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Quantification of Influential Surface Fuel Parameters in Fire-Prone Ecosystems of the Netherlands

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QUANTIFICATION OF INFLUENTIAL SURFACE FUEL PARAMETERS IN FIRE-PRONE ECOSYSTEMS OF THE NETHERLANDS

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ABSTRACT

Changing climate conditions in northwest Europe present an increasing wildfire risk in the Netherlands. Focus on fuels monitoring in this region is not as extensive as it is in the United States. Accurate estimation of biomass fuel loading is integral to prevention of wildfires which pose a significant risk to both human lives and property. This research project attempted to create predictive models for three major fuel categories (litter/duff, shrub, and downed woody material). Reduction of the number of parameters to measure would streamline the process of fuel load estimation by reducing the number of measurements that need to be taken in the field. The results of this study show that certain parameters contribute more to predicting fuel loads than others in the litter/duff and shrub categories. More parameters need to be collected to determine if a model can be created for the downed woody material category. The findings indicate that the models produced in this study containing these parameters can be used to more quickly and efficiently estimate fuel loading in certain fire-prone communities in the Netherlands. This research can assist land managers in this region in more accurate fuel estimation, therefore creating a more proactive approach to understanding and preventing the risks of destructive wildfire events.

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INTRODUCTION

Large wildfires impacting human communities are becoming more common due to several compounding issues (e.g., climate change, historic and ongoing sprawl of human communities, and fire suppression). Areas that were previously not considered to be fire-prone, such as northwestern Europe, where the Netherlands is located, are now experiencing a rise in damaging wildfires. Changes in precipitation levels and heightened mean temperatures, especially during seasonal heatwaves, have coincided to create a higher risk climate for fire danger in the Netherlands (Kok and Stoof, 2020). In conjunction with warmer, drier climate, there is the confounding factor of human activity and inhabitance. The Netherlands is one of the most densely populated countries in Europe, and combined with the small area of the country, this results in a large percentage of land in the wildland-urban interface (WUI). In the forested Veluwe region, where fire danger is generally higher than the rest of the country, most private property would be considered WUI (Oswald et al., 2018). This further complicates the wildfire issue with certain scientific and social challenges that managers must face, such as determining effective defensible spaces and coordinating fuel management on both sides of the interface. Educating WUI citizens to keep them informed of the reasoning behind and importance of actions taken can aid with making effective management decisions (Gill and Stephens, 2009). Earlier projects have been conducted on public wildfire preparedness and risk perception and canopy fuel estimations (Oswald et al., 2018, Hibler et al., 2020). The physical structure of the vegetation in each community plays an important role in which variables can be used to predict biomass fuel loading (Brown et al., 1982). In shrub communities, basal stem diameter and stem length have both been shown to be predictors of biomass (Brown, 1976). Above ground biomass in tree-dominated communities can be predicted using diameter at breast height, as demonstrated by Durkaya et al. (2010) in Scots pine forests in Turkey. Grassland above ground biomass is often measured using remote sensing techniques to determine the amount of green vegetation present but can also be predicted using wet and dry vegetation weights (Bonham, 2013). Considering these previous studies, it appears multiple models are most likely need to be estimated for communities dominated by grasses, shrubs, and trees due to the difference in influence of explanatory variables based on cover type (Bonham, 2013).

Data collected from previous studies between 2012-2017 in the Netherlands by students from Stephen F. Austin State University in Nacogdoches, Texas, in conjunction with the Instituut Fysieke Veiligheid, were used to assess the influence of a large number of variables on biomass. Since the wildland fire issue is relatively recent, no specific research has been conducted to determine which vegetation parameters would potentially drive wildfire behavior. As a result, methodologies from research in North America were utilized (Brown et al., 1982, Ottmar et al., 2000). An emphasis on analyzing surface vegetation considers the ladder fuel effect, in which fires that begin in low and mid-level stories can result in more severe fires if they spread to canopy vegetation (Menning and Stephens, 2007). Estimating wildfire potential by measuring fuels where they are often first ignited may be the best way to prevent higher severity fires. This project could ultimately aid fire researchers and managers by thereby reducing the time and labor needed to assess wildfire risks. A more streamlined approach to measuring fuel loads can provide them with the ability to mitigate wildfire risks as climate conditions continue to change. Using linear regression analysis techniques, the variables that are most related to estimating these above ground biomass fuel loads will be identified and included in the final predictive models.

RESEARCH GOAL AND OBJECTIVES

The goal of this project was to create predictive models that can then be used to improve the process of assessing wildfire risk more efficiently, particularly in areas where fuel load measurement is time and labor intensive. In this study, above ground biomass is used as a measurement of fuel loading and will be the response variable in the models.

The specific objectives of this study are to:

1: Determine which surface fuel measurements contribute the most towards predicting biomass levels that might contribute to potential wildland fire behavior in fire-prone communities in the Netherlands.

2: Develop multiple regression models to predict biomass fuel loading for different fire-prone shrub and grassland communities based on the above parameters.

LITERATURE REVIEW

Wildfire in the Netherlands

The Netherlands historically has not had significant issues with wildfires, but as the regional climate becomes drier and warmer, that risk has increased (Oswald et al., 2018). A growing concern is how to reduce that risk and prevent large-scale destructive wildfires like those occurring at increasing rates across the globe. As a small yet densely populated country with a high amount of wildland urban interface (WUI) communities, such an event could endanger the people who live there and cause significant financial damage (Hibler et al., 2020). According to Oswald et al. (2018), few people living in these WUI communities recognized the true threat of wildfire to them. Although most citizens are at least aware of the risks, the widely held attitude is that a wildfire event will not happen to them or the community in which they live. Quantitative measurements such as biomass estimation and fuel loads may be a step in the process of informing the public about wildfire risks.

One potential effort that can be made to mitigate wildfire risk following fuel estimation is application of fuel reduction treatments, particularly in areas with high fuel loads. Although information on the application and efficacy of fuel treatments in the Netherlands is lacking, it is a common practice in the U.S., especially in the western states where fire suppression policies and climate change have combined to produce more high severity fires than ever before (Stephens et al., 2012). Some of the fuel reduction practices in fire-prone U.S. cover types could most likely be adapted for use in similarly structured communities in the Netherlands.

The main fuel reduction methods include both regular prescribed burning and mechanical treatments such as thinning. According to Stephens et al. (2012), a regular prescribed fire interval approximating the historic fire regime of an area consisting of multiple burns over a period of time can reduce potential high-risk fire behavior. In the Netherlands this is problematic as they have no estimation of historic fire regimes or historical fire return intervals. While mechanical treatments can help managers meet the objective of reducing fuel loads, there are certain ecological processes that require the presence of fire in some forest communities, like seed germination of fire-dependent species. However, when combined, the two methods generally have the support of the public (Shindler and Toman, 2003). This is important because the public is frequently wary of using fire, even intentionally-set, low-intensity prescribed burns. Public education increases trust in such management activities, but until then the use of both burning and mechanical removal of fuel loads could help in preventing catastrophic fire events.

Measuring and Predicting Biomass

Total biomass is a commonly used metric for representing fuel load and is especially useful in non-forested cover types. Shrub communities with a height of less than 6 feet and grasslands specifically can use biomass as a reliable representation of fuel loading on a site. (Sikkink et al., 2009).

Measuring biomass using destructive sampling can be a difficult and time-consuming process, especially in areas that are rich in vegetation. Cost can be an issue as well, as collecting field samples is labor-intensive (Chieppa et al., 2020, Davies et al., 2008). It can also cause unintentional effects in the composition of the site that is being sampled. Certain plant species respond more negatively than others to clipping, causing those species that are not negatively affected to become more dominant. For example, removal of foliage or stems from a shrub will cause more damage than clipping a part of a perennial grass (Chieppa et al., 2020).

Biomass measurements can be estimated through dimensional analysis, or taking other measured parameters to predict biomass using regression equations (Bonham, 2013). The predictor variables that need to be measured depend on the type of vegetation that is being studied. In Brown (1976), both stem length and stem diameter were shown to be related to shrub biomass weights. Measuring either parameter is not a difficult task and would be less labor-intensive than destructive sampling, where each stem must be clipped and collected then measured. Because shrub weight could then be converted into a biomass estimation, this method could be used for the purposes of this study as well. Cover-based methods have also been shown to be effective in estimating above-ground biomass and are particularly effective in shrub and grassland ecosystems. Including height measurements in the predictive model can improve it and make predictions more accurate (Chieppa et al., 2020). These parameters were measured in several of the years of study for this project, and utilizing these would also be an easier process than destructive sampling.

Biomass estimation is related to fuel load prediction, as it is essentially showing the amount of vegetation there is on a given site that could burn. Both also demonstrate site productivity, as they indicate what has been able to grow and how much has grown, and possibly through obtaining biomass measurements the amount of fuel and the flammability of a site can be known (Bonham, 2013).

Description of Community Types of Concern in the Netherlands

Many of these community types of interest are described by the BIJ12 Nature Information and Management Unit in the Nature and Landscape Index for use by Dutch citizens to increase their knowledge of the landscapes around them and how to properly manage them. Communities are separated into “nature type” classifications and described on the BIJ12 website (Interprovincial Consultation, 2014). The Interprovincial Consultation Association (IPO) implements the interests of Dutch provinces in The Hague and Brussels regarding policy and distribution of information. BIJ12 was set up by the IPO to represent those interests that relate to rural living and the physical environment.

Pine, Oak, and Beech

These forests are a mix of species containing varying degrees of pine, oak, and beech trees, some of which are native to the Netherlands, while others are introduced. They are commonly found in the Veluwe, a hilly, forested region in the province of Gelderland, and in the province of Drenthe located in the northeast. They occur on acidic, dry, sandy soils and are often found on sites that were formerly used for timber production or agriculture. Scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*), pedunculate oak (*Quercus robur*), and beech (*Fagus* spp.) form the overstory, and one species may dominate an area depending on the site characteristics. Scots pine is the most common pine species in the Netherlands, and while black pine is less common, it may be the dominant species at some sites, especially along the coast. Black pine is slightly more tolerant of shade compared to Scots pine. Silver birch (*Betula pendula*) can also make up a portion of the over and mid-stories. Understory shrub species include blackberry (*Rubus* spp.), holly (*Ilex* spp.), mountain-ash (*Sorbus aucuparia*) and sea buckthorn (*Hippophae rhamnoides*). Heather (*Calluna vulgaris*) may also be present if the area is grazed by livestock. These forests can vary widely in structure depending on canopy openness, available nutrients, and previous site management.

Douglas-fir

Douglas-fir (*Pseudotsuga menziesii*) was introduced to the Netherlands from North America during the twentieth century and planted throughout Europe due to its potential productivity (Hintsteiner et al., 2018). It has since become naturalized and is an important Dutch timber species. Douglas-fir is grown in plantations as both a monoculture and as part of a mixed forest. In mixed forests, it often grows alongside shade-intolerant trees such as larch (*Larix* spp.) and birch (*Betula* spp.) until it becomes dominant and shades out those species (Schelhaas, 2008). When naturally occurring, it grows similarly in mixed forest environments, with European blueberry (*Vaccinium myrtillus*), bunch grasses and rushes (*Juncus* spp.) composing the understory.

Grasslands

According to BIJ12, there are several types of grasslands that occur due to differences in site moisture and soil nutrient availability, as well as past and current management practices.

Wet grasslands were previously used for production of hay, and a small number of these are still actively managed for that purpose. These grasslands are often on areas of low elevation and are regularly flooded by nearby bodies of water. When dry, they are mowed, and the clippings are removed from the site to deter willow thicket growth. Wet grasslands are now rare in the Netherlands due to being converted into agricultural land, but some are protected because of their ecological significance. Many sedge species

(*Carex* spp.) occur in this cover type, as well as some plant species that are rare and of national importance, like snake's head fritillary (*Fritillaria meleagris*). It also provides suitable habitat for several important bird and butterfly species (Interprovincial Consultation, 2014).

Dry grasslands are characterized by a different origin than wet grasslands. Most dry grasslands were dry forests that were converted into grazing areas for livestock and are still grazed today. Soils in dry grasslands are loamy and sandy and depend on short periods of flooding or underground animal activity for nutrient replacement. While common grass species can overrun this rare cover type, well-maintained dry grasslands can support characteristic herbaceous and animal species that do not occur in other places. Additionally, heather occurs frequently in large numbers in dry grasslands and can in those cases be referred to as heather grasslands (Interprovincial Consultation, 2014).

Unlike wet and dry grasslands, which are generally nutrient-poor, the third type of grassland is rich in soil nutrients. Nutrient-rich grasslands were formerly used for agriculture and have therefore been fertilized. How these grasslands are managed now depends on the present abiotic factors and previous site use, but they must be continuously maintained to retain that richness. Because nutrient-rich grasslands are essentially grasslands managed for some use, such as high-quality habitat, cultural-historical landmarks, or nature reserves, their composition and structure vary widely

(Interprovincial Consultation, 2014).

Heather

Heather-dominated landscapes in the Netherlands occur on both dry sites and wet peat bogs. Dry heather sites mainly consist of common heather but can also support perennial grass species and juniper (*Juniperis* spp.) thickets. Mosses and forbs form the groundcover layer where bare soil is not exposed. The soils in these sites are often depleted of nutrients, and heather is often the most productive species present (Matthews, 1993). Wet heather sites occur on peat bogs formed over thousands of years. Heather is highly productive and dominant in these sites, and other vegetation includes blackberry and Scotch broom thickets (*Cytisus scoparius*), grasses such as wavy hair grass (*Deschampsia flexuosa*) and purple moor grass (*Molinia caerulea*), and occasional solitary trees, usually Scots pine or downy birch (*Betula pubescens*). Sphagnum mosses are abundant, and small areas of standing stagnant water are present (Interprovincial Consultation, 2014).

Dune Ecosystems

Dune ecosystems in the Netherlands vary by the type of vegetation that covers them. Although they differ in dominant cover types, they can be seen as various points in the process of succession, much like the peatland ecosystems that are also present in this region. Over time, if they are undisturbed, these dune ecosystems will slowly become dune forests as they approach the final stage of succession. Dune grasslands are composed of mainly beachgrass species and exist in the dune regions of the Netherlands. These regions exist on the coasts of North Holland as well as on Texel Island off the northernmost coast of the country. Commonly found species are marram grass (*Ammophila arenaria*), wavy hair grass, and grey hair grass (*Corynephorus canescens*), which can pioneer on sandy landscapes such as those in the dunes (Interprovincial Consultation, 2014).

Dune valleys are moist, humid areas in between the dunes that are near the ocean and develop unique communities of vegetation. Shrub species such as creeping willow (*Salix repens*) and blackberry form thickets on edges of the valleys. Many ecotones exist in dune valleys, which leads to a high biodiversity. Herbaceous species' richness can be increased through mowing, and grazing can increase the number of perennial sedges and grasses (Interprovincial Consultation, 2014).

Dune heather landscapes contain both dry and wet sites, causing a slight variation in the vegetation. While both sites are dominated by common heather, wetter sites have a mossy ground layer and contain species such as crowberry (*Empetrum nigrum*) and creeping willow. These wet heaths develop from dune valleys and have more acidic soils. Drier sites contain heather and sand sedge (*Carex arenaria*) along with pioneering species. These soils are generally sandy and decalcified from being formed from old dune grasslands.

Dune forests also occur in the dune regions and are found on both sandy, limepoor soils that are high in calcium, as well as in moist valleys. Dominant species include Scots pine, pedunculate oak, silver birch, and beech. Thickets commonly occur in this cover type, and in these areas, understory species include hawthorn (*Crataegus* spp.), buckthorn, and common elderberry (*Sambucus nigra*). In more open sites such as forest clearings dewberry (*Rubus* spp.) can be found in the understory. Some of these forests were planted in formerly open dune regions to anchor drifting sand (Interprovincial Consultation, 2014).

Dune regions with low amounts of vegetation and areas of bare sand are known as open dunes. This cover type is characterized by a lack of mid- and overstory vegetation and occurs in windy coastal regions. Instead, mosses, lichen-dependent herbaceous species, and grasses dominate the landscape. Shrub thickets of blackberry and sea buckthorn exist, and forests can occur in areas with older dunes that are protected from the wind by thickets (Interprovincial Consultation, 2014).

Peatlands

Peat systems in the Netherlands are regions where peat has accumulated over time as vegetation and animals die and begin decomposition in waterlogged environments. They can be categorized into high peat and low peat. High peat systems are located in the northern, central, and southern sandy regions of the country, while low peat systems exist in the northern and western coastal plain regions. These areas vary in amounts of nutrients and types of vegetation present, due to the variety of ways these peatlands can be formed. The type of organic matter that is decaying at these sites generally dictate the composition and structure of present vegetation (Verhoeven, 2013).

Vegetation in high peat communities can be largely affected by microtopography, as concave areas with pooled water exist alongside convex areas known as bog lenses. Sphagnum mosses can cover large areas of the ground, and in wetter sections heather and reed (*Phragmites* spp.) are present. In drier sections of this community, sedges and thickets of blackberry and Scotch broom can be observed (Interprovincial Consultation, 2014).

In low peat communities, sphagnum mosses, potentially different species than those present in high peat communities, comprise the main ground cover. Heather-dominated swamp areas can be present in areas where the land transitions to a higher peat community. These heather swamps are now considered to be rare in the Netherlands, although they were once abundant. Swamp sawgrass (*Cladium mariscus*), rushes, and reeds are present in areas not covered in water (Interprovincial Consultation, 2014).

Peat forest communities can occur in both high and low peat systems, with high forests considered a rare type of bog forest. Water sources dictate the vegetation in these areas. If rainfall is the main source of water at a site, low-growing vegetation such as sphagnum moss and small shrubs as well as downy birch dominate. These forests tend to be more open and provide important habitat for herpetofauna. If groundwater is the main water source, marsh plants and black alder (*Alnus glutinosa*) are dominant. Alder-dominated peat forests can form higher structural variety as they age due to the gradual formation of pools where trees have fallen and root balls that cause some trees to be higher. Thickets formed by species such as gray willow (*Salix cinerea*) and black chokeberry (*Aronia melanocarpa*) are common in peat forests (Interprovincial Consultation, 2014).

METHODS

Study Areas and Site Descriptions by Year

When the collaborative project began in 2012, the classification system described above (Interprovincial Consultation, 2014) was not known. As a result, the descriptions of the sites below do not conform to that classification system.

2012

Study areas were in the province of Gelderland in the southern part of the forested Veluwe region, near the towns of Hoenderloo and Assel (Figure 1). The cover types were classified as beech, Douglas fir, grassland, heather, and Scots pine (Oswald and Stoof, 2012). The plots sampled in the beech-dominated areas also included some oak trees and a few larch seedlings, with little to no understory. There were two plots in the grassland community, one with grass but little other vegetation and one that was moderately dense with grass and tree seedlings. The main grass species present were bunchgrasses, and there were heather and birch seedlings present in the moderately dense plot.

Douglas fir plots were located in five different types of stands; thin (or open canopy), regenerating, dense, thinned, and mature plantation (Oswald and Stoof, 2012). Understory species that were present in this community include European blueberry, bedstraw *(Galium* spp.), ferns, bunchgrass, and wavy hair grass (*Deschampsia flexuosa*). Scots pine seedlings were also represented in the understory; in the mid- and overstory of some plots, mountain-ash was recorded.

Heather plots consisted either of almost pure stands of heather or mixed communities also containing grass or scattered Scots pine. Plots in the pure heather areas did contain some bunchgrass, but the heather-grass community had a much higher percentage of grass cover consisting of either bunchgrass or wavy hair grass. The heather-scattered Scots pine plots also contained a high amount of red berry (*Ribes* spp.) but low numbers of Scots pine.

The final community consisted of Scots pine. Understory strata in these plots contained bunchgrass, wavy hair grass, blueberry, rushes, as well as birch and oak seedlings, and in the midstory of some plots, mountain-ash was present. Plots measured in this year had no history of fire (Oswald and Stoof, 2012).

2013

Plots were located on Texel Island and near Haarlam on the mainland in the coast dune regions of the Netherlands (Figure 1). These dune ecosystems contain plant species that are not typically seen in other regions of the country. Plots were in one of four dune-specific cover types: dune grassland, dune heather, dune valley, and open dune (Oswald and Brouwer, 2013). Because these are not forested environments, crown closure, density, and stem counts were all low or nonexistent.

In the dune grasslands, common beachgrass species marram grass and grey hair grass were dominant, in addition to various species of sedge. Shrub species such as rose (*Rosa* spp.), heather, and blackberry were also present. Ground-covering vegetation included mosses and forbs. Fuel loads were low or nonexistent in these plots, but fire behavior is still classified as high to extreme due to the flammability of grasses (Oswald and Brouwer, 2013).

Dune heather plots were covered mostly in heather and moss, with some black cherry (*Prunus serotina*), birch, and rose as well. Marram grass, sand couch grass (*Elytrigia juncea*), and sedges persisted in the understory but heather was the dominant species. Heather contains volatile compounds that are highly flammable, which can lead to high intensity fires, and fire behavior ratings in these plots ranged from high to extreme (Oswald and Brouwer, 2013). Dune valley plots contained mainly low vegetation species such as sedges, grasses, and heather. Thickets of creeping willow and blackberry were noted as well. Fire behavior in these plots was rated as very high to extreme (Oswald and Brouwer, 2013).

2014

In 2014, sites were in the Northumberland National Park in the United Kingdom (Figure 2). The sites were located in various peat ecosystems, and plots were placed in one of four classifications: peatland bog, peatland heather, peatland shrub, and peatland forest (Oswald and Brouwer, 2014). Although these sites were in the U.K., they were chosen by IFV since they did represent systems that are present throughout Europe, including in the Netherlands.

Peatland bog plots consisted of lower vegetation common to peat systems. Purple moor grass, wavy hair grass, and common rush (*Juncus effusus*) are present in addition to the layer of sphagnum mosses covering the ground. Heather was also present in some of the plots but was not overly common. Fire behavior at these sites is largely dependent on the moisture level in the layer of organic matter. If it is too dry, fires can burn quickly and with high intensity (Oswald and Brouwer, 2014).

Peatland heather plots were comprised mostly of heather, with hare's-tail cottongrass (*Eriophorum vaginatum*) making up much of the remaining vegetation. Sphagnum moss as well as various shrubs like blueberry were present as well. No overstory was observed at these plots. Fire in these sites is carried mostly by the volatile heather and not grass species. Due to the volatility of fuels, the fire behavior rating was classed as very high in these plots. Another risk factor in peatland heather systems is that they are often close to Scots pine stands. Wildfires may be able to spread more quickly and intensely into these pine forests than they would if the fire was ignited within the forest itself. This can be exacerbated if there have not been any recent precipitation events (Oswald and Brouwer, 2014).

Peatland shrub plots had over- and midstories dominated by black alder and goat willow (*Salix caprea*). These species can be counted as either trees or shrubs depending on how they have grown at the site. Downy birch was also present in shrub form. Grasses such as common bent (*Agrostis capillaris*), common rush, and sedge as well as rosebay willow-herb (*Chamaenerion angustifolium*), a forb commonly known as fireweed, composed the understory. The presence of fireweed suggests a recent disturbance, most likely fire, as this species is known for its occurrence on disturbed sites. Peatland shrub plots had very open canopies, indicating that shrubs were the dominant growth form at this site. The fire behavior classes in these plots ranged from high to very high, although fuel loads were low (Oswald and Brouwer, 2014).

Peatland forest plots overstories were composed entirely of stands of downy birch. The understory contained heather and several grasses such as hare's tail-cottongrass and purple moor grass. Sphagnum mosses were very common in these plots also. Much like the peatland shrub plots, fuel loads in the peatland forest cover type were low and the fire behavior class ranged from high to very high in these plots (Oswald and Brouwer, 2014).

2015

In 2015 there were study sites in both the Netherlands and the U.K. (Figures 1 and 2). Cover types of study in the Netherlands were dune, dune forest, and peat forest and plots were placed in or around De Loonse en Drunense Duinen National Park in the province of North Brabant. In the U.K., plots were placed in the New Forest National Park in a mixed forest cover type.

Dune plots were placed in areas of large sand dunes, an important ecosystem in the Netherlands. A wildfire occurred in the spring of 2014 but not all plots were in the burn area. Litter and duff depths in the unburned plots were higher than those in burned plots. The overstory at this site was composed of Scots pine and silver birch. The understory was common heather, wavy-hair grass, bracken (*Pteridium aquilinum*) and broad-buckler fern (*Dryopteris dilatata*). Several plots were noted to contain downed woody debris such as downed branches.

Dune forest plots were placed on an open forest site, with the overstory dominated by black pine. There was no understory present in some plots, and where it was present it consisted of wavy-hair grass, common polypody (*Polypodium vulgare*), and honeysuckle (*Lonicera periclymenum*). A few plots had scattered shrub species, which include mountain-ash, blackberry, and holly. Being in the dunes along with the regular dune plots, there was variation in elevation and slope. Plots with shrubby or grassy understories had higher layers of litter and duff. No fire history was recorded for the dune forest site.

Peat forest plots were placed in a mixed deciduous forest composed of downy birch, pedunculate oak, Norway maple (*Acer platanoides*) and black alder. The understory was sparse, with seedlings, blackberry, and bracken located throughout. A high amount of downed woody fuels were observed in these plots, with several centimeters of litter and duff covering the ground.

The mixed forest plots in the U.K. had an overstory of Scots pine, Norway spruce (*Picea abies*), beech, pedunculate oak and silver birch. The understory was bracken, holly, heather, common rush, and moss. This mixed forest was dense and the relatively open understory contained a large amount of downed woody debris in some plots.

2016

In 2016, sites from 2012 located in the Veluwe region, in or around the Hoge Veluwe National Park, were again used (Figure 1). Minimal site data are available for this year because the focus was measuring surface area volume. Shrub data were collected at each plot, so not all species were recorded as they were for vegetation coverage percentages or line intercept readings as in other years. The cover types studied in 2016 were grasslands, heather and Scots pine which have been described with more detail in the literature review as well as in the site descriptions of other years. At Scots pine sites the understory was specifically measured to obtain those measurements, and canopy measurements were taken separately.

At the grassland site, plots contained unspecified grasses and common heather and a small amount of black cherry. Heather sites were composed mainly of heather, with one plot containing a large percentage of crowberry. Other species such as purple moor-grass, Scots pine, catsear (*Hypochaeris radicata*) and common sorrel (*Rumex acetosa*) were recorded as well. Scots pine sites had understories dominated by common heather, European blueberry and unspecified grasses. Small trees or seedlings such as mountain-ash, silver birch, black cherry and pedunculate oak were present in small percentages.

2017

In 2017, the plots placed in grassland and heather communities in 2012 were used, as well as the open and grassland dune sites on Texel Island from 2013 (Figure 1). The grassland plots were composed of mainly grey hair grass and purple moor-grass, but heather was present in some of the plots as well. Moss covered portions of the ground in three of the four plots. Compared to the other sites in this year, litter and duff depths were higher and fine, 1-hour fuels made up much of the fuel load. 10-hour and 100-hour fuels were also in most of the grassland plots.

Heather plots mainly consisted of common heather, but some grasses and a few other species were also observed and measured. Grey hair grass and purple moor-grass were also in most of these plots, as well as some unspecified mosses and a small amount of *Rubus*. Cross-leaved heath (*Erica tetralix*), a close relative of common heather, is also present in significant percentages in a few of the heather plots. Litter and duff depths were considerably lower than in grassland plots. 1-hour and 10-hour fuels were measured in most of the heather plots.

The sites on Texel Island were classified as either open dune or dune grassland. Open dune plots contained only a couple grass species common to dunes, sand couch grass and marram grass. The remaining herbaceous cover was comprised of sand and moss. Grassland plots were slightly more diverse and also contained sand couch grass and marram grasses, as well as sand sedge. A few plots contained small amounts of other species, such as sea spurge (*Euphorbia paralias*), lesser hawkbit (*Leontodon saxatilis*), and burnet rose (*Rosa spinosissima*). A percentage of unvegetated sand and moss also existed within most grassland dune plots. For both cover types, litter depths were low and duff was nonexistent. Only fine 1-hour fuels were present in either cover type.

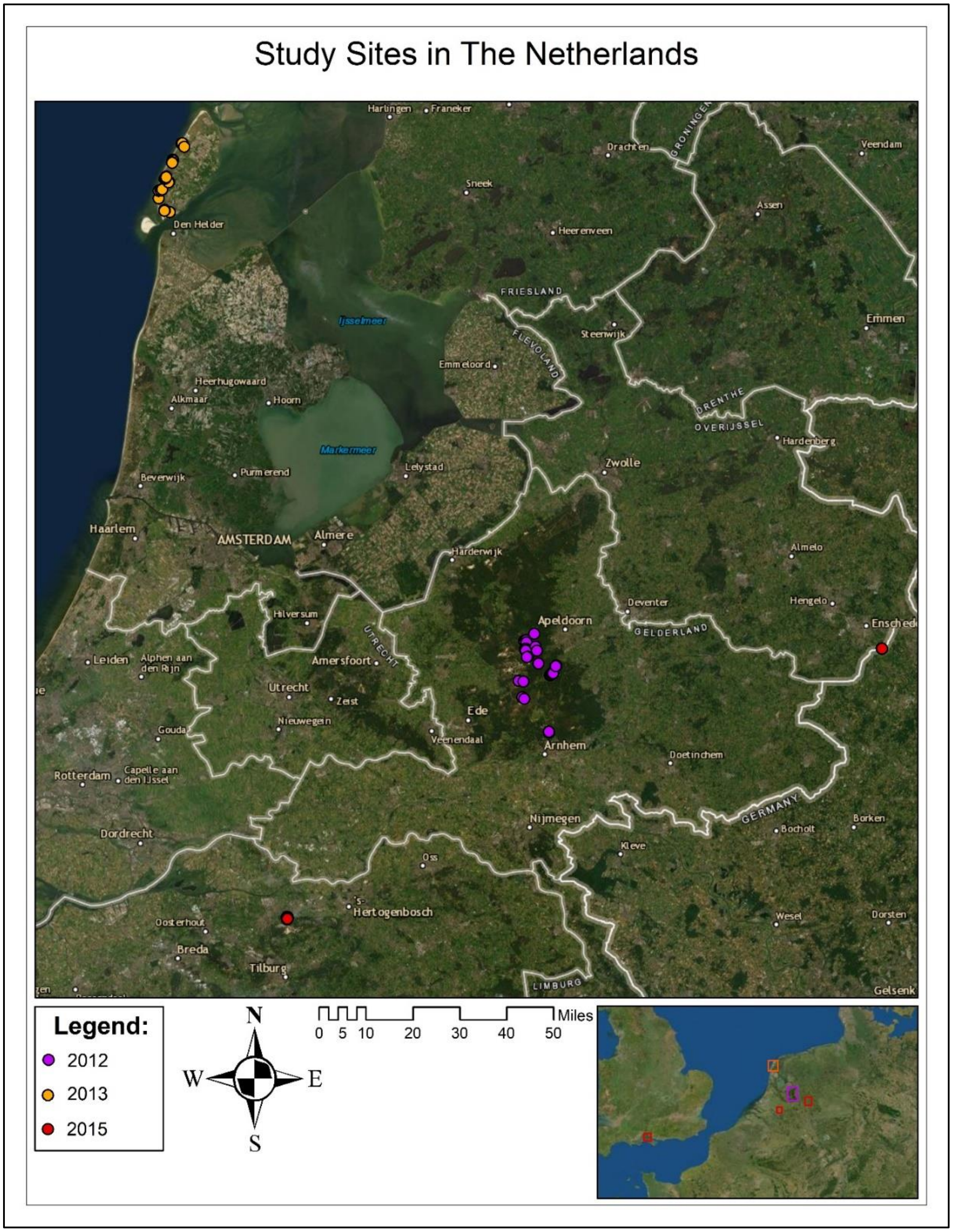

Figure 1. Study sites in the Netherlands that were established in 2012, 2013, and 2015. Sites were located on the mainland as well as Texel Island off the northwestern coast.

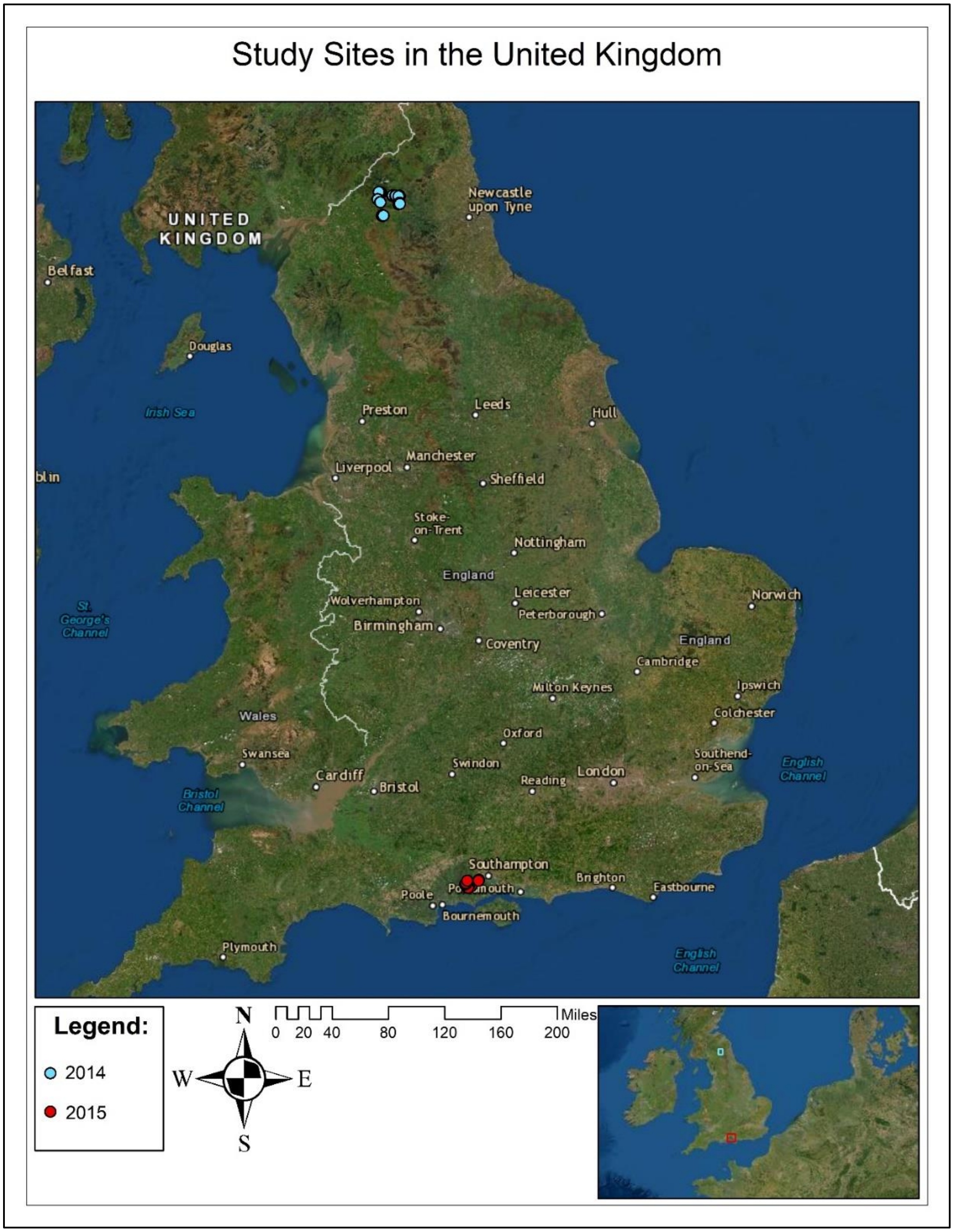

Figure 2. Study sites in the United Kingdom that were established in 2014 and 2015 in conjunction with the ongoing study in the Netherlands.

Field Methods and Data Collection

2012-2014

In these first three years the same plot design was used. This design was adapted from Stereo Photo Series for Quantifying Natural Fuels in the United States (Ottmar et al., 2000). The wedge-shaped layout consisted of five transect lines emanating from the same point with five arcs crossing these lines at 9.1, 18.3, 27.4, 36.6, and 45.7 meters. Twenty-five plots were placed where the arcs cross the transect lines and 12 more plots were systematically placed throughout the sample area where tree and shrub measurements were taken. Six of these subplots fall on an arc and overlapped with the first 25 plots and the other six were placed between arcs (Figure 3).

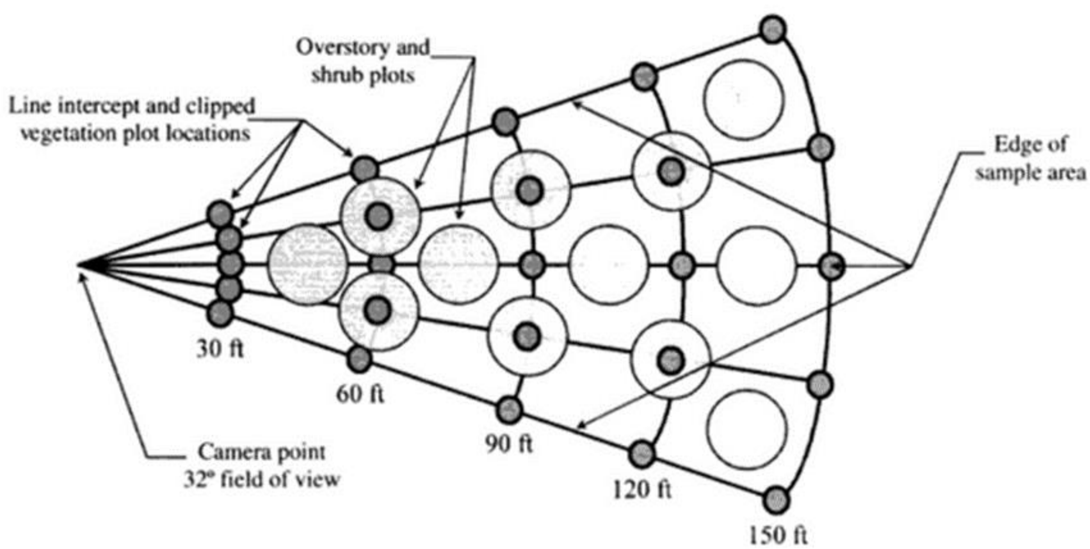

Figure 3. Original plot layout design by Ottmar et al. (2020), adapted for use in field measurements taken during the summer by Stephen F. Austin State University students from 2012 to 2014. Units in this figure are English, not metric, as the original layout was first used in the U.S.

In the 50 subplots, litter and duff depths were measured. For overstory measurements, a densiometer was used to determine the percentage of open canopy at each of the 12 tree and shrub plots. Each species present was recorded and diameter at breast height (DBH), total height, and basal diameter were measured. Live or dead status of each overstory tree in the plot was determined and live or dead height was measured correspondingly. The canopy diameter was measured at both the widest point and at 90 degrees. For shrub and understory measurements, the species present were recorded and live or dead status was determined. Understory vegetation was categorized into seedlings and saplings. Shrub density, number of stems and basal diameter were recorded and two canopy diameters were taken for each shrub.

Measurements used to determine fuel loads were taken along the transects in the sample area. Line intercept percentages of species and ground cover were taken at each of the 25 plots as well as the 6 mid/overstory subplots not placed on an arc. Downed woody fuels were classified using time lag values. Litter and duff bulk densities were measured by filling a can of a known volume with litter or duff, then drying and weighing it.

2015

In 2015, the adapted plot design (Figure 3) was again used. Similar data were recorded using the transect lines and subplots as in 2012 through 2014. Litter and duff depths were recorded in centimeters, and densiometer readings were taken to estimate the percentage of open canopy at each plot. Fuel loading data were collected along the line intercepts and downed woody fuels were measured along these lines as well. Herbaceous vegetation densities were recorded by percentages along with heights in centimeters. In addition to observing herbaceous species, woody species were observed as well. Overstory data included species, diameter at breast height in centimeters, total height in meters, as well as live and dead status and heights. Canopy widths at the widest point and at a 90° angle were measured in meters at each plot with an overstory. Understory species were recorded, then classified as either seedlings or saplings. Live or dead status of understory vegetation was determined. Shrub were measured by recording the species and its density, the number of stems and the height in meters. Each measured shrub was determined to be live or dead, and shrub canopy diameters were recorded. Shrubs were classed into phases, including juvenile, seedling, or sapling.

2016

In 2016, the previous plot design was not utilized. Herbaceous coverage, live and dead foliage, and stem diameters and lengths were taken to determine surface area volume (SAV) in grassland, heather, and Scots pine communities. In each cover type, two plots were located. Species and their respective coverage percentages were recorded along with the maximum height observed. Cover percentages of live and dead vegetation were estimated separately. Herbaceous cover heights were recorded in centimeters and used in surface area volume calculations. Stem diameters were measured in millimeters, and stem lengths were measured in centimeters.

2017

In 2017, the same plot layout design that was utilized in 2012-2014 was used at grassland and heather sites (Figure 3). Using this layout, litter and duff depths, herbaceous vegetation heights, and fuel loading information including line intercept and downed woody fuel measurements were taken as they were in the previous years. In addition, herbaceous cover densities were recorded by percentage covered within the plot. Surface area volume was determined by collecting shrub data including total height, live and dead crown heights, basal diameter, and canopy diameters.

Statistical Analysis

The data collected during these years were divided based on which fuel category they were most relevant to: litter/duff, shrub, and downed woody material (Table 1). The separation of these variables was done so that a distinct linear regression analysis could be performed for each fuel category. Linear regression was chosen to demonstrate the relationship and predictive capability between the variables in each fuel category to biomass. Data were analyzed using RStudio 4.2.0 (R Core Team, 2022).

Table 1. Potential explanatory variables are separated below by growth form dominant cover type and year selected. These parameters were split into the three fuel categories in this study based on relevance, although not all were utilized.

Year	Shrubs	Grasses	Litter
2012	Basal diameter (cm), Density (%), Height (cm)	Wet/dry weights (g)	Litter/duff depths (cm), Bulk density (g/cm³)
2013	Basal diameter (cm), Density (%), Height (m)	Herbaceous density (%)	Litter/duff depths (cm),
2014	Basal diameter (cm), Height (m)	Herbaceous density (%)	Litter/duff depths (cm)
2015	Basal diameter (cm), Height (m)	–	Litter/duff depths (cm), Bulk density (g/cm³)

Litter and Duff Fuels

To determine the suitability of using litter depth, duff depth, and bulk density to predict loading in terms of available biomass, mean subplot values were calculated to provide a single value of each variable for each plot, with plots placed in one of five cover types. This resulted in 26 total mean values for each litter/duff vegetation parameter. Summary statistics were calculated for each variable using the psych package (Revelle, 2022) and the describe function. Assumptions of linearity, independence of observations, and normality were tested in the base R package. Linearity was tested by using the plot function to demonstrate the relationship between each vegetation parameter and biomass. Due to the nonlinear relationship between litter depth and biomass, litter depths and duff depths were combined into total O horizon depth. Independence of observations was tested by using the cor function in the R base package to check for potential correlation between variables. Normality of distribution of the data was tested using the hist function to graph the variables in a histogram.

To determine differences among and between cover types, a Kruskal-Wallis test and a pairwise comparison using the Wilcoxon rank sum test were performed using the stats package (R Core Team, 2022). A nonparametric test was utilized because of the non-normal distribution of the data. A boxplot was produced to demonstrate the distribution of data in the five cover types. The Akaike information criterion (AIC) was applied using the AICcmodavg package (Mazerolle, 2020) to discern the best variable selection among a set of possible models. This method is preferable to traditional model selection approaches such as forward, backward, and stepwise selection because it offers more consistent and robust estimates and does not rely on significance values to show best fit (Mazerolle, 2006). Utilizing this method demonstrated which vegetation parameters can best be used to accurately predict biomass fuel loading and justifies their inclusion in the final model. Following model selection, MLR was performed using the linear model function to fit the data to a linear model.

Shrub Fuels

A similar methodology was used to analyze the shrub fuel load data. The variables stem count, basal diameter (cm), total height (cm), and canopy diameters 1 and 2 (cm) were all tested to determine their ability to predict fuel loading, represented using dry weight (g) of biomass. Variables were first standardized, as the original data collection was not performed using consistent units. The dominant species in each plot was specified, and the dry weight was calculated using the components that were determined by Brown (1976). The summary statistics and assumptions of linearity, independence of observations, and normality were obtained and tested using the same methods as the litter/duff fuel category. A Kruskal-Wallis test to test for significant differences between shrub species was done.

To perform regression analysis, the dataset was further split into five significant cover types. Using a minimum sample size requirement recommended for regression analysis ($n \geq 30$), the dataset was narrowed down to five cover types: heather, Scots pine, dune heather, dune valley, and peat heather (Jenkins and Quintana-Ascencio, 2020). For each of these cover types, a separate analysis process was followed for each one to produce five different regression models. First, simple linear regression was applied to each of the five variables to determine the nature of the relationship between these and dry vegetation weight. Then a separate AIC was run for each of these significant cover types to find the best fitting regression model. The assumptions for regression were tested for each model produced by creating a histogram to check for normality and by looking at the Pearson's correlation coefficients between variables.

Downed Woody Material Fuels

For the downed woody material (DWM) data, a MLR analysis was not performed due to the lack of quantifiable variables collected. DWM was measured using the planar intercept method (Brown, 1974). Following this method, DWM was divided into 1-hour, 10-hour, 100-hour, 1000-hour solid, and 1000-hour rotten timelag values amongst 17 cover types. As these are categorical values, they cannot be utilized in a predictive model. Tons per acre of downed woody material were used as a measurement of available biomass and were calculated using the method demonstrated by Brown (1974). Summary statistics and assumptions of linearity, independence of observations, and normality were obtained following the same methods as the previous fuel categories. The data were not found to follow normal distribution, so a Kruskal-Wallis test was performed to determine differences in tons per acre among cover types. The cover types were then divided into three subcategories: forested, peat, and dune types. Each of these subcategories were tested for differences amongst them again using the Kruskal-Wallis test. A post-hoc Wilcoxon rank sum test was used to determine which cover types in the forested and peat subcategories had significant differences. A boxplot was made for all three subcategories to demonstrate the distribution of data of each cover type.

RESULTS

Litter and Duff Fuels

All observations in this category are from 2012 due to lack of data from other years. There were significant differences in total biomass among and between the five cover types (p-value of 0.001). These differences were greatest between forested and non-forested cover types, with litter/duff biomass levels at 0 or nearly 0 for plots in grassland and heather covers. AIC analysis results indicated that the best model selection includes total O-horizon depths and bulk density, with the lowest AICc value of 573.93 (Table 2). This model carries 73% of the cumulative model weight. Significant relationships were found between these vegetation parameters and biomass fuel loading. The model with separate litter and duff depths is not as strong, indicating that combination of these two variables can be done with no adverse effect on total biomass prediction. Significant relationships exist between total fuel loads demonstrated through biomass and total O-horizon depth and bulk density ($p < 0.0001$ and $p < 0.001$, respectively). As total O-horizon depth and bulk density increase, total biomass increases as well. Multiple linear regression with the best model determined by the AIC resulted in an equation with an R^2 value of 0.967 (Table 3).

Table 2. Akaike information criterion for the litter and duff fuel category showing the best fit model with the potential explanatory variables of litter, duff, combined total O horizon and bulk density.

Proposed model	K	AICc	Delta AICc	AICc Weight	Cumulative Wt	Log Likelihood
Total O-horizon+Bulk density	4	573.93	0.00	0.73	0.73	-282.01
Litter+Duff+Bulk density	5	575.99	2.06	0.26	0.99	-281.49
Total O-horizon	3	582.20	8.27	0.01	1.00	-287.55
Bulk density	3	628.27	54.34	0.00	1.00	-310.59

Table 3. Parameter estimates for the predictive model used to estimate above ground litter and duff biomass (R^2=0.97).

Variables	Estimate	Standard Error	T-value	Pr(>|t|)
Intercept	-5867.70	4874.90	-1.20	0.2410
Total O horizon	39269.60	2893.30	13.57	<0.0001
Bulk density	2453.50	701.80	3.50	0.0019

Shrub Fuels

Significant differences between the amounts of dry vegetation weights existed among and between species (p-value < 0.001). All species showed similar ranges but blueberry showed higher dry weights than the others, most likely due to high stem counts. Heather is a species of interest, as its volatile compounds have the capacity to significantly influence fire behavior. Differences between heather and sea buckthorn and blueberry are the most distinct.

This dataset contained many missing values which made both AIC and regression analysis difficult. Many cover types had little to no observations, so the entire shrub dataset was divided into cover types to allow for a more accurate model. Stem count was observed to be causing the models to have an inflated R^2 value, so it was removed from the analyses. AIC results indicated that for each cover type, the most significant variables were total height and basal diameter (Table 4). The models for the heather (R^2=0.13) and Scots pine (R^2=0.20) cover types contained only total height. The model for the dune heather cover type (R^2=0.07) contained only basal diameter. The models for both dune valley (R^2=0.20) and peat heather (R^2=0.62) cover types contained both total height and basal diameter (Table 5). As evidenced by the mostly low R^2 values, the predictive power of these models is relatively weak. However, total height and basal diameter are both significant in estimating shrub fuel loading in these cover types. The measurements of canopy diameter were not included in any of the best-fitting models. Canopy diameter measurements may be useful in future models, as they serve as a surrogate for shrub density. Shrub crown area may be a useful predictor in a predictive model to measure.

Table 4. The best fitting models for prediction of shrub fuel loading according to the Akaike information criterion for five cover types.

Cover Type	Model	K	AICc	AICc Weight	Log Likelihood
Heather	total height	3	592.01	0.37	-292.76
Scots pine	total height	3	526.64	0.34	-260.07
Dune heather	basal diameter	3	553.65	0.29	-273.60
Dune valley	basal diameter + total height	4	330.63	0.43	-160.65
Peat heather	basal diameter + total height	4	454.04	0.56	-222.71

Table 5. Parameter estimates for each of the predictive models used to estimate above ground biomass (dry weight in g) for the five shrub cover types.

Variables	**Estimate**	**Standard Error**	**T-value**	**Pr(>|t|)**
		Heather		
Intercept	370.75	30.4	12.2	<0.0001
Total height	-2.08	0.71	-2.95	0.0048
		Scots pine		
Intercept	226.77	13.77	16.47	<0.0001
Total height	1.66	0.44	3.74	0.0005
		Dune heather		
Intercept	247.82	11.01	22.51	<0.0001
Basal diameter	4.84	2.15	2.26	0.0280
		Dune valley		
Intercept	253.24	8.17	30.98	<0.0001
Basal diameter	5.82	1.95	2.98	0.0054
Total height	-0.52	0.17	-3.07	0.0043
		Peat heather		
Intercept	167.71	4.48	37.43	<0.0001
Basal diameter	6.96	0.74	9.41	<0.0001
Total height	0.38	0.09	4.50	<0.0001

Downed Woody Material Fuels

Significant differences between cover types of tons per acre of biomass were not detected following the initial Kruskal-Wallis test (p-value > 0.05). Following these results, the subcategories were tested using the same method. Within these three subcategories, significant differences within forested cover types and peat cover types were apparent (p-value of 0.002 and 0.0003, respectively). No significant differences were observed between the dune cover types. Of the forested cover types, dune forest and Douglas-fir communities displayed the greatest differences according to the pairwise Wilcoxon rank sum test (p-value of 0.024). Differences are also shown between Douglas-fir and new forest plots (p-value of 0.041).

Of the peat cover types, differences between peat bog and peat forest plots were the most significant (p-value of 0.035). Peat forest cover types were sampled both in 2014 and 2015, and they displayed significant differences with the peat heather cover type (p-value of 0.056 in 2014 and p-value of 0.081 in 2015). Interestingly, the peat heather and heather cover types differed significantly from each other (p-value of 0.084).

DISCUSSION

In two of the three separate fuel categories certain vegetation parameters were determined to significantly contribute to fuel loading more than others. In these two categories, regression models were developed to predict biomass fuel loading. Several factors including fuel category and predominant vegetation structure and composition influenced which variables were more useful in predicting total above ground biomass. For the litter and duff fuels category, combining litter and duff measurements into total O horizon measurements was found to provide better predictions of total biomass fuel loading. Combined with bulk density measurements, a multiple linear regression model was estimated to predict above ground biomass in the sampled fire-prone systems. For the shrub fuels category, cover types were too varied in vegetation species and composition to develop one singular comprehensive predictive model for total dry weight of fuels. Five separate regression models were developed for the cover types with the most data available, each with varying degrees of predictive power. In each of these models, total height, basal diameter, or a combination of both were found to be the most significant variables. In the downed woody material (DWM) fuels category, the nature of the sampled data prevented the ability to develop a regression model. However, significant differences were determined to be present amongst cover types in tons per acre of DWM based on dominant vegetation type. Implications do exist from these findings regarding predicting fuel loads in certain fire-prone systems in the Netherlands.

Litter and Duff Fuels

The measurement of fuels can be difficult even when utilizing standardized and established methodologies. Fuels are complex in structure and highly variable across large spatial scales (Keane et al., 2013). Because of this complexity, ideally all vegetative components of wildland fire fuels would be measured separately. According to Brown et al. (1982), litter and duff have differing effects on fire behavior and often burn independently of each other, particularly in regions where duff buildup is high due to increased fire return intervals such as the western United States. The duff layer typically smolders and therefore results in higher, more prolonged temperatures around the base of trees and root systems, leading to increased overstory mortality. Negative effects are also seen on the seed bank of forest floors due to this effect (Hille and Stephens, 2005).

However, simplification of the measurement process could prove helpful especially in areas such as the Netherlands where management and monitoring practices are not as extensive as in the United States. Differentiating between litter and duff layers can often be imprecise and subjective, in most cases depending on the judgement of the individual who is collecting the measurement (Vega et al., 2021, Federer, 1982). According to Yanai et al. (2003), making distinctions between litter and duff layers is difficult to do unless in a lab setting where samples can be weighed. These layers, even when differentiated in the field, are often mixed not only with each other but with particles from the underlying A horizon (Vega et al., 2021). To simplify the process of data collection and potentially reduce error, it is suggested that litter and duff layers be combined into total O-horizon depth when measuring fuels in systems in the Netherlands. This will also have the effect of requiring less labor and time spent attempting to teach individuals how to differentiate between the two layers in a region where fuels monitoring work is not as commonly performed as it is in the United States.

Bulk density is a parameter that has been widely accepted to be important in determining a fuel bed's ability to ignite. It is often used to decide which fuel models a system falls into to calculate important fire behavior variables such as rate of spread, reaction intensity, duff consumption and smoke production (Rothermel, 1972, Albini, 1976, Anderson, 1982). Bulk density is an especially important variable when predicting the flammability of litter fuels (van Wagtendonk et al., 1998, Cornwell et al., 2014). As it is a measure of the compactness of soil, including the O-horizon, bulk density indicates the amount of fuel weight in the fuel bed. Therefore, measuring this parameter will help managers of these fire-prone cover types predict potential risk of wildfire and fire behavior.

Shrub Fuels

Fuel loading across large spatial scales containing many different plant communities can vary greatly due to changes in vegetation composition and structure (Keane et al., 2012). In many regions where multiple heterogenous systems exist, levels of biomass can differ from each other from cover type to cover type (Kauffman et al., 1994). These differences in fuel loading are also caused by intensity of large-scale disturbances, which can cause variation within a system even on a small scale (Thaxton and Platt, 2006). Due to these differences between cover types, it can be helpful to the prediction of amount of biomass to analyze them separately. Different cover types produce different fuel loads, so it can limit the usefulness of large datasets that contain vegetative measurements from multiple plant communities. Creating different predictive models for each community helps to give better understanding of the potential fire behavior that managers should expect, which in turn reduces risks that wildfire poses to human-populated areas. This is especially important in countries like the Netherlands, where fragmented landscapes lead to close proximity of human property and living spaces to fire-prone cover types.

Total height and basal diameter of shrubs were shown to be the most significant variables related to predicting total dry weight in each separate cover type. Similar heather systems to what exists in the Netherlands can also be found in other regions of Europe, such as Spain and Portugal. Understanding fuel loads in heather cover types is particularly important, as fire behavior within them can present significant risk to nearby human populations. Not only does this species contain volatile fat compounds which can lead to higher burn temperatures, it also grows commonly on peatlands, which can often continue to smolder for days following a fire event (Davies et al., 2010). In these communities, shrub height has been shown to be useful in predicting fire behavior such as rate of spread (Fernandes, 2001). According to Caceres et al. (2019), shrub height is one of several vegetative parameters that can be used to estimate total biomass in these systems. Basal diameter is also shown to be integral to estimating fuel loading in similar systems. Small-flowered gorse (*Ulex parviflorus*) is a species that has many comparable qualities to heather, such as being evergreen and accumulating dead biomass that remains part of the living plant's structure. In *U. parviflorus* communities, basal diameter is an important predictor of biomass (Baeza et al., 2006).

Although the results of the shrub fuel analyses were mixed, they can inform management of fire-prone shrublands in the Netherlands in several ways. First, total height and basal diameter should continue to be collected to estimate fuel loading in these shrub communities. Canopy diameter measurements may be useful in future models or other applications, but in the interest of creating a more streamlined methodology for predicting biomass, they can be removed. Furthermore, separation of height measurements into dead heights and live heights would be helpful in better prediction of wildfire effects in heather communities (Baeza et al., 2006, Caceres et al., 2019). Dead standing fuels can make already susceptible communities even more hazardous in wildfire events and are therefore important to measure.

Downed Woody Material Fuels

A standardized method for detecting downed woody material biomass has existed since the line-intersect sampling method was first introduced in logged forests in New Zealand (Warren and Olsen, 1964). It was further refined since then by Brown (1974) into the planar intersect method, which utilized numerous shorter transect lines instead of fewer longer ones. This method has been widely used in the United States, especially in the western region (Brown, 1974). As with most methods of measuring organic matter, there are some potential errors present within line-intersect sampling. The most major issue is a lack of proper measurement metric for coarse woody debris (CWD), such as fallen trees or large downed branches (Waddell, 2001). CWD can vary in shape and position on the landscape, making it difficult to estimate its makeup in the fuel loading of an area. Waddell (2001) found that the inclusion of CWD estimation equations could enable a new understanding of the makeup of fuels in a region. In a country with wildfire risk such as the Netherlands, this could be an important factor in estimating biomass fuel loading accurately and precisely. However, because there are already minimal resources provided for this purpose here, it may be considered an unnecessary extra step. Considering the current state of forest management in the Netherlands, it could be adequate to follow the current methodology put forth by Brown (1974).

CONCLUSION

The Netherlands, like most other parts of the world, is facing the negative effects of changing climate conditions. Increased wildfire risk is occurring throughout northwestern Europe. In a region where the wildland-urban interface is common throughout, prevention and prediction of the risk is key. Changes in management are necessary to prevent further wildfire risk in both natural and human-populated areas. The first step in this process is to gather information, which can be done with efficient data collection. The Netherlands already has experience with management of natural resources, as flood prevention and water management are part of the country's history. A switch has been made in Dutch water management that could be implemented in wildfire risk management as well. It is a focus on staying aware of the potential risk before a disaster occurs and being proactive by monitoring the issue (Lambrechts et al., 2023). Ongoing observation such as fuels monitoring is an example of such management, as prediction of what can burn will help prevent damage to private citizens and property. According to a recent comparison by Lambrechts et al. (2023), regular updates in knowledge about wildfire risk is vital to prevention.

The combination of changing climates and high density of population in the Netherlands creates a need for measuring fuel loading to prevent wildfire risk. With a simplified approach to fuels monitoring in the Netherlands, this process can be streamlined and efficient. This research project takes steps towards that end, with the goal of isolating the most significant predictors to fuel load estimation. Once fuel loads can be better understood, this information can be combined with public education of fuel reduction techniques. These techniques can then begin to be applied to fire-prone ecosystems in the Netherlands, thus reducing risk of catastrophic wildfire events that will negatively impact the country. This research could potentially be used as a first step to create a fire behavior prediction program specific to cover types in the Netherlands, similar to Behave+ in the United States. A program like this that is based on fuel models specific to systems in the Netherlands could assist natural resource managers in making effective decisions regarding fuel management.

However, as regular prescribed burning is not currently an option in the Netherlands, other fuel reduction techniques may be considered. Mastication of fuel beds is a mechanical method of reducing fuels where above ground biomass is shredded using large equipment such as a tractor, leaving the material below the ground's surface undisturbed (Potts & Stephens, 2009). This method would achieve the goal of fuel reduction and therefore create a reduced risk of wildfire. It also has the added benefit of creating a layer of mulch which could assist in the germination and survival of new plants (Potts & Stephens, 2009). Although this method could potentially be difficult to administer in areas where mobility of large mechanical equipment is not possible, it is much more likely to be used than prescribed fire in a country like the Netherlands where that is not currently an accepted practice.

Overall, fuel management in the Netherlands is in its beginning stages still as methodologies become more established. The United States has been dealing with the negative effects of fire suppression and lack of understanding of fire ecology for over a century, and management practices here still leave much to be desired. It is a complex issue with many facets such as public perception and understanding, governmental regulations, and constantly ongoing ecological processes. The course of creating practices that reduce wildfire risk and increase the safety of the public, particularly in fragmented regions like the Netherlands, needs to begin with understanding the fuel loading and how it can be estimated. By identifying which surface parameters need to be measured to estimate fuel loads and producing predictive models with them, this research takes one small step in that direction.

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APPENDIX

Table 6. Summary statistics for each of the fuel categories outlined in this research. Means, standard deviations, and ranges for each category dataset are included.

	Mean	**Standard deviation**	**Range**
Litter/Duff			
All	96775.00	73193.48	0.00 - 200114.00
Shrub			
Dune heather	271.30	28.52	202.50 - 321.80
Dune valley	237.40	27.89	195.60 - 302.90
Peat heather	210.70	9.64	191.30 - 236.50
Heather	284.10	59.68	198.80 - 390.00
Scots pine	274.60	41.07	201.20 - 338.30
All	257.20	49.74	191.30 - 428.70
Downed Woody Material			
Forested	1143.50	1327.43	0.00 - 5024.00
Dune	117.05	218.39	0.00 - 888.21
Peat	142.69	452.66	0.00 - 2067.10
All	498.47	992.36	0.00 - 5024.00

Table 7. These plant species are referenced throughout this text. Below are their common names in both English and Dutch, as well as their scientific names.

English	Dutch	Scientific
pedunculate oak	zomereik	*Quercus robur*
blackberry	braam	*Rubus* spp.
mountain-ash	wilde lijsterbes	*Sorbus aucuparia*
sea buckthorn	duindoorn	*Hippophae rhamnoides*
common heather	struik heide	*Calluna vulgaris*
purple moor grass	pijpenstrootje	*Molinia caerulea*
downy birch	zachte berk	*Betula pubescens*
marram grass	helm	*Ammophila arenaria*
grey hair grass	buntgras	*Corynephorus canescens*
creeping willow	kruip wilg	*Salix repens*
crowberry	kraai heide	*Empetrum nigrum*
sand sedge	zand zegge	*Carex arenaria*
hawthorn	eensteilige meidoorn	*Crataegus spp.*
common elderberry	gewone vlier	*Sambucus nigra*
reed	reit	*Phragmites spp.*
gray willow	grauwe wilg	*Salix cinerea*
rose	roos	*Rosa* spp.
black cherry	Amerikaanse vogelkers	*Prunus serotina*
sand couch grass	biestarwegras	*Elytrigia juncea*
rosebay willow-herb	wilgenroosje	*Chamaenerion angustifolium*
common polypody	gewone eikvaren	*Polypodium vulgare*
honeysuckle	wilde kamperfoelie	*Lonicera periclymenum*
common sorrel	zuring	*Rumex acetosa*
lesser hawkbit	kleine leeuwentand	*Leontodon saxatilis*
burnet roos	duinroos	*Rosa spinosissima*

VITA

Lauren R. Lara was born in Odessa, Texas on June 29, 1993 and raised in the Dallas/Fort Worth area of Texas. After graduating from Mansfield Timberview High School in 2011, she earned her Associate of Arts at Tarrant County College in Arlington, Texas. In 2018, she moved to Nacogdoches, Texas to attend Stephen F. Austin State University where she earned her Bachelor of Science in Forestry in 2020. Following this, she pursued her Master of Science in Forestry at Stephen F. Austin State University. During graduate school, she was employed as a Graduate Teaching Assistant under Dr. Brian Oswald and Mr. John Kidd in the Arthur Temple College of Forestry and Agriculture at SFASU.

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Formatting of the Literature Cited section and in-text citations followed APA guidelines; all other formatting followed SFASU Graduate School guidelines or preferences of the thesis committee.

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