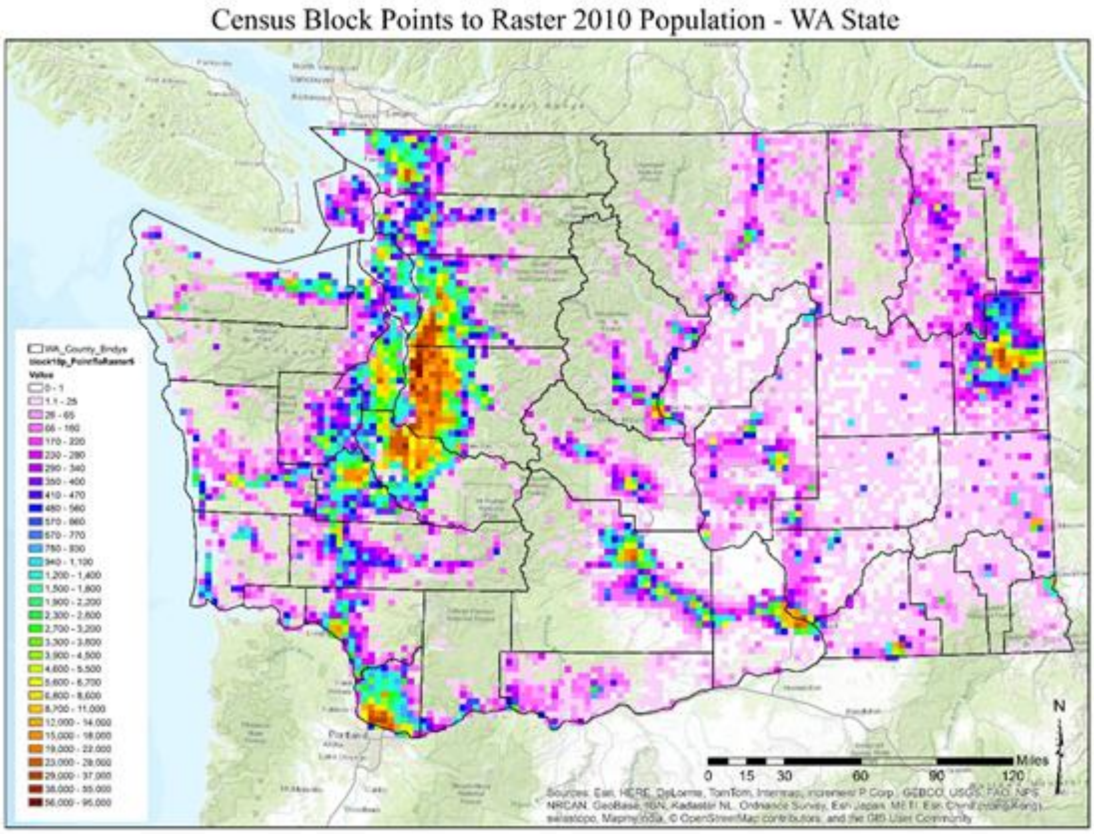

Figure 19. 2010 Census population result using points to raster method of census blocks (people per pixel).

2.6.3 AIRPACT data analysis

Figure 20 displays the AIRPACT PM2.5 output with the Bluesky scenario pile additions for the date of November 29, 2011 in the southwestern region of Washington. On that particular day, the region had a total of five pile burns, which are represented by circular symbols in the map. As seen in the map, there are higher concentrations of PM where the burns are located. Although some pile burn emission plumes can be observed initially, additional analysis needs to be conducted in order to extract the emissions from only the piles burns. Pile burn plumes can become lost in the background AIRPACT concentrations as they are combined with emissions from other sources such as factories or vehicles. The extraction process will be explained in the next sections.

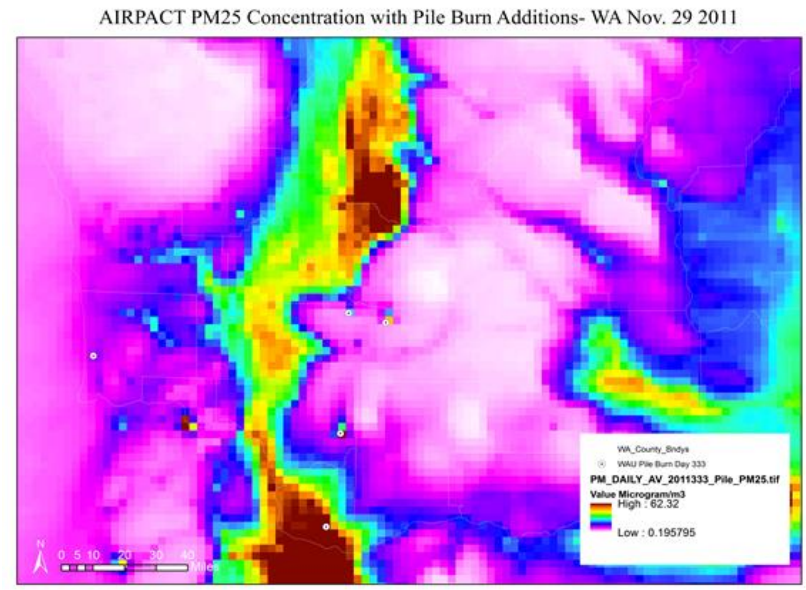

Figure 20. AIRPACT PM2.5 concentrations with Bluesky pile additions November 29, 2011, Southwestern Washington.

2.6.4 Pile emissions extraction

In order to determine the emissions only from contributing pile burns additional analysis is needed. To extract the data, the layers are displayed in ArcMap and the "Minus" tool is applied. While other methods can achieve the goal of finding the difference between layers but the "Minus" tool method was deemed to be the most suitable for the raster layers.

The baseline AIRPACT data without Bluesky input was vital in order to find the difference. The Figures 21 (CO) and 22 (PM2.5) show the baseline or "background" AIRPACT data without the Bluesky burn additions for November 29, 2011 in southwestern Washington. The "Minus" tool is applied and essentially subtracts a pixel value in the first layer from the same pixel in the 2nd layer. This method finds the difference between two raster layers and provides the outputs as a new raster layer. This method was applied to the PM2.5, PM10, and CO data. The results of this method are displayed in the results section.

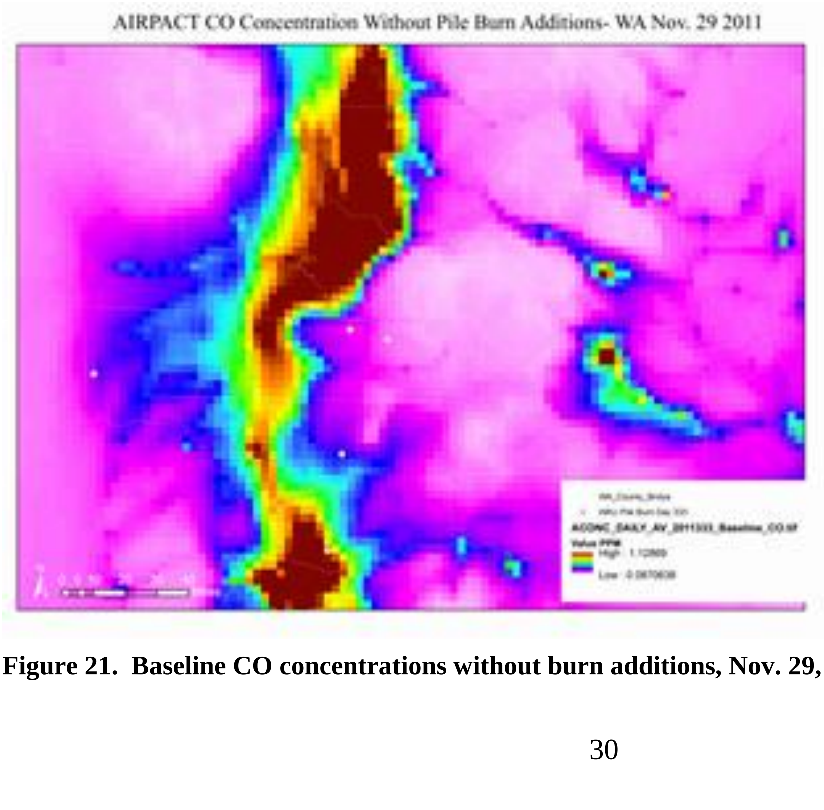

Figure 21. Baseline CO concentrations without burn additions, Nov. 29, 2011.

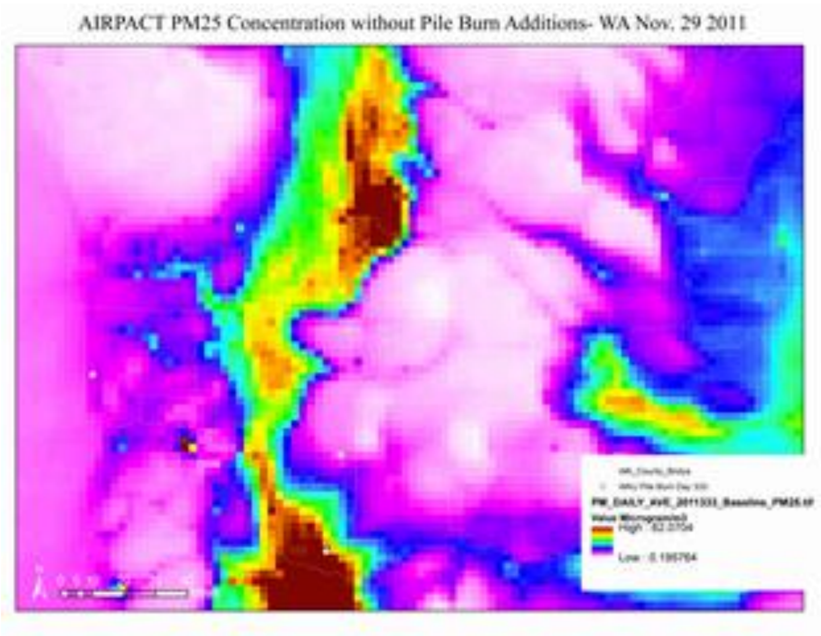

Figure 22. Baseline PM2.5 concentrations without burn additions, Nov. 29, 2011.

2.6.5 AIRPACT pile emission extraction results

Figure 23 displays a map of the results obtained after using the “Minus” tool method. The baseline or background AIRPACT daily average PM2.5 layer is subtracted from the daily average AIRPACT PM2.5 Bluesky pile addition layer, isolating the PM2.5 emissions from the burns. The extraction process estimates the difference between the two layers. Figure 23 shows that the PM2.5 differences range from 0-1 were generally observed although in the vicinity of the pile burns, a difference of up to 33 microgram/m3 can occur. Because the pile burns vary in the total amount of biomass burnt, the burn emissions vary based on the volume burnt. An example of this can be seen on the in Figure 23 where the western most pile burn displays a relatively low difference relative to the other pile burns occurring on that day.

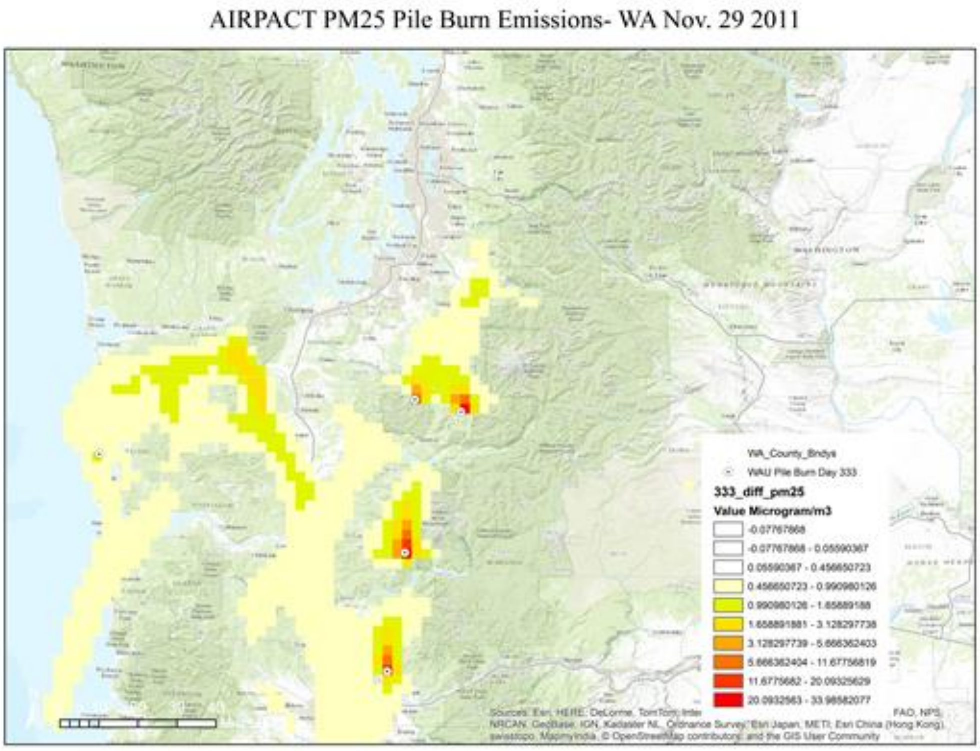

Figure 23. Result of the method for finding the difference between AIRPACT PM2.5 layers.

It is important to note that the emissions can travel a significant distance from the source pile burn. In Figure 23, PM plumes of higher concentrations traveled 4-6 pixels or approximately 12 miles away from the pile location. Lower PM concentrations traveled over 40 miles from the pile burn source.

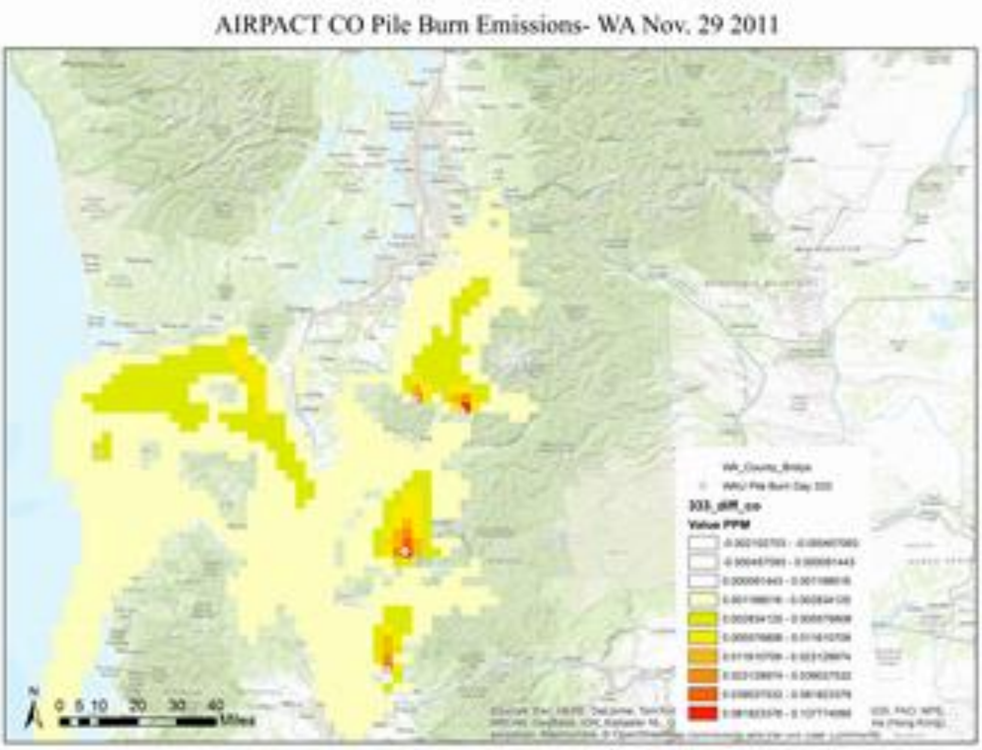

Figure 24. Result from using "Minus" method for CO concentration.

Figure 24 displays the results of the "Minus" tool method. The baseline or background AIRPACT daily average CO layer was subtracted from the daily average AIRPACT CO Bluesky pile addition layer, isolating the CO emissions from the burns. Note that the differences are very small (<1 PPM). The small values occur because the CO modeled concentrations are across over the entire modeled area. Although the differences appear insignificant because of the low values, when compared to the baseline concentrations (maximum is ~1.3PPM), there is significantly higher difference.

3 Results

3.1 CO concentration from pile burning results

Table 6 displays the final CO concentrations obtained from the pile CO extraction methods. For the 29 days under review, the maximum value and the sum of the statewide pixels were calculated. This is the final CO analysis as most regulations are based upon hourly exposure levels, although the EPA has a guideline of an 8-hour measure of 9 ppm or less and an hour measure of 35ppm or less (EPA 2012). The additional CO emitted by the burns appears small with the highest value pixel being modeled at 1 ppm during a burn. Then results show that the total CO emissions (pile burn and ambient) did not exceed the EPA guideline of 9 ppm over an 8-hour period.

Table 6. CO concentration daily totals for the pile burns statewide.

CO from pile burning CO Unit= ppm/V per day				
BURN DAY	Date	MIN	MAX	SUM
305	Nov. 1	0	0.3608	3.3038
306	Nov. 2	0	0.1301	2.7688
307	Nov. 3	0	0.1704	2.0430
308	Nov. 4	0	0.2037	3.6225
309	Nov. 5	0	0.2350	3.4446
310	Nov. 6	0	0.6703	8.6096
311	Nov. 7	0	0.2376	9.9741
312	Nov. 8	0	0.1875	6.0689
313	Nov. 9	0	0.1906	2.9845
314	Nov. 10	0	1.0928	7.5575
315	Nov. 11	0	0.2210	6.4538
316	Nov. 12	0	0.2145	1.9141
317	Nov. 13	0	0.1842	1.5616
318	Nov. 14	0	0.3353	6.6216
319	Nov. 15	0	0.1535	4.5853
320	Nov. 16	0	0.2595	7.4395
321	Nov. 17	0	0.1110	1.5524
322	Nov. 18	0	0.4356	3.6445
323	Nov. 19	0	0.0829	1.5914
324	Nov. 20	0	0.3163	2.1633
325	Nov. 21	0	0.1241	1.4502
326	Nov. 22	0	0.7497	5.9531
327	Nov. 23	0	0.0933	2.0937
328	Nov. 24	0	0.1390	2.1057
329	Nov. 25	0	0.1030	1.0014
330	Nov. 26	0	0.4240	11.7307
331	Nov. 27	0	0.3715	4.7603
332	Nov. 28	0	0.1161	3.4913
333	Nov. 29	0	0.0964	1.3730
			Total=	121.8642

Although there were other chemicals available from the output of AIRPACT, PM2.5 was focused on as the main impacting pollutant due to the large impact to human health and the current PM2.5 research available. Preliminary PM10 analysis was conducted although health standards were not regularly exceeded because the health standard thresholds for PM10 are much higher due of the lower impact that PM10 has on human health.

3.2 Potential human intake of particulate matter (PM) results

3.2.1 Results for Nov. 2nd of PM 10 emissions

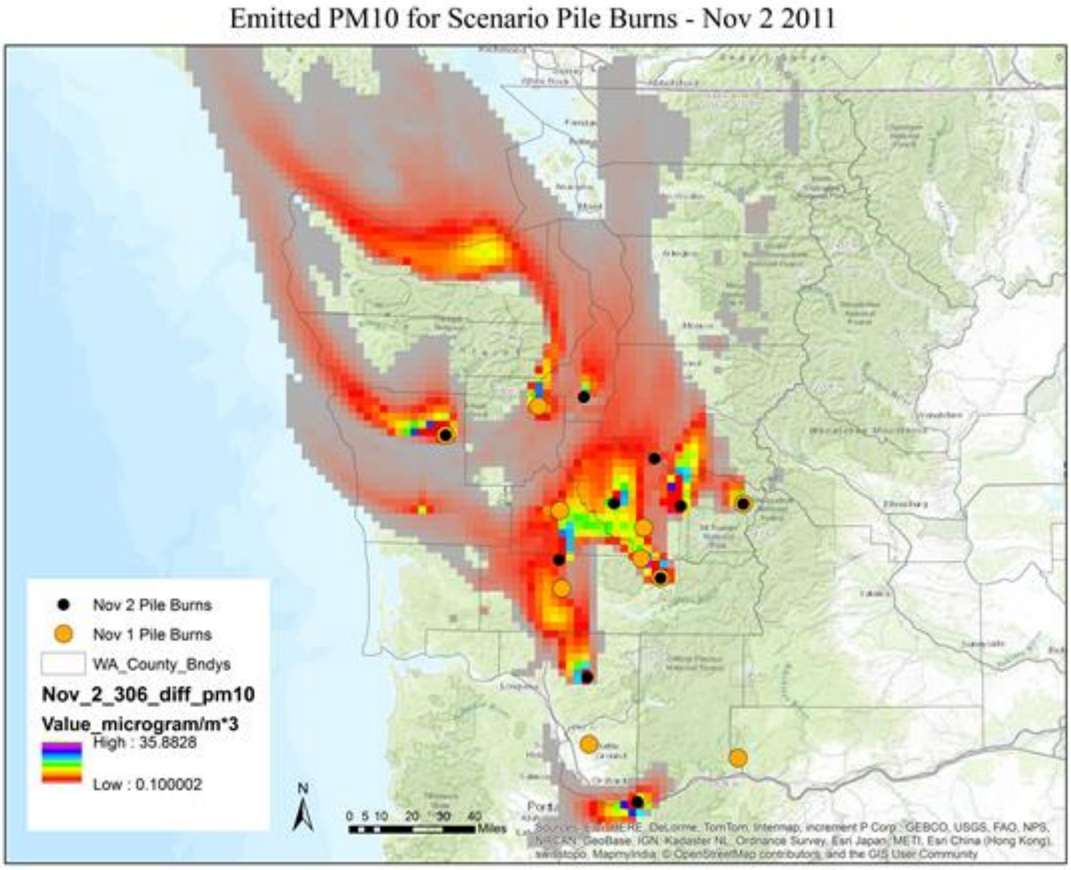

Figure 25. Map displaying emitted PM10 for Nov. 2 pile burns.

In order to estimate the human impacts from the PM concentration AIRPACT results (Figure 25), values were first multiplied by a human inhalation rate of 13 m3/day (EPA 1997; Huijbregts et al. 2015) that reflect an average concentration of PM that can be inhaled by a person daily. The final step was to multiply the PM inhalation layer by the population density layer to obtain the potential intake of PM10 result. The pile burns on Nov. 2nd are represented as black dots while the burns from Nov. 1st are represented as larger orange dots in order to show where the previous days burns occur. Lower concentrations of PM emissions are represented by the pixels in shades of green, yellow, orange, and red. Higher concentrations of PM emissions are represented by shades of white, pink and blue. On Nov 2nd, 33,728 tons of residual biomass was burnt (Table 7). Table 7 includes the WAU name and size as well as the amount of biomass for each pile size.

Table 7. Table showing the piled biomass amounts to be burnt on November 2nd.

WAU_CD	WAU_NM	WAU_Acres	Sum_All_Piles	Large	Medium	Small
100106	Upper White	29,942	887.08	442.06	370.61	74.42
220315	Lower Wynoochee	41,296	8626.37	6230.73	2315.96	79.68
110110	Mineral Creek	21,692	13255.35	4396.42	7010.56	1848.36
230405	Hanaford	41,792	1223.63	817.40	372.79	33.44
280107	MT Zion	22,693	1146.17	312.51	651.29	182.37
100418	Carbon	89,631	4685.09	2586.56	1789.45	309.09
100302	Lower White	46,759	23.18	8.30	11.85	3.03
150107	S Sinclair Inlet	26,203	247.50	177.30	67.43	2.78
110301	Muck Creek	79,444	682.75	507.54	173.71	1.51
260709	Upper Coweeman	45,108	2951.73	689.62	1754.05	508.06
				Total=	33728.87	tons

The results of combing the PM10 inhalation data and the population density data are displayed in Figure 26. The PM10 concentrations that impact higher densities of people are represented by the green, yellow, orange, and red colored pixels. Lower impacted populations are represented by the white, pink and blue colored pixels. In order to estimate the total amount of PM for the entire day, the pixels were summed in ArcMap and exported as .dbf tables. This process of combining daily rasters with the population layer and to generate total PM tables was conducted for the entire 29 days of pile burns for both PM10 and PM2.5. On the day of November 2nd, the total amount of PM10 to which the population was exposed totaled in 23,446,113 micrograms (Table 8). The “Burn Day” value of 306 represents the day of the year and the “Max” value of 484,015 micrograms represents the maximum PM pixel value that occurred in the raster.

Total Human Intake of PM10 for Scenario Pile Burns on Nov 2 2011

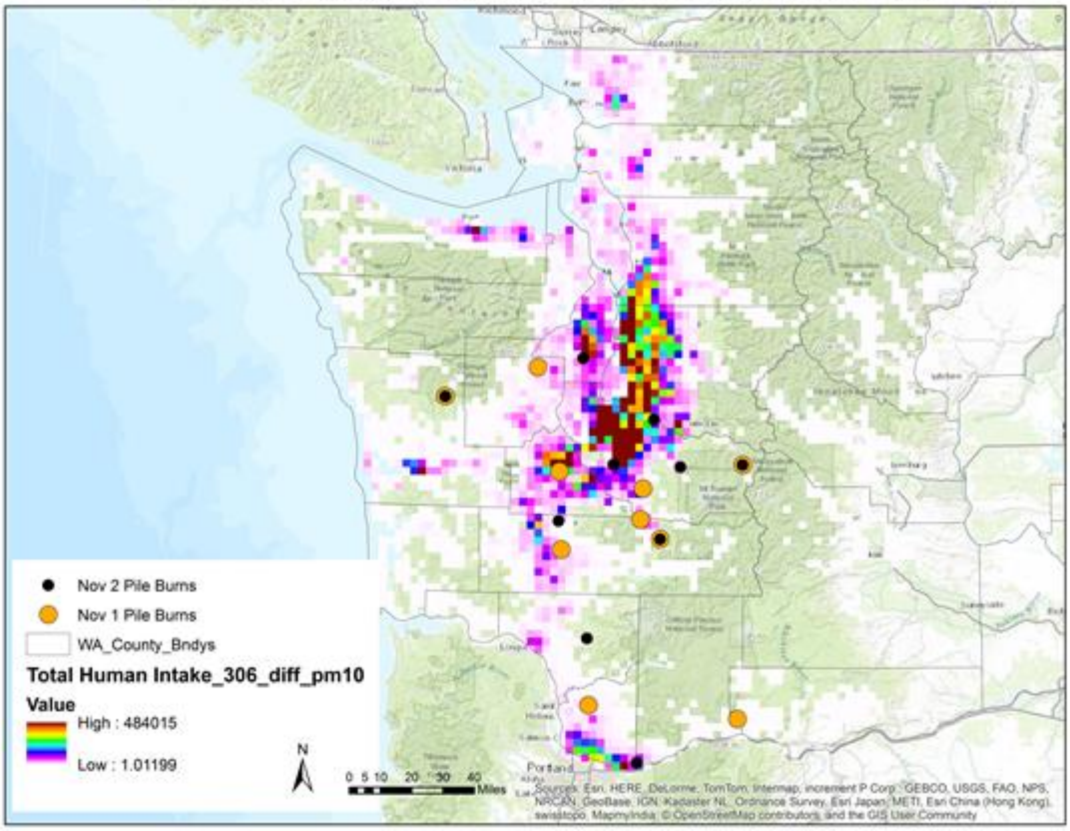

Figure 26. Map displaying PM10 potentially inhaled by the population for November 2nd.

Table 8. Burn date and the associated final sum of PM10 that can potentially be inhaled by the state population. (Unit= micrograms of PM10 breathed by the population per day)

Unit= µg				(micrograms per day)
BURN DAY		MIN	MAX	SUM
306	Nov. 2	0	484,015.38	23,446,113.40

3.2.2 Result example Nov. 13th PM2.5

Figure 27 displays another example of the PM emissions analysis. The PM2.5 concentrations for the day of November 13th is shown in Figure 27 with higher concentrations of PM2.5 emissions shown as pixels in shades of green, yellow, orange, and red. Lower concentrations of PM2.5 emissions are represented by the red and gray colored pixels. The orange dots represent the pile burn locations for November 13th.

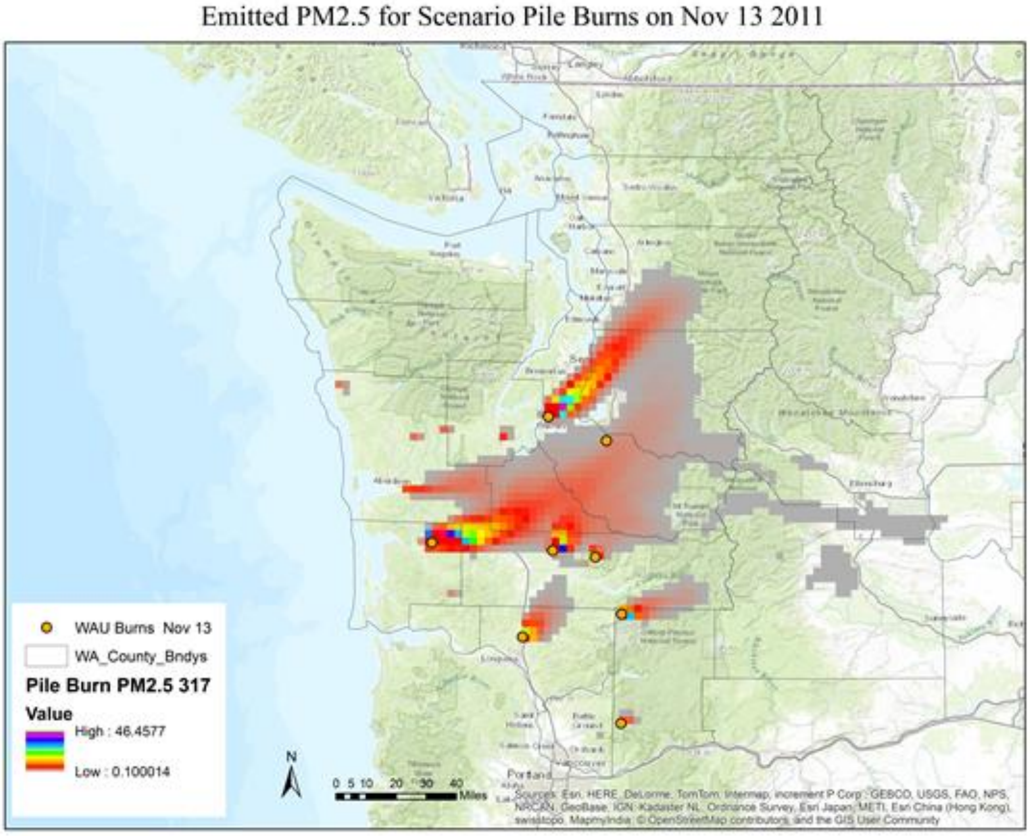

Figure 27. Map displaying PM2.5 for November 13th.

The analysis shows that on Nov. 13th, 26,541 tons of residual biomass was burnt, Table 9. The results include the watershed administrative unit name and size as well as the amount of biomass in each pile size.

Table 9. Table showing the amount of biomass to be burnt of each pile on Nov. 13th.

WAU_CD	WAU_NM	WAU_Acres	Sum_All_Piles	Large	Medium	Small
150106	Key Peninsula	83447	4766.99	3541.36	1214.33	11.29
260824	Lower Cowlitz	27941	1172.15	653.05	443.74	75.35
100601	Lower Puyallup	88673	29.95	21.57	8.08	0.30
240304	Wilson Creek	30344	8012.05	2822.14	4127.61	1062.30
230307	NF Newaukum	33533	4001.25	1454.30	2031.41	515.55
270507	Copper Creek	30691	300.49	90.15	165.27	45.07
260332	NF Tilton	20832	1495.66	264.18	945.62	285.85
260506	Upper Green	38926	6762.15	3252.666	2903.17	606.32
				Total=	26540.68	tons

The results obtained by multiplying the November 13th PM2.5 inhalation data with the population density data are displayed in Figure 28. Concentrations of PM2.5 emissions that impact a higher density of people are represented by the shades of green, yellow, orange, and red colored pixels. Lower impacted populations are shown in the white, pink and blue colored pixels. The results clearly show that t was more PM2.5 being potentially inhaled by people around the Seattle region, due to the larger density of people in the region as well as the higher concentration of PM2.5 in the atmosphere.

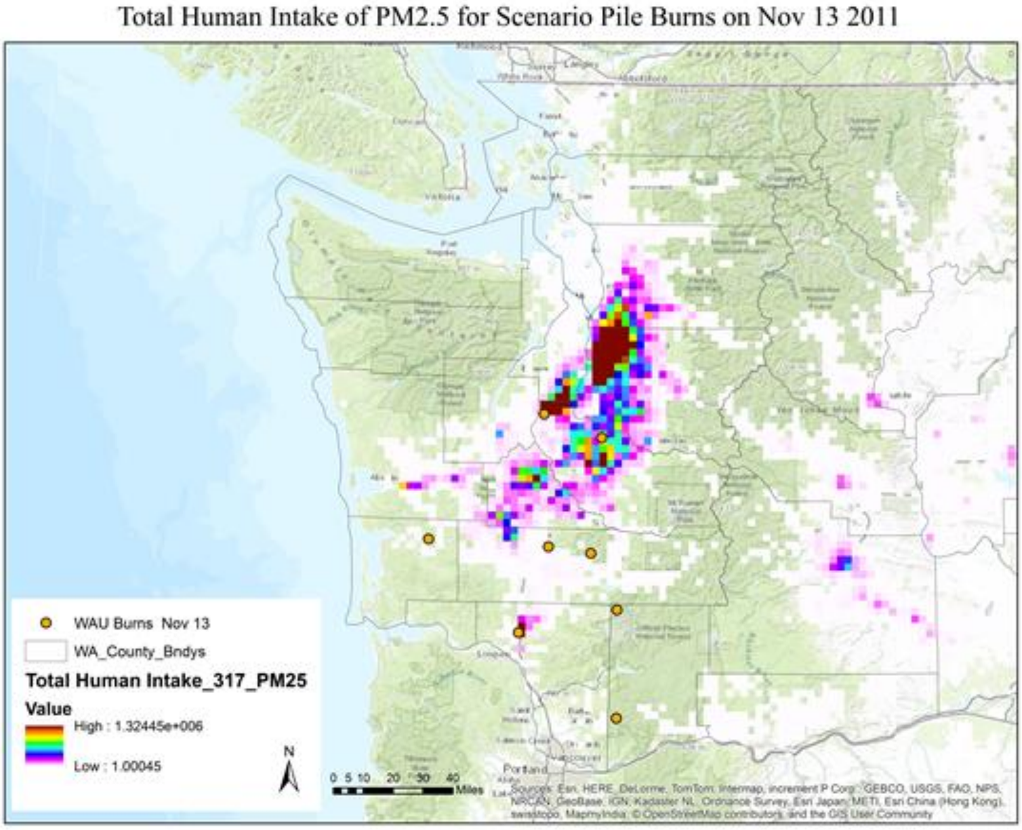

Figure 28. Map displaying PM2.5 potentially inhaled by the population for November 13th.

On the day of November 13th, the total amount of PM2.5 exposures to the population in the region was 19,309,572 micrograms, Table 10. The "Burn Day" value of 317 represents the day of the year and the "Max" value of 1,324,449 represents the maximum PM2.5 exposures that occurred in the raster.

Table 10. Burn date and the associated final sum of PM2.5 to be inhaled by the state population. (Unit= micrograms of PM2.5 breathed by the population per day).

(micrograms per day) Unit= µg					
BURN DAY		Date	MIN	MAX	SUM
317		Nov. 13	0	1,324,448.75	19,309,571.82

3.2.3 Results for the statewide potential intake totals for PM

Table 11 displays the estimate of the PM10 human intake maximum value and the total potential exposure for the state each day.

Table 11. PM10 potential intake totals for the state for the 29-day burn.

PM10 Exposure per day Unit=μg					
BURN DAY			MIN	MAX	Total PM10 potential intake for the state
305		Nov. 1	0	1,992,367.00	9,235,275.55
306		Nov. 2	0	484,015.38	23,446,113.40
307		Nov. 3	0	209,314.34	7,633,545.09
308		Nov. 4	0	310,354.34	9,667,358.75
309		Nov. 5	0	221,363.36	15,175,312.11
310		Nov. 6	0	2,056,446.13	25,236,862.91
311		Nov. 7	0	1,377,497.50	92,731,602.99
312		Nov. 8	0	1,180,283.75	44,912,250.42
313		Nov. 9	0	1,998,223.38	26,725,476.91
314		Nov. 10	0	2,382,254.00	53,036,418.19
315		Nov. 11	0	924,382.56	43,142,519.87
316		Nov. 12	0	450,273.69	21,083,892.32
317		Nov. 13	0	1,362,703.25	19,857,682.33
318		Nov. 14	0	4,738,167.00	39,785,321.32
319		Nov. 15	0	1,776,898.88	58,011,696.82
320		Nov. 16	0	335,816.47	15,272,348.93
321		Nov. 17	0	96,534.96	4,086,308.82
322		Nov. 18	0	562,646.25	7,153,828.35
323		Nov. 19	0	540,408.63	9,590,814.98
324		Nov. 20	0	234,725.41	12,303,410.12
325		Nov. 21	0	590,906.63	23,619,920.34
326		Nov. 22	0	184,908.84	2,025,524.61
327		Nov. 23	0	1,324,942.13	11,351,305.45
328		Nov. 24	0	194,734.72	14,417,233.31
329		Nov. 25	0	214,628.36	11,002,986.45
330		Nov. 26	0	1,424,635.13	35,646,460.99
331		Nov. 27	0	562,556.38	12,257,766.20
332		Nov. 28	0	627,727.31	21,990,657.68
333		Nov. 29	0	297,348.59	14,625,599.28
				29 Day Total=	685,025,494.48

Table 12 displays the estimate of the PM2.5 human intake maximum value and the total potential exposure of the state each day.

Table 12. PM2.5 potential intake totals for the state for the 29-day burn.

PM2.5 Exposure per day Unit=µg					
BURN DAY			MIN	MAX	Total PM2.5 potential intake for the state
305		Nov. 1	0	1,783,064.88	8,528,891.87
306		Nov. 2	0	453,206.94	22,413,154.05
307		Nov. 3	0	197,664.00	7,266,473.38
308		Nov. 4	0	275,025.63	9,182,696.69
309		Nov. 5	0	212,823.16	14,647,845.57
310		Nov. 6	0	1,835,805.63	23,687,915.07
311		Nov. 7	0	1,321,427.00	88,826,835.67
312		Nov. 8	0	1,112,600.00	43,159,930.97
313		Nov. 9	0	1,766,233.00	25,088,654.57
314		Nov. 10	0	2,122,776.00	49,312,566.89
315		Nov. 11	0	890,401.25	41,350,883.85
316		Nov. 12	0	448,339.19	20,966,244.71
317		Nov. 13	0	1,324,448.75	19,309,571.82
318		Nov. 14	0	4,232,970.50	38,006,567.19
319		Nov. 15	0	1,717,142.13	56,376,745.15
320		Nov. 16	0	325,344.31	14,811,994.86
321		Nov. 17	0	88,697.24	4,026,046.28
322		Nov. 18	0	495,710.44	6,775,097.85
323		Nov. 19	0	476,577.59	9,107,010.30
324		Nov. 20	0	220,155.05	11,604,473.53
325		Nov. 21	0	583,523.50	23,125,046.97
326		Nov. 22	0	166,059.25	1,911,590.86
327		Nov. 23	0	1,187,471.88	10,634,720.96
328		Nov. 24	0	190,256.27	14,009,854.95
329		Nov. 25	0	210,975.11	10,737,742.25
330		Nov. 26	0	1,386,673.25	34,557,926.48
331		Nov. 27	0	500,423.25	11,794,283.29
332		Nov. 28	0	610,872.81	21,514,362.39
333		Nov. 29	0	265,987.13	14,243,084.29
				29 Day Total=	**656,978,212.72**

3.3 Concentration results and air quality standards

Recent changes to the EPA air quality standards are shown in Table 13. These recently updated health guidelines for PM are used for this research. The World Health Organization PM guideline was also utilized in this research (WHO 2013). These guidelines are continuously being updated as more research is conducted involving the impact of air pollution on human health, as seen in the revisions since 1971. Research in this area is becoming more important due to an increase in anthropogenic sources of pollution (vehicle exhaust, industry, etc.) but also non-anthropogenic sources such as emissions from wild fires.

Table 13. Revisions of PM 2.5 Air Quality Index (AQI). (EPA 2012)

AQI Category	Index Values	Previous Breakpoints ($\mu g/m^3$, 24-hour average)	Revised Breakpoints ($\mu g/m^3$, 24-hour average)
Good	0 - 50	0.0 - 15.0	0.0 – **12.0**
Moderate	51 - 100	>15.0 - 40	12.1 – **35.4**
Unhealthy for Sensitive Groups	101 – 150	>40 – 65	35.5 – **55.4**
Unhealthy	151 – 200	> 65 – 150	55.5 – 150.4
Very Unhealthy	201 – 300	> 150 – 250	150.5 – 250.4
Hazardous	301 – 400	> 250 – 350	250.5 – 350.4
Hazardous	401 – 500	> 350 – 500	350.5 – 500

3.3.1 WHO annual standards

PM concentration results were compared to EPA and WHO air quality long-term annual guidelines based on the 29-day average during the burn period. The average concentrations are based on the scenario pile burns and the modeled ambient air quality. Figure 29 displays the 29-day average for PM2.5 where concentrations exceeded the EPA annual guideline of 12 micrograms per cubic meter and the WHO long-term guideline of 10 micrograms per cubic meter. The poor air quality shown in Figure 30 around the more highly populated Seattle, Tacoma, and Portland regions is related more to other sources such as vehicles and industry, although the scenario pile burns do contribute to the poor air quality but mainly have a higher impact on a daily basis instead of averaged over the burn period.

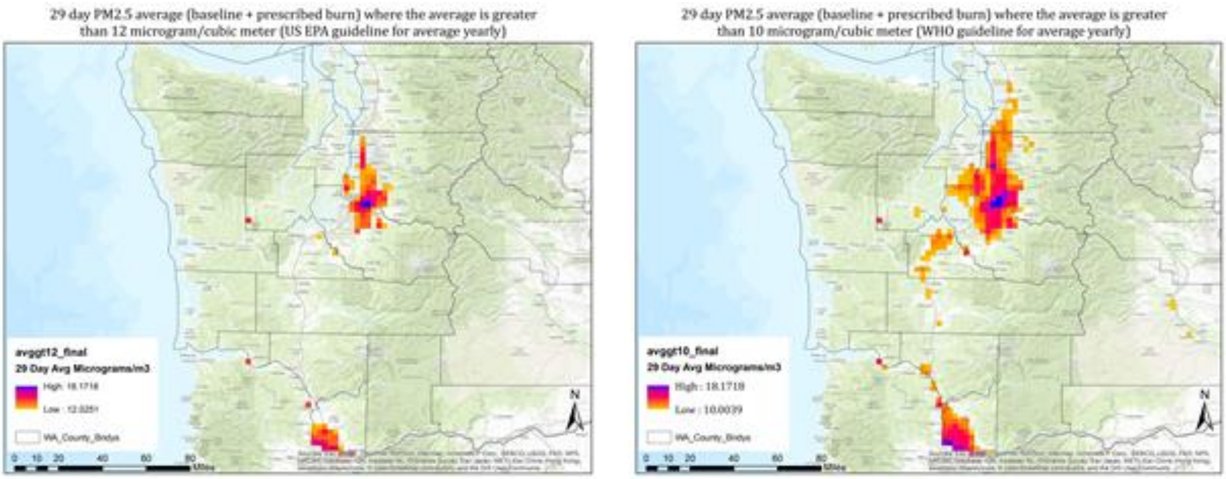

Figure 29. 29-day average values for the burn period and the air quality annual guidelines.

3.3.2 Side-by-Side Baseline and Pile Comparison

Maps were created for several days that include the days "Baseline" or ambient PM2.5 concentrations (without pile burns) and the pile burns with the baseline data. The PM2.5 values were categorized into ranges from 0-10 $\mu g/m^3$, 10-15, 15-25, 25-35.5 (WHO guideline), 35-55.4 (EPA "Unhealthy for Sensitive Groups" guideline), 55.5-150.4 (EPA "Unhealthy" guideline). Classifying the PM2.5 values into categories created a better visual result for displaying areas where poor air quality occurred. The comparison between the 2 sets of data show where the additional emissions from pile burns contributed to the PM2.5 concentrations in the region shown in Figures 30-31. The dots in

Figure 30 on the represent pile burn locations and the black arrows point to various areas where pile burns occurred and sometimes increased the pixel values into the next higher category. The areas where the arrows point display concentrations where the PM has increased due to the additional pile burn emissions.

Figure 30 depicts the results for November 7th and there are several areas where pixel categories are increased due to the additional pile burns. The blue and purple dots represent the two previous days burn locations in a case where the PM2.5 emissions from large pile burns were still lingering.

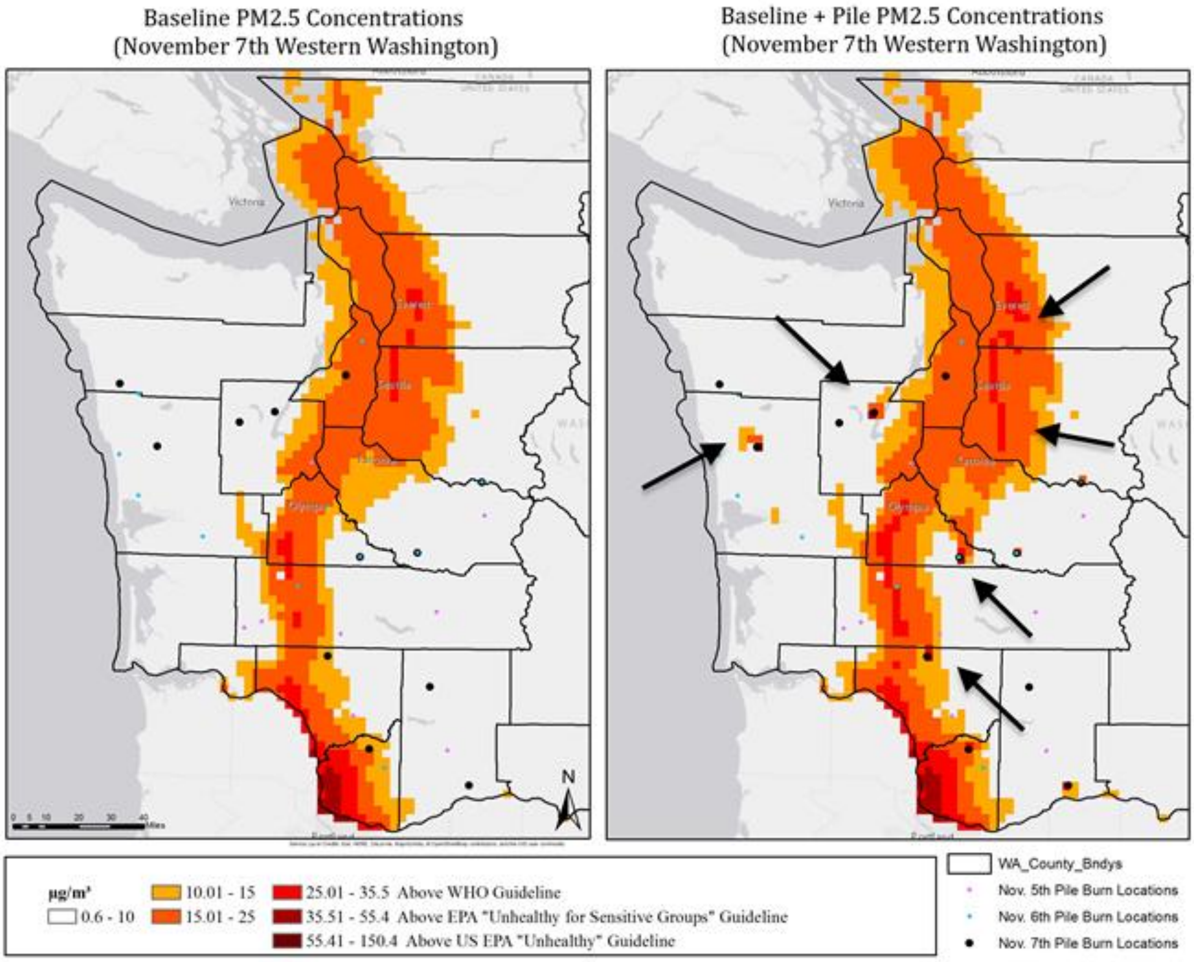

Figure 30. Maps displaying baseline and piles concentrations categorized by air quality guidelines (Nov. 7).

Figure 31 is another comparison example of PM2.5 concentrations for November 28th. There are some areas of higher concentration where there is a pile burn but if the concentrations were not above the lowest threshold, no values are shown.

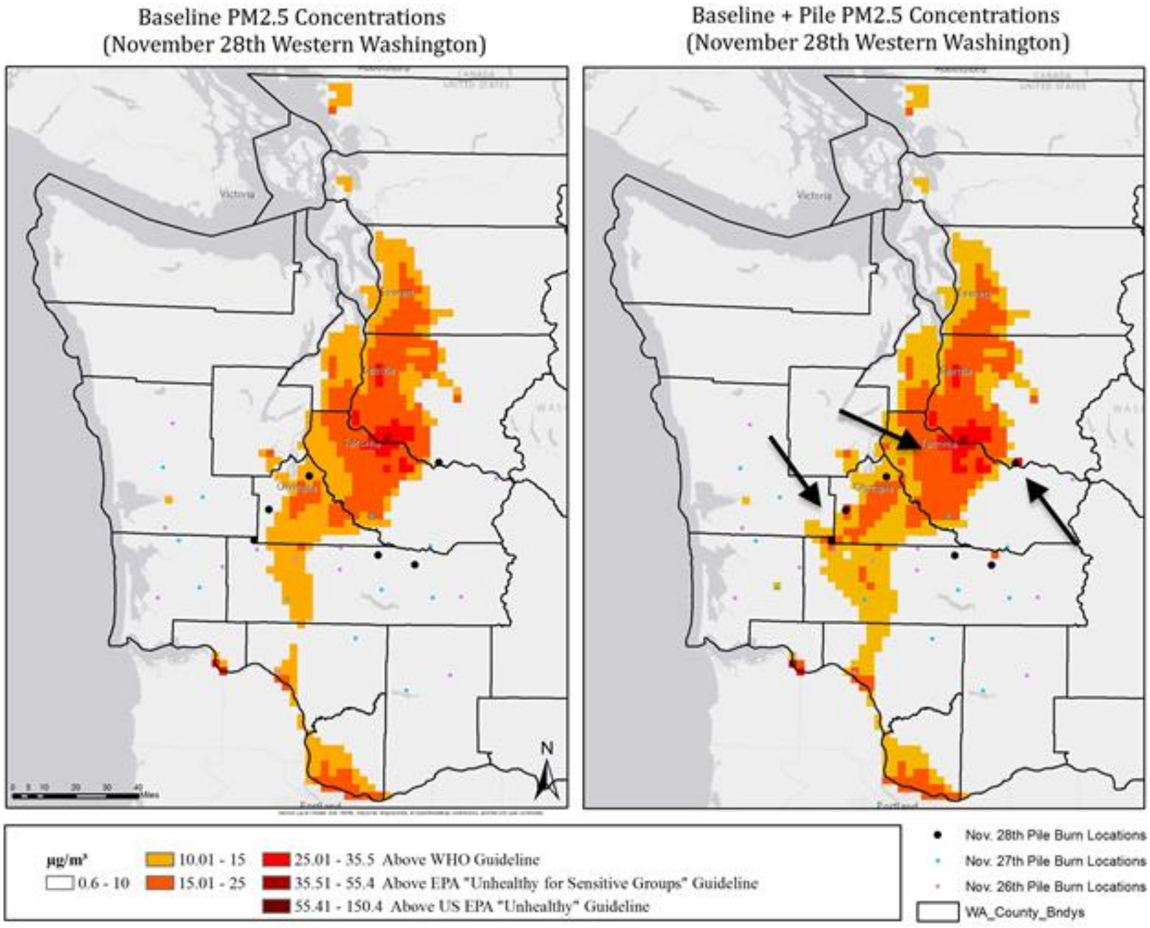

Figure 31. Maps displaying baseline and piles concentrations categorized by air quality guidelines (Nov. 28).

Table 14. Chart showing the daily maximum daily average values statewide and the PM2.5 air quality guidelines

Days when a pixel of the total ambient 24 hours pm2.5 average is greater than:
(Max pixel (AIRPACT 4x4km Cell) value of PM2.5 daily Avg µg/m3)

Burn Day of Year	Burn Day		**25 microgram/cubic meter** (WHO guideline)		**35.5-55.4 microgram/cubic meter** (US EPA guideline - Unhealthy for Sensitive Groups)	**55.5-150.4 microgram/cubic meter** (US EPA guideline - Unhealthy)	**150.5-250.4 microgram/cubic meter** (US EPA guideline - Very Unhealthy)	**250.5-350.4 microgram/cubic meter** (US EPA guideline - Hazardous)
			AIRPACT Baseline With No Burns	AIRPACT Baseline with Pile Burns				
305	Nov. 1	305	**36.49**	104.00	104.00	104.00	104.00	104.00
306	Nov. 2	306	**22.41**	33.97	33.97	33.97	33.97	33.97
307	Nov. 3	307	**19.98**	46.63	46.63	46.63	46.63	46.63
308	Nov. 4	308	**40.34**	57.84	57.84	57.84	57.84	57.84
309	Nov. 5	309	**24.71**	67.91	67.91	67.91	67.91	67.91
310	Nov. 6	310	**42.85**	182.37	182.37	182.37	182.37	182.37
311	Nov. 7	311	**40.15**	65.50	65.50	65.50	65.50	65.50
312	Nov. 8	312	**31.76**	51.98	51.98	51.98	51.98	51.98
313	Nov. 9	313	**24.73**	49.06	49.06	49.06	49.06	49.06
314	Nov. 10	314	**27.45**	291.65	291.65	291.65	291.65	291.65
315	Nov. 11	315	**37.89**	57.81	57.81	57.81	57.81	57.81
316	Nov. 12	316	**15.29**	53.06	53.06	53.06	53.06	53.06
317	Nov. 13	317	**15.11**	48.23	48.23	48.23	48.23	48.23
318	Nov. 14	318	**17.31**	92.04	92.04	92.04	92.04	92.04
319	Nov. 15	319	**29.19**	42.49	42.49	42.49	42.49	42.49
320	Nov. 16	320	**13.84**	45.95	45.95	45.95	45.95	45.95
321	Nov. 17	321	**6.91**	26.44	26.44	26.44	26.44	26.44
322	Nov. 18	322	**20.96**	116.04	116.04	116.04	116.04	116.04
323	Nov. 19	323	**26.17**	26.34	26.34	26.34	26.34	26.34
324	Nov. 20	324	**42.47**	128.60	128.60	128.60	128.60	128.60
325	Nov. 21	325	**18.39**	32.48	32.48	32.48	32.48	32.48
326	Nov. 22	326	**5.89**	109.29	109.29	109.29	109.29	109.29
327	Nov. 23	327	**15.15**	24.34	24.34	24.34	24.34	24.34
328	Nov. 24	328	**15.74**	36.47	36.47	36.47	36.47	36.47
329	Nov. 25	329	**16.50**	28.11	28.11	28.11	28.11	28.11
330	Nov. 26	330	**32.78**	115.26	115.26	115.26	115.26	115.26
331	Nov. 27	331	**13.19**	96.32	96.32	96.32	96.32	96.32
332	Nov. 28	332	**35.70**	42.10	42.10	42.10	42.10	42.10
333	Nov. 29	333	**37.68**	38.80	38.80	38.80	38.80	38.80
				28 /29 Days concentration surpasses WHO guideline	**23/29** Days concentrations within US EPA "Unhealthy for Sensitive Groups" level	**13 /29** Days concentrations within US EPA guideline "Unhealthy" level	**2/29** Days concentrations within US EPA guideline "Unhealthy" level	**1/29** Days concentrations within US EPA guideline "Hazardous" level

Table 14 displays the days where the PM2.5 maximum value exceeded an air quality guideline and the corresponding day of only the baseline/ambient max value. A maximum daily average value is the highest pixel value occurring anywhere in the state during that day. Days when the total (baseline + prescribed burn) ambient 24 hours pm2.5 average is greater than:

- 25 microgram/cubic meter (WHO guideline)
  Exceeded 28 out of 29 days
- 35.5 microgram/cubic meter (US EPA guideline "Unhealthy for Sensitive Groups")
  Exceeded 23 out of 29 days
- 55.5 microgram/cubic meter (US EPA guideline "Unhealthy")
  Exceeded 13 out of 29 days
- 150.5 microgram/cubic meter (US EPA guideline "Very Unhealthy")
  Exceeded 2 out of 29 days
- 250.5 microgram/cubic meter (US EPA guideline "Hazardous")
  Exceeded 1 out of 29 days

The table data that was shown previously is portrayed in Figure 32 as a chart. The green line displays the baseline/ambient concentrations over the 29-day period. The red line shows the values of the baseline data in addition to the pile burn emissions. The WHO guideline of 25 micrograms per cubic meter is shown as a thin purple line and the EPA guideline of 35.5 micrograms per cubic meter "unhealthy for sensitive groups" is shown as a thin orange line. Shown in Figure 32, the pile burn and baseline maximum values can be significantly higher than the initial EPA and WHO guidelines.

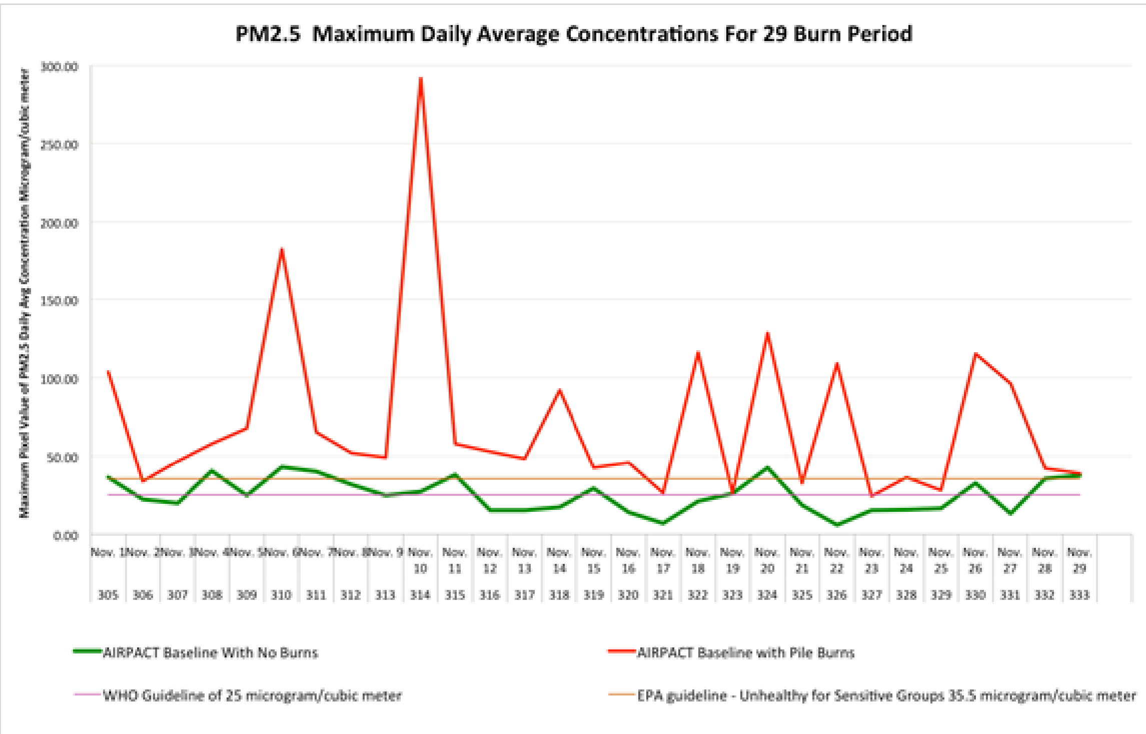

Figure 32. Chart displaying the previous table maximum values of the baseline and the pile burns and EPA/WHO initial guidelines.

3.3.3 Impacted Populations

For the final result, the populations that are impacted daily by the pile burns was calculated. Figure 33 displays populations that were impacted daily by a concentration of PM2.5 greater than 25µg/m³. The population that was impact by the baseline or ambient PM2.5 is displayed by orange colored pixels. The additional population that was impacted daily by the added pile burns is represented as red colored pixels. Some areas will have a larger number of additional impacted populations due to the densely populated area.

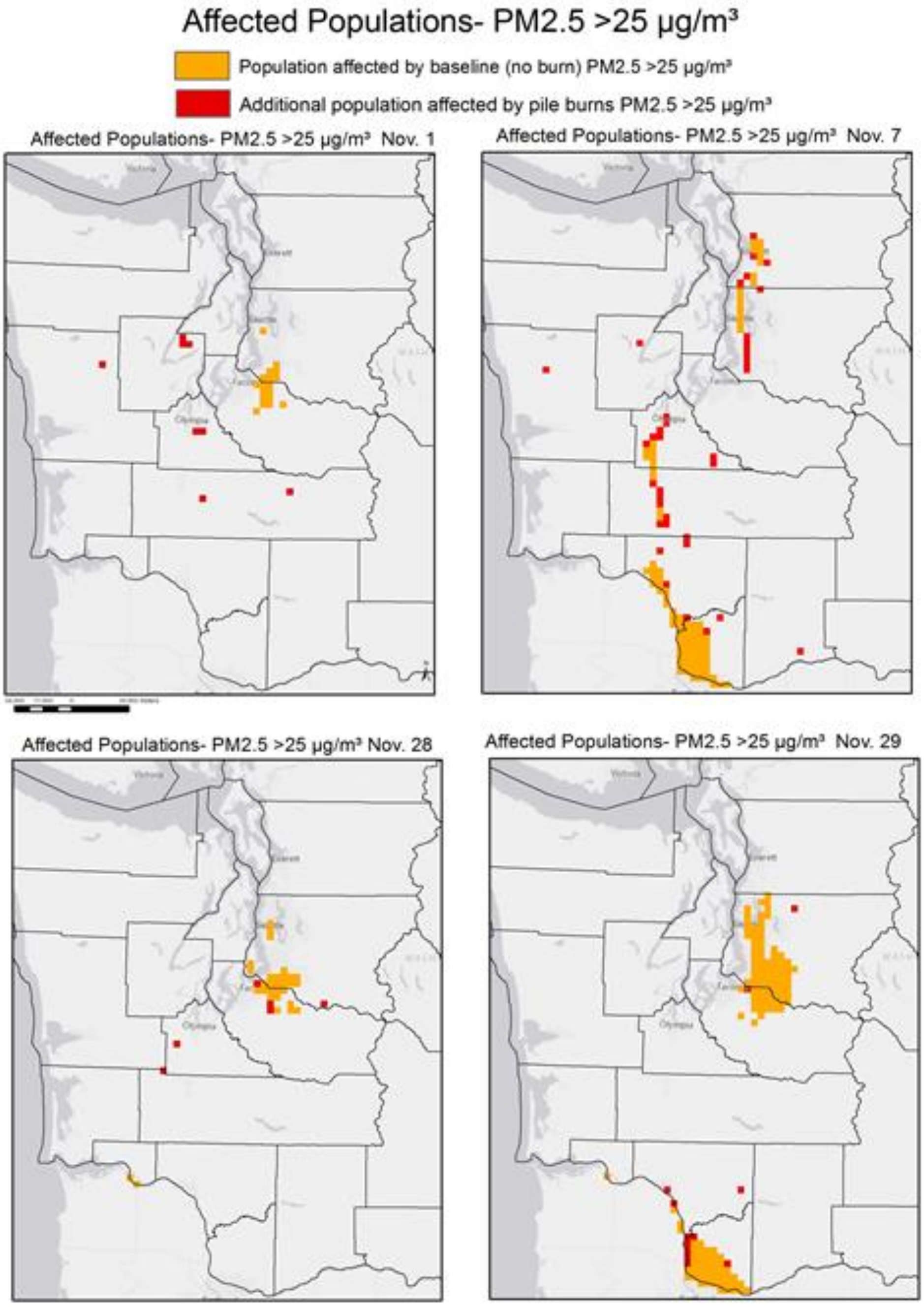

Figure 33. Impacted populations by baseline shown in orange pixels and additional impacted populations as a result of pile burns shown in red pixels.

Table 15. Impacted populations by baseline per day and additional impacted populations per day as a result of pile burns. Corresponding daily pile burn amounts are listed.

		People affected by PM2.5 greater than 25 (µg/m³)		
Burn Date	Burn Day	Baseline w/out burns affected people	Baseline with burns affected people	Additional people affected from the added piles burns PM2.5 >25 µg/m³
Nov. 1	305	245,028	259,650	14,622
Nov. 2	306	0	14	14
Nov. 3	307	0	21	21
Nov. 4	308	371,046	375,026	3,980
Nov. 5	309	0	5	5
Nov. 6	310	885,655	904,431	18,776
Nov. 7	311	815,933	1,093,547	277,614
Nov. 8	312	3,600	5,049	1,449
Nov. 9	313	0	10,487	10,487
Nov. 10	314	0	14,590	14,590
Nov. 11	315	283,039	284,041	1,002
Nov. 12	316	0	172	172
Nov. 13	317	0	1,646	1,646
Nov. 14	318	0	6,813	6,813
Nov. 15	319	2,588	4,308	1,720
Nov. 16	320	0	64	64
Nov. 17	321	0	0	0
Nov. 18	322	0	1,070	1,070
Nov. 19	323	28,525	40,577	12,052
Nov. 20	324	698,644	699,926	1,282
Nov. 21	325	0	2	2
Nov. 22	326	0	97	97
Nov. 23	327	0	0	0
Nov. 24	328	0	51	51
Nov. 25	329	0	0	0
Nov. 26	330	0	280	280
Nov. 27	331	0	386	386
Nov. 28	332	421,535	461,346	39,811
Nov. 29	333	1,430,332	1,460,917	30,585
29 Day total number of additional affected people from pile burns=				**438,591**

Table 15 displays the daily population totals of the PM2.5 impacted populations for the state. The impacted population is a population data pixel that occurs where a PM2.5 concentration pixel greater than 25µg/m³.   Shown in Table 15, there were numerous amounts of impacted populations as a result from the baseline PM2.5 concentrations, due to mostly anthropogenic sources. The "additional people affected by the pile burns per day" column shows the difference between the baseline and the pile burn impacted populations. The result also shows there are multiple days where there are less than 100 additional daily impacted people due to pile burns. This can be due to low concentrations of PM2.5 initially emitted or the emissions concentrations above 25µg/m³ are not occurring in a densely populated area. Shown in Table 15, when the PM2.5 concentrations occur over highly populated areas, thousands of additional people can be affected per day by a PM2.5 concentration that exceeds the WHO guideline of 25µg/m³.   3 days of burn on the 7th, 28th, and 29th account for 80% of the additional impacted populations per day for the whole burn period. The largest amounts of biomass burnt did not occur on these days but the higher concentrations of emissions were transported to more densely populated areas, impacting more people.

4 Discussion and conclusion

4.1 Discussion and conclusion

This method for calculating the emissions and impact of residual pile burning on a local scale involves many types of data and modeling systems, which are essential to reach the final results. Each of the research methodologies yields singular results that build up to the final result of concentrations, potential human intake, and impacted populations. While there are several types of models that contribute to one of the results in this research, a combination of models and the results that are created is the primary goal. Each of the individual methods in this research has a brief discussion of the singular results but the final results culminate into an expansive assessment of pile burning and the emissions involved.

Adding the human population element to the air quality assessment on the same fine scale is an important additive. While the air quality may already be poor in densely populated regions with more sources of pollution, there may not be an affected population in the area. The results showing the amount of PM that the population breathes in is important because it calculates intake of PM on a 4km by 4km scale. This fine scale shows importance because the way that air pollution behaves, often following geographical features and weather patterns. The results show that a county may have a mountain range on one side with low population, while the other side is a valley with dense population, more people can be affected if the emissions flow through a denser population. The results show an estimated total amount of PM that might be inhaled by an underlying population, calculated on the same 4km scale. These results can be more practical than other methodologies due to addressing the unique behavior of air pollution and the population density of a region.

It is widely known that biomass burning emits harmful air pollutants that can be transported in the atmosphere. Relating this information spatially and in combination with other types of data such as air chemistry interaction and affected population remains the issue. The final results of this research display how more PM emissions from pile burning are added to the atmosphere, where the plumes travel, how many people are affected in its path and other information such as how many more peaks in bad air quality can occur in combination with poor ambient air quality. The side-by-side comparison shows that the addition of pile burns to the region can significantly decrease air quality daily and increase the PM concentrations into the next poor air quality category, exceeding health standards.

The results also show that the addition of the scenario pile burns combined with the ambient air quality can influence the chance of exceeding air quality standards. PM estimates exceeded the WHO air quality standards and EPA air quality standards on many days. Some days the values climbed into the very unhealthy category and had the potential to be very detrimental to human health. These results send a message that represents how much PM from biomass burning and other sources can potentially be inhaled causing illness and shortening life spans. Alternative uses of this biomass material could reduce PM human intake and reduce health issues that reach populations much further away than just in the burn vicinity.

This research estimates the potential impacts of pile burning on humans and displays how pile burning emissions can impact an airshed. This information can be used to influence and inform officials of the impacts of pile burning so that better policies can be implemented. Better airshed management will require policy changes in order to address the sources of pollution. Creating more strict regulations for air pollution sources such as industries can be difficult, so time may be better invested in developing infrastructure for practices such as biomass conversion into biofuel. Addressing the other sources of air pollution such as wildfires and biomass pile burning may prove to be a better way to improve an airshed. Investing in more forest management practices and alternative uses of biomass (e.g. biofuel conversion) could reduce impacts to human health and the environment.

4.2 Limitations and recommendations

Further assessment should be implemented to influence policy and air quality standards. Sensitive population areas such as hospitals and schools could be a part of future research in order to break down population into a finer scale. More species of chemicals could be assessed also in future research in order to add to the potential impact to human health. Application of this method to other regions would be beneficial to get a better idea of how pile burning affects populations in other parts of the country. Several computer models were utilized and assumptions were inherited, but this research is about creating a method using the available tools and models.

The research presented produces results that put biomass burning emissions into perspective, showing that PM can travel far away from a pile burn. Plume direction and chemical fate is influenced by weather, geographical features, burn amount, and burn location. Calculating the impact of biomass burning will need to continue to improve and become more precise in order to change policies and regulations, adapting to the changing climate conditions.

The results show that significant amounts of particulate matter are added to the airshed from biomass burning and not only have impacts to human health, but can possibly have an economic impact to a community. Future research should include assessments of the economic impacts that biomass burning can do a community such as reducing tourist visitation or create travel restrictions.

References

Adams, D. M., & Latta, G. S. (2007). Timber trends on private lands in western Oregon and Washington: a new look. *Western Journal of Applied Forestry*, *22*(1), 8–14

Agee, J. K. 1996. *Fire Ecology of Pacific Northwest Forests*. Island Press

Agee, J. K. Johnson, D. 1988. *Ecosystem Management for Parks and Wilderness.* University of Washington Press

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., … Wennberg, P. O. (2011). Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chemistry and Physics*, *11*(9), 4039–4072

Andreae, M. O., & Marlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles,* 15(4), 955–966

Chen, J., Vaughan, J., Avise, J., O'Neill, S., & Lamb, B. (2008). Enhancement and evaluation of the AIRPACT ozone and PM 2.5 forecast system for the Pacific Northwest. *Journal of Geophysical Research*, *113*(D14)

Clewell, A. Aronson, J. (2013). *Ecological Restoration, 2nd Ed: Principles, Values and Structure of an Emerging Profession*. Island Press.

Consume Model. http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml

Department of Ecology, S. of W. (2012). *How Wood Smoke Harms Your Health*. 023(July).

Dixon, G. (2002). *Essential FVS : A User's Guide to the Forest Vegetation Simulator*, (January), 226

Dockery, D. W., & Pope, C. a. (1994). Acute respiratory effects of particulate air pollution. *Annual Review of Public Health*, *15*, 107–132. doi:10.1146/annurev.pu.15.050194.000543

Durán, S., Flannigan, M., Reisen, F., Elliot, C., & Rideout, K. (2015). *Wildfire smoke and public health risk*, 26

EPA. (1997) Exposure factors handbook-volume 1. Office of Research and Development, Washington DC

EPA. (2012). *National Ambient Air Quality Standards (NAAQS)*. Retrieved from EPA: http://www3.epa.gov/ttn/naaqs/criteria.html

EPA. (2012). *Revised Air Quality Standards for Particle Pollution and Updates To the Air Quality Index* (Aqi), 1–5

EPA. (2014). *Particulate Matter (PM) Basic Information.* EPA. Webpage. Accessed 6 Feb. 2014. http://www.epa.gov/pm/basic.html

Goodrick, S. L., Achtemeier, G. L., Larkin, N. K., Liu, Y., & Strand, T. M. (2013). Modelling smoke transport from wildland fires: A review. *International Journal of Wildland Fire*, *22*(1), 83–94. doi:10.1071/WF11116

Gray, A. N., Veneklase, C. F., & Rhoads, R. D. (2005). *Timber Resource Statistics for Nonnational Forest Land in Western Washington*, 2001

Hardy, C.C. (1996). *Guidelines for estimating volume, biomass and smoke production for piled slash*. Gen. Tech. Rep. PNW-GTR-364. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p

Henderson, S. B., Burkholder, B., Jackson, P. L., Brauer, M., & Ichoku, C. (2008). Use of MODIS products to simplify and evaluate a forest fire plume dispersion model for PM10 exposure assessment. *Atmospheric Environment*, *42*(36), 8524–8532. doi:10.1016/j.atmosenv.2008.05.008

Herron-Thorpe, F. L., Lamb, B. K., Mount, G. H., & Vaughan, J. K. (2010). Evaluation of a regional air quality forecast model for tropospheric NO_2 columns using the OMI/Aura satellite tropospheric NO_2 product. *Atmospheric Chemistry and Physics*, *10*(18), 8839–8854

Herron-Thorpe, F. L., Mount, G. H., Emmons, L. K., Lamb, B. K., Jaffe, D. a., Wigder, N. L., Vaughan, J. K. (2014). Air quality simulations of wildfires in the Pacific Northwest evaluated with surface and satellite observations during the summers of 2007 and 2008. *Atmospheric Chemistry and Physics Discussions*, *14*(8), 11103–11152. doi:10.5194/acpd-14-11103-2014

Hope, B. K. (2005). *Health effects from exposure to smoke*. Retrieved from Oregon Department of Environmental Quality: http://www.deq.state.or.us/aq/burning/docs/smoke_bhope.pdf

Huijbregts, M., Margni, M., Hauschild, M., Jolliet, O., McKone, T., Resenbaum, R., & Meent, D. van de. (2015). USEtox 2.0 User Manual (v2). *USEtox.org*, (Version 2), 30. Retrieved from www.usetox.org

Jain, R., Vaughan, J., Heitkamp, K., Ramos, C., Claiborn, C., Schreuder, M. Lamb, B. (2007). Development of the ClearSky smoke dispersion forecast system for agricultural field burning in the Pacific Northwest. *Atmospheric Environment*, *41*(32), 6745–6761

Johnston, F. H., S. B. Henderson, Y. Chen, J. T. Randerson, M. Marlier, R. S. DeFries, P. Kinney, D. M. J. S. Bowman, and M. Brauer (2012), Estimated global mortality attributable to smoke from landscape fires, *Environ. Health Perspect*., 120, 695–701

Keane RE, Burgan R. Wagtendonk JV. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire*. 2001; 10, 301–319

Lamb, B., Chen, J., Neill, S. O., Avise, J., Vaughan, J., Larkin, S., & Solomon, R. (2007). *Real-Time Numerical Forecasting of Wildfires and Regional Air Quality*

Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C. Ferguson, S. a. (2009). The BlueSky smoke modeling framework. *International Journal of Wildland Fire*, *18*(8), 906. doi:10.1071/WF07086

Latta, G., Nalts, A. Van, Randall, R. S., Adams, D. M., & Nalts, A. Van. (2002). *Timber Harvest Projections for Private Land in Western Oregon.*

Lippke, B., Gustafson, R., Venditti, R., Steele, P., Volk, T. a., Oneil, E., Skog, K. (2012). Comparing Life-Cycle Carbon and Energy Impacts for Biofuel, Wood Product, and Forest Management Alternatives. *Forest Products Journal*, 62(4), 247–257. doi:10.13073/FPJ-D-12-00017.1

Littell, J. S., Oneil, E. E., McKenzie, D., Hicke, J. A., Lutz, J. A., Norheim, R. A., & Elsner, M. M. (2010). Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, 102(1-2), 129–158

Loudermilk, E. L., Stanton, A., Scheller, R. M., Dilts, T. E., Weisberg, P. J., Skinner, C., & Yang, J. (2014). Effectiveness of fuel treatments for mitigating wildfire risk and sequestering forest carbon: A case study in the Lake Tahoe Basin. *Forest Ecology and Management*, 323, 114–125

Mott, J. a., Mannino, D. M., Alverson, C. J., Kiyu, A., Hashim, J., Lee, T., Redd, S. C. (2005). Cardiorespiratory hospitalizations associated with smoke exposure during the 1997 Southeast Asian forest fires. *International Journal of Hygiene and Environmental Health*, *208*(1-2), 75–85

National Interagency Fire Center. 2014 National Report of Wildland Fires and Acres Burned by State, 61–71

Oneil, E. E., Johnson, L. R., Lippke, B. R., Mccarter, J. B., Mcdill, M. E., Roth, P. A., & Finley, J. C. (2010). Life-cyle Impacts of Inland Northwest and Northeast / Northcentral Forest Resources. *The Consortium for Research on Renewable*, 42, 29–51

Oneil, E. E., & Lippke, B. R. (2010). Integrating Products, Emission Offsets, and Wildfire into Carbon Assessments of Inland Northwest Forests. *Wood and Fiber Science*, 42, 144–164

O'Neill, S. M., Lamb, B. K., Chen, J., Claiborn, C., Finn, D., Otterson, S., Anderson, M. (2006). Modeling ozone and aerosol formation and transport in the Pacific Northwest with the Community Multi-Scale Air Quality (CMAQ) modeling system. *Environmental Science and Technology*, *40*(4), 1286–1299. doi:10.1021/es048402k

O'Neill, S. M., Larkin, N. (Sim) K., Hoadley, J., Mills, G., Vaughan, J. K., Draxler, R. R., Ferguson, S. a. (2008). Regional Real-Time Smoke Prediction Systems. *Developments in Environmental Science*, *8*(08), 499–534. doi:10.1016/S1474-8177(08)00022-3

Perez-Garcia, J., Oneil, E., Hansen, T., Mason, T., McCarter, J., Rogers, L.,McLaughlin, M. (2012). *Washington forest biomass supply assessment*, March, 183. Retrieved from http://www.dnr.wa.gov/Publications/em_finalreport_wash_forest_biomass_supply_assess.pdf

Schwartz, J. (1993). Particulate air pollution and chronic respiratory disease. *Environmental Research.* doi:10.1006/enrs.1993.1083

Sullivan, D. C., Raffuse, S. M., Pryden, D. A., Craig, K. J., Reid, S. B., Wheeler, N. J. M., Street, N. (n.d.). Development and Applications of Systems for Modeling Emissions and Smoke from Fires : The BlueSky Smoke Modeling Framework and SMARTFIRE

Sun Y. Hu L. Liu H. A GIS-based approach for comparative analysis of potential fire risk assessment. SPIE Proceedings. 2007; Vol. 6754

Tan, W. C., Qiu, D., Liam, B. L., Ng, T. P., Lee, S. H., van Eeden, S. F., … Hogg, J. C. (2000). The human bone marrow response to acute air pollution caused by forest fires. *American Journal of Respiratory and Critical Care Medicine*, *161*(4 Pt 1), 1213–1217. doi:10.1164/ajrccm.161.4.9904084

Van Wyngarden R. Dixon R. Application of GIS to model forest fire rate of spread. *Proceedings of Challenge for the 1990's GIS*, *1989*; Ottawa. 967- 977.

Vaughan, J., Lamb, B., Wilson, R., Bowman, C., Kaminsky, C., Otterson, S., Boyer, M., Mass, C., Albright, M., Koenig, J., Collingwood, A., Gilroy, M., and Maykut, N. 2004. A numerical daily air-quality forecast system for the Pacific Northwest. *Bull. Amer. Meteorol*. Soc. 85, 549–561

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, 313(5789), 940–3. doi:10.1126/science.1128834

Wiedinmyer, C., Quayle, B., Geron, C., Belote, A., McKenzie, D., Zhang, X., Wynne, K. K. (2006). Estimating emissions from fires in North America for air quality modeling. *Atmospheric Environment*, *40*(19), 3419–3432. doi:10.1016/j.atmosenv.2006.02.010

World Health Organization. (2013). *Health Effects of Particulate Matter*, 50(2), 20. doi:10.5124/jkma.2007.50.2.175

Wright, C. S. (2009) *Estimating The Biomass of Hand-Piled Fuels for Smoke Management Planning*., 1–1