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Evaluating environmental predictors of breeding waterfowl population distribution and abundance in the Central Interior of British Columbia (2007-2017)

ABSTRACT

Conservation biology has seen an explosion of species distribution models (SDMs) in the recent published literature and growing numbers of governments and organizations responsible for small-scale regional to global conservation activities are actively utilizing them or have embarked on their own predictive studies (Franklin and Miller 2009; Guisan, Wilfried, and Zimmermann 2017). Waterfowl conservation planning in British Columbia (BC) however currently does not have the benefit of breeding waterfowl SDMs. To address this gap I have developed methods to generate SDMs using 11 years of survey data from BC's annual Breeding Waterfowl Survey between 2007 and 2017. Models utilizing a random forest-based approach were used to produce predictive maps for ten species and five species groups within each of the eight ecozones within the central interior representing core provincial breeding waterfowl habitat. The developed methods, techniques and recommendations form a template for future studies in the generation of species distribution maps for guides in conservation planning.

Keywords: waterfowl, random forest, species distribution model, conservation

INTRODUCTION

While the uses and practical applications of species distribution models in conservation decision-making are diverse (Guillera-Aroita et al. 2015; Guisan et al. 2013; Guisan and Thuiller 2005) the overarching aim is to conserve biodiversity and support better land use planning and environmentally sustainable management practices. The breadth of practical applications include predicting climate change adaptation, invasive species management, critical habitat identification, reserve selection, impact assessment and ecological restoration (Elith and Graham 2009; Franklin and Miller 2009).

Recognizing the lack of waterfowl species distribution models (SDMs) to support conservation actions in response to the urgency of conservation challenges in Canada's boreal forests, Barker et al (2014) published the first national-scale waterfowl SDMs in 2014 based on the traditional Waterfowl Breeding Population and Habitat Survey (WBPHS) database. The WBPHS has been described as "arguably the largest and best-designed population survey in the world" (Murray, Anderson, and Steury 2010), continental in scale and running on a continuous annual basis since 1955, the survey captures what is recognized to be "core waterfowl breeding habitat" in North America. Designed primarily to provide annual breeding population estimates and inform hunting regulations in the U.S. and Canada, these data additionally provide a long-term population monitoring dataset that has since informed countless studies on species-habitat relationships in support of waterfowl conservation. While the models performed well over all, the results of extrapolation to out-of-sample areas were variable for a number of reasons as outlined by the authors. British Columbia (BC) is not within the traditional survey and no survey data from BC informed the models which predicted low total densities for the Western Cordillera between the Pacific coast and Rocky Mountains—a result that conflicts with anecdotal expert opinion (A. Breault, personal communication 2018). As such there are currently no adopted waterfowl

breeding population distribution models in use for the province. This study aims to fill the this gap and help support the mandate of the Canadian Wildlife Service (CWS) to conserve biodiversity (Environment and Climate Change Canada 2019; Environment Canada - Biodiversity Convention Office 1995). In the early 2000s after exploratory pilot surveys in BC's central and sub-boreal highlands determined waterfowl population abundances to be significant enough to justify a regional breeding survey program, the British Columbia Breeding Waterfowl Survey began in earnest in 2006. BC's May surveys, run jointly by the CWS and the U.S. Fish and Wildlife Service and conducted in partnership with Ducks Unlimited Canada, inform the annual population status of migratory game birds in the Central Interior Plateau of BC and contributes to adaptive harvest strategies for mallards in the Pacific Flyway (Zimpfer, Breault, and Sanders 2019).

I developed methods to create SDMs for the top ten most abundant species as well as five group classifications based on life history traits and community descriptors (Baldassarre 2014) (Tables 1 and 2). Guisan et al (2013) have observed that despite the oft-cited assumption of the utility of SDMs in conservation decision-making there is little evidence demonstrating their application in real-world conservation management. Following their recommendation that modellers make explicit the objectives of the framework within which models were developed, I provide guidance on how the SDMs may be improved and implemented as a decision-making platform for conservation planning by the Canadian Wildlife Service and partners in conservation.

MATERIALS AND METHODS

Survey Methods

The study area was designed to capture BC's prime waterfowl breeding habitat of the humid, continental plateaus of the central and sub-boreal Interior between the Coast mountains to the west and Rocky Mountains to the east. The region of interlocking highlands and valleys are mainly forested and sparsely populated. The main industries include forestry, cereal crop agriculture within lowland valleys, ranching and mining (Demarchi 2011).

The survey design consists of latitudinal strip transects 400 metres wide, spaced ten miles apart (16.09 km) and delineated by the boundaries of eight ecosections which represent the finest scale, sub-regional stratum within the Ecoregion Classification System of British Columbia—a small-scale ecosystem management framework stratifying nested regions of “similar climate, physiography, oceanography, hydrology, vegetation and wildlife potential” (Demarchi 2011) (Figure 1). The classification levels ordered from high to low include Ecodomains for global mapping applications, ecodivisions for national-scale, ecoprovinces for provincial scale, ecoregions for regional and ecosections for sub-regional planning. While designed for small-scale mapping ecosection boundaries are drawn at large scale (1:20,000).






The southern two-thirds of the study area falls within the Fraser Plateau Ecoregion. The flat and rolling hills of the region contain numerous meandering streams and low-lying depressions that create an abundance of wetland habitat (Demarchi 2011) while the Central Interior Ecoprovince in which it nests supports 65% of all species known to occur and 61% of all bird species known to breed in BC. with the greatest total abundances of waterfowl occurring in the Cariboo Basin ecosection within the Riske Creek area (Demarchi 2011; Savard, Sean Boyd, and John Smith 1994). The remaining northernmost third of the study area stretches into the Sub-boreal Interior Ecoprovince which supports 57% of all bird species known to occur and 45% known to breed in the province (Demarchi 2011). Table # provides general descriptions of study area ecosections.

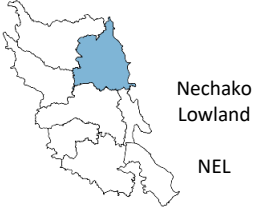
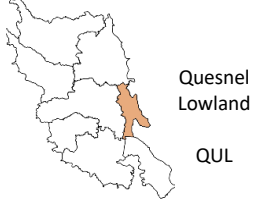
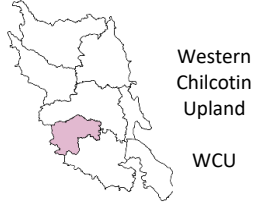
The surveys are conducted by helicopter and surveyed by a consistent survey crew of two to three experienced observers (Zimpfer, Breault, and Sanders 2019). The transects when originally conceived were designed within the NAD 1983 geographic coordinate system and were based on the mapped Ecoregion Classification System version 2.0 (1995). The ecosection boundaries have since been updated with finer scale vegetation zonation data in version 2.1 (2006) however the annual surveys continue to follow the extent of the original design. All analyses were based on the areal overlap between the two versions with the boundaries redefined in alignment with version 2.1.



Figure 1. The survey area divided into the ecosections of the Ecoregions of British Columbia Classification system (Demarchi, 2011). Latitudinal strip transects (horizontal lines) are spaced ten miles (~16 km) apart within the Central and Sub-boreal plateaus of BC.

Table 1. General summary descriptions of ecosections within study area as described in Demarchi (2011).

Ecoregion	Ecosection	Topography	Climate	Vegetation	Governance, Protection, Development
Fraser Basin	 <p>Babine Upland BAU</p>	Rolling upland with low ridges; many small streams and lakes and several large lakes	Sub-continental--extreme winter cold and snow events, humid and rainy	Sub-boreal spruce dominated forests	Sparsely populated, seasonal lodges; many protected areas
Fraser Plateau	 <p>Bulkley Basin BUB</p>	Broad, lowland valleys with many lakes	Rainshadow effect of Coast mountains	Dominated by lodgepole pine; trembling aspen in lower south-facing valleys	Extensive development and agriculture within Yellowhead Hwy corridor and surrounding Francois Lake; protected areas include Francois lake Park
Fraser Plateau	 <p>Cariboo Basin CAB</p>	Rolling uplands; many streams, wetlands and lakes	Warmest temperatures within ecoregion; relatively high summer precipitation	Vegetation zonation changes	Small farms, ranches and logging are main industries. Williams Lake is largest city
Fraser Plateau	 <p>Chilcotin Plateau CHP</p>	Rolling uplands with many small lakes and wetlands; higher relief in south and northwest abutting Chilcotin Ranges and west Chilcotin; many small streams and rivers	Pronounced rain shadow effect	Douglas fir near rivers and lodgepole pine at higher elevations	Ranching and logging are main industries; Big Creek Park is largest park
Fraser Plateau	 <p>Nazko Upland NAU</p>	Rolling uplands with high relief within north-central region; slow moving streams and wetlands	Sub-continental climate--cold winters, warm summers, maximum precipitation in late spring/early summer; subject to cold balasts of Arctic air	Lodgepole pine in south and white spruce/lodgepole pine/subalpine fir in north	Ranching and First Nations reserves but no large communities

Fraser Basin		Flat or gently rolling lowlands	Sub-boreal climate-humid summers and harsh winters	Sub-boreal spruce forests and lodgepole pine	Largest city is Prince George; cereal crop farming in southern lowlying areas and ranching
Fraser Plateau		Lowland trench bisected by the Fraser River; small lakes and wetlands but no large lakes	Subject to cold Arctic air; increased precipitation as air moves east over Columbia Mountains and in summer due to upland wetlands	Douglas-fir on dry south-facing slopes and trembling aspen, lodgepole pine, white spruce to subalpine fir with increasing elevation	Quesnel is the largest and only city but many communities; farming ranching and forestry (with extensive logging)
Fraser Plateau		Rounded upland with a large lowland area containing many lakes	Sub-continental climate subject to blasts of Arctic winter air	Mainly lodgepole pine and white spruce in higher elevations	Anahim Lake is largest community

The survey does not follow the design methodology of the traditional WBPHS, however the survey techniques are consistent with the methods outlined in Smith (1995) and the Standard Operating Procedures (US Fish and Wildlife Service (USFWS) and Canadian Wildlife Service (CWS) 1987). Prior to 2010, the survey technologies employed consisted of paper maps, field notes and GPS units with navigation determined by piloting along bearings to GPS waypoints. In 2010, the mobile GIS software PC-Mapper with Airborne Inspection (version 4.0, Corvallis Microtechnology Inc, 2015) was adopted for both survey navigation and data collection. The software is run on Panasonic Toughbooks (CF-19 and CF-31) with the screen in view of both the pilot and observer. Real-time navigation is guided by the GIS with reference base data containing strip transect boundaries, freshwater polygons and stream segments, ecosection boundaries and fuel waypoints. Digital data collection via georeferenced voice recordings transcribed by the observer post-survey collection have replaced paper analogue methods.

The survey is designed to capture the primary breeding period beginning in early May but is weather and climate dependent and has taken place as early as late April (April 28, 2015) and as late as mid-May (May 13, 2011). Heavy snowpack and/or cold spring temperatures can delay accessibility to open water and wetlands. The study area extent is almost 11 million hectares and takes an average 23 days (~105 flying hours) to survey.

Table 2. Species included in the study and their nesting and feeding guilds based on Baldassarre (2014) and Cornell (2015). Species-specific models for only the top ten most common species were created however less common species were accounted for in the groups outlined in Table 2.

Species Code	Common Name	Scientific Name	Species Group	Foraging Guild	Nesting Guild
AMWI	American Wigeon*	<i>Mareca americana</i>	Dabblers	Dabbler - Plants	Ground
BAGO	Barrow's Goldeneye*	<i>Bucephala islandica</i>	Divers	Surface - Dive - Insects	Cavity
BUFF	Bufflehead*	<i>Bucephala albeola</i>	Divers	Aerial Dive - Insects	Floating

BWTE	Blue-winged Teal*	<i>Spatula discors</i>	Dabblers	Dabbler - Seeds	Ground
CAGO	Canada Goose*	<i>Branta canadensis</i>	Geese	Ground Forager - Seeds	Ground
CANV	Canvasback	<i>Aythya valisineria</i>	Divers	Surface - Dive - Plants	Floating
CITE	Cinnamon Teal	<i>Spatula cyanoptera</i>	Dabblers	Dabbler - Seeds	Ground
COGO	Common Goldeneye	<i>Bucephala clangula</i>	Divers	Surface - Dive - Insects	Cavity
COME	Common Merganser	<i>Mergus merganser</i>	Mergansers	Surface - Dive - Fish	Cavity
GADW	Gadwall	<i>Mareca strepera</i>	Dabblers	Dabbler - Plants	Ground
GWTE	Green-winged Teal*	<i>Anas crecca</i>	Dabblers	Dabbler - Seeds	Ground
HADU	Harlequin Duck	<i>Histrionicus histrionicus</i>	Divers	Surface - Dive - Insects	Ground
HOME	Hooded Merganser	<i>Lophodytes cucullatus</i>	Mergansers	Surface - Dive - Fish	Cavity
LTDU	Long-tailed Duck	<i>Clangula hyemalis</i>	Divers	Surface - Dive - Insects	Ground
MALL	Mallard*	<i>Anas platyrhynchos</i>	Dabblers	Dabbler - Seeds	Ground
NOPI	Northern Pintail	<i>Anas acuta</i>	Dabblers	Dabbler - Seeds	Ground
NSHO	Northern Shoveler*	<i>Spatula clypeata</i>	Dabblers	Dabbler - Plants	Ground
RBME	Red-breasted Merganser	<i>Mergus serrator</i>	Mergansers	Surface - Dive - Fish	Ground
REDH	Redhead	<i>Aythya americana</i>	Divers	Surface - Dive - Plants	Floating
RNDU	Ring-necked Duck*	<i>Aythya collaris</i>	Divers	Surface - Dive - Plants	Floating
RUDU	Ruddy Duck	<i>Oxyura jamaicensis</i>	Divers	Surface - Dive - Insects	Ground
SCAU**	Lesser Scaup*	<i>Aythya affinis</i>	Divers	Surface - Dive - Insects	Ground
SNGO	Snow Goose	<i>Anser caerulescens</i>	Geese	Ground Forager - Plants	Ground
TRUS	Trumpeter Swan	<i>Cygnus buccinator</i>	Swans	Dabbler - Plants	Ground
WFGO	White-fronted Goose	<i>Anser albifrons</i>	Geese	Dabbler - Plants	Ground
WODU	Wood Duck	<i>Aix sponsa</i>	Dabblers	Dabbler - Plants	Ground

* Species within the top ten most commonly observed for which a species-specific model was created.

** The waterfowl population survey does not distinguish scaup species however only lesser scaup are observed in the area.

Table 3. Group classifications for which group-specific species distribution models were generated (refer to Table 1 for specific species included within the groups).

Abbreviation	Explanation
sp_div	Index of species richness—number of unique species
sp_tot	Count of total indicated breeding population of all waterfowl
dabblers	Count of total indicated breeding population of dabbling ducks
divers	Count of total indicated breeding population of diving ducks
cavity	Count of total indicated breeding population of cavity nesting species

Population estimates

The surveys are conducted by helicopter along meandering paths at altitudes and speeds lower than fixed-wing aircraft (30-50 m and 40-80 km/h, respectively) therefore no complementary ground surveys are conducted and no visibility correction factor is applied as visibility is assumed to be complete. The total indicated breeding population estimates were derived from raw counts based on species, sex and grouping as outlined in Smith (1995). The temporal subset of the analysis was from 2007 to 2017 inclusive (data from 2006 was excluded due to data inconsistencies and 2018 was excluded due to the absence of interpreted climate data). Survey observation points record the location of the observer within the helicopter and not the bird on the ground. Efforts to correct locations guided by reference data and field observation notes were discontinued from 2012 onward due to resource constraints and inconsistent observational record-keeping. In order to account for this spatial uncertainty, observation location points were collated to the nearest 400m interval along the center line of the strip transect.

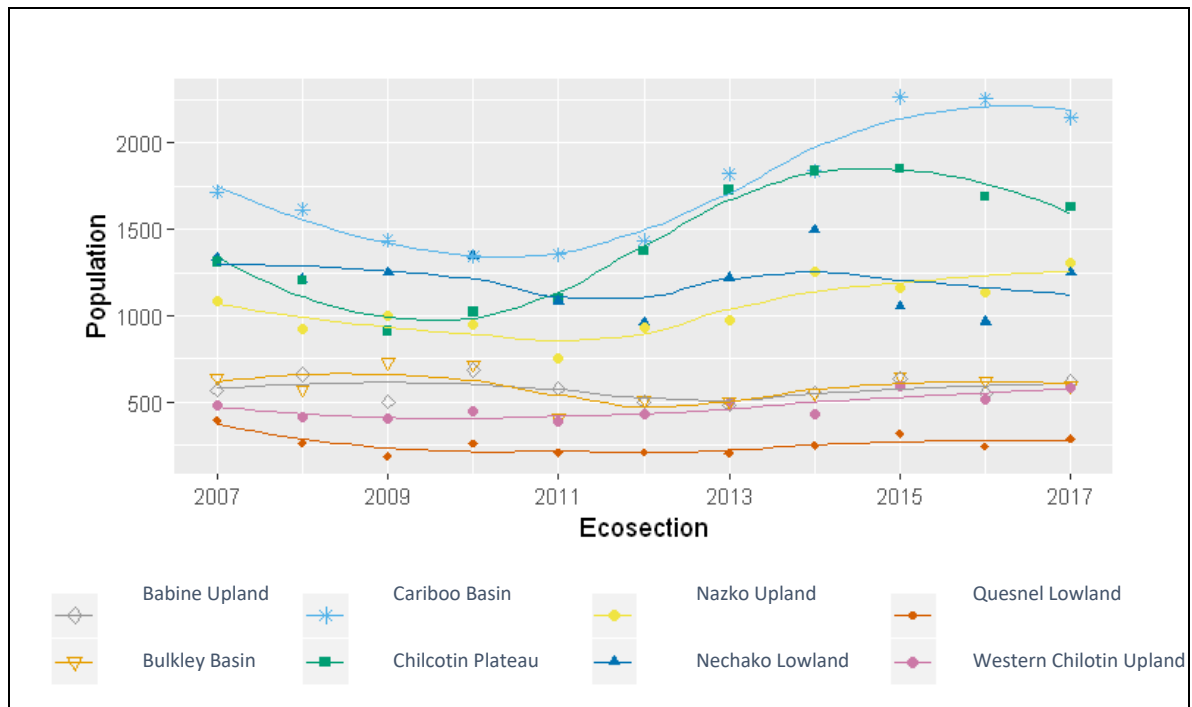


Figure 2. Total indicated breeding population of the top ten most common species observed within the transect (2007-2017).

The Cariboo Basin is by far the most populous ecosystem with the greatest total count (Figure 2) and population density (Figure 3) followed by the Chilcotin Plateau, Nechako Lowland and Nazko Upland. The remaining ecosystems—Bulkley Basin, Quesnel Lowland, Western Chilcotin Upland and Babine Upland—have similar population densities with the lattermost consistently the least populous. These ecosystems share similarly stable year-to-year trends while the densities in the two most populous ecosystems, Cariboo Basin and Chilcotin Plateau, display concordant fluctuations and appear to be increasing.

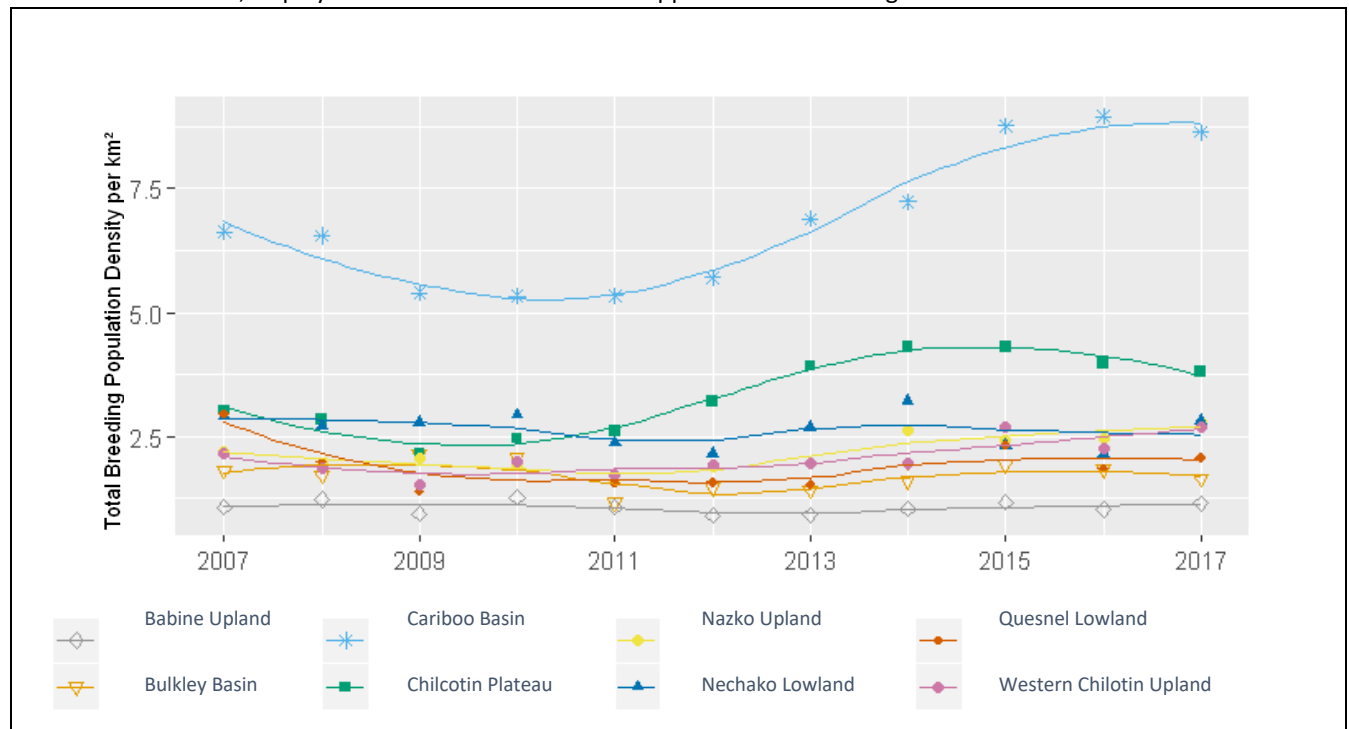


Figure 3. Total annual indicated breeding population density per square kilometre of the top ten most common species by ecosystem observed within the transect.

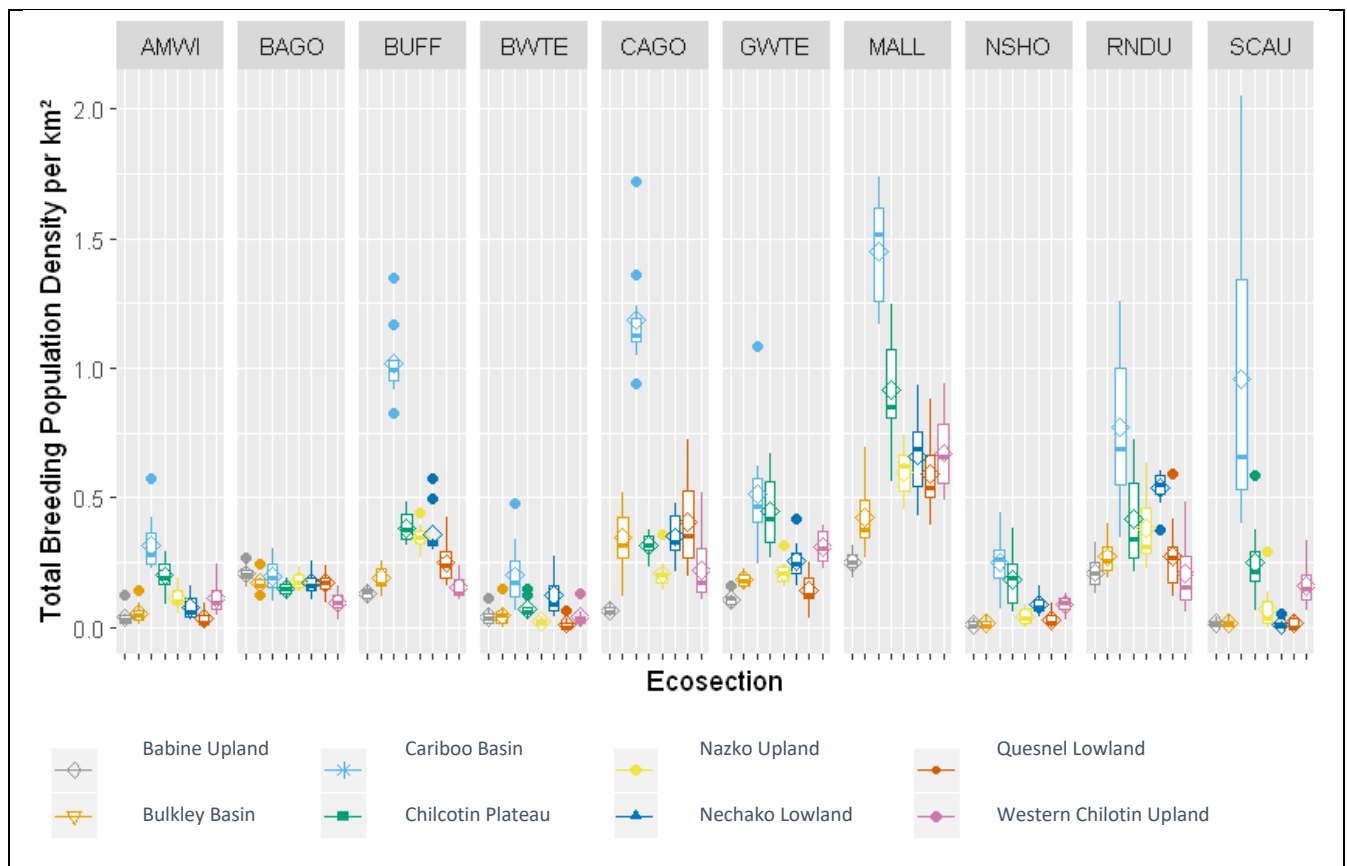


Figure 4. Boxplots of total annual indicated breeding population density per square kilometre of the top ten most common species by ecosection observed within the transect.

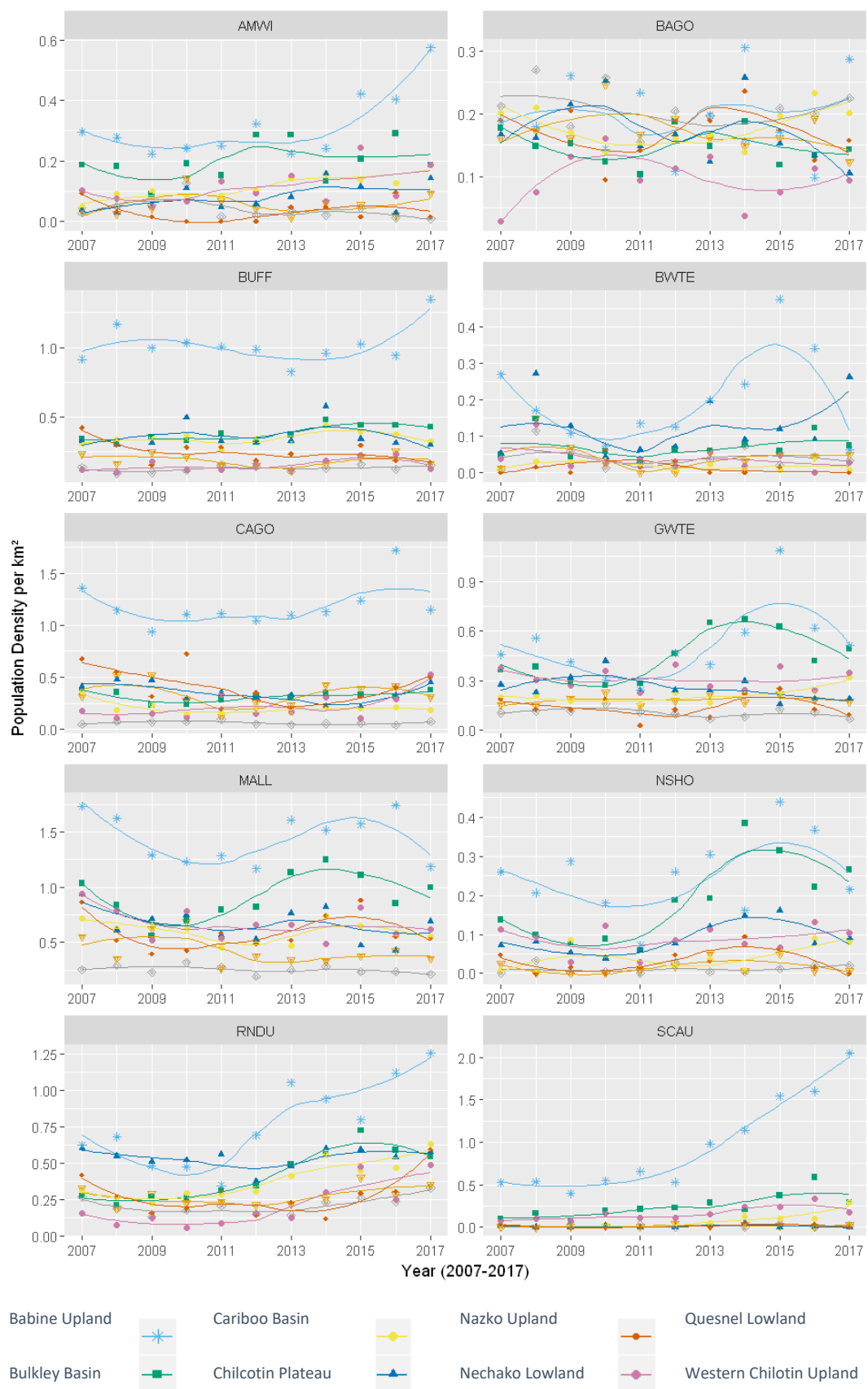


Figure 5. Total indicated breeding population of the top ten most common species observed within the transect (2007-2017).

Of the top ten most commonly observed species, the species demonstrating the greatest year-to-year variability in abundance include Lesser Scaup* (LESC), Ring-necked Duck (RNDU), Canada Goose (CAGO), and Mallard (MALL) (Figure 5). The distributions suggest it is LESC and RNDU species driving the increasing population trends in the Cariboo Basin and the Chilcotin Plateau. Mallard (MALL), Canada Goose (CAGO), Green-Winged Teal (GWTE), Blue-Winged Teal (BWTE), and Northern Shoveler (NOSH) reflect concordant annual fluctuations—decreasing from 2007 to 2010, increasing between 2010 and 2015, and decreasing again to 2017. American Wigeon (AMWI) to a lesser degree follows the main trend but appears to be slightly increasing in the Cariboo Basin. Barrow's Goldeneye (BAGO) distributions remained steady throughout their distributions in all ecosections during the study period.

Environmental data

Environmental predictor variables were pre-selected based on ecological theory of life history traits and physiological processes: hydrological features associated with wetlands, and land use practices and disturbances that can potentially influence waterfowl habitat (Table 2). Where possible direct measures of predictor variables rather than proxy data was selected. For example, measures of temperature and precipitation rather than the indirect measure of elevation were included in the analyses. A number of datasets were collated and evaluated but the final data inputs were constrained by availability, resolution, coverage, and currency, and complicated by interpretation and relevance (Appendix 1). Technical constraints—processing hardware and time—necessitated limiting the number of candidate predictors to improve both interpretation and efficiency however more accurate predictions may be generated with fewer restrictions.

Annual, seasonal, monthly and 30-year normal climatic variables were extracted from ClimateBC software (version 6.10, Wang, Hamann, Spittlehouse, & Carroll, 2016) based on the coordinates and elevation at 400m interval points along the transect center line. Growing degree days and average April temperature were included to capture primary productivity. To represent and characterize hydrological regimes which are driven mainly by snowpack accumulation in winter within the study area (Demarchi 2011; Islam et al. 2017; R. Pike et al. 2010) precipitation as snow and the climatic moisture deficit (precipitation minus potential evapotranspiration) were selected. The Biogeoclimatic Zones of British Columbia (BEC) is a standardized provincial dataset that classifies ecosystems within nested classes of regional, site and chronological levels of apex vegetation (Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRO), 2018) and was included to represent the combined influence of soil chemistry, vegetation, topography and climate. Additionally, the BEC Zone classifications provide an alternative regional classification system to the Ecoregions of BC ecosections for supplemental model development. Moreover, predicted changes to BEC Zone boundaries due to predicted climate change scenarios can be extracted from ClimateBC for future climate impact studies.

Land cover variables to characterize habitat were derived from 2010 Landsat imagery published by the North American Land Change Monitoring System (CCRS/CCMEO/NRCAN 2017). Cover classes were aggregated and reclassified to account for imbalanced classes (Appendix #). Topographic data included slope and aspect derived from 1:20,000 DEM (FLNRO, 2014).

Hydrological variables were derived from the provincial reference dataset for standardized hydrological features, and included polygons of lakes, rivers, man-made waterbodies and wetlands as well as stream lines (FLNRO, 2011). Lakes were classified by size class and streams were aggregated by stream order values (Appendix 2). To account for shoreline complexity and avoid correlation a lake perimeter to area index was derived.

The line network of unpaved roads was included to represent anthropogenic disturbance of resource extraction activities (Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2013).

Land management practices were represented by the Agricultural Land Reserve (Agricultural Land Commission, 2018)—provincial designation designed to identify and conserve agricultural productivity, and by the Protected Areas Database of lands under federal, provincial and municipal protection and land conservancy trusts (CWS, 2018).

Table 4. Environmental predictor variables selected for model inputs.

Predictor - abbreviation	Predictor - description	Resolution	Time Period	Source	Calculation
fwa_1	Freshwater Atlas - Lakes < 1 ha	1:20,000	Static (Variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_2	Freshwater Atlas - Lakes 1-2 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_3	Freshwater Atlas - Lakes 3-5 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_4	Freshwater Atlas - Lakes 5-10 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_5	Freshwater Atlas - Lakes 10-20 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_6	Freshwater Atlas - Lakes 20-50 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_7	Freshwater Atlas - Lakes 50-100 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_8	Freshwater Atlas - Lakes > 100 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_10ha_plus	Freshwater Atlas - Lakes > 10 ha	1:20,000	Static (variable)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
shorecx_10plus	Freshwater Atlas - Shoreline index of lakes < 10 ha	1:20,000	Static (variable)	Data BC	Ratio of total perimeter to area of lakes, multiplied by 100,000
shorecx_10plus	Freshwater Atlas - Shoreline index of lakes > 10 ha	1:20,000	Static (variable)	Data BC	Ratio of total perimeter to area of lakes, multiplied by 100,000
str_s	Freshwater Atlas - Stream order 1-3	1:20,000	Static (variable)	Data BC	Total length of streams of stream orders 1 to 3
str_m	Freshwater Atlas - Stream orders 4-6	1:20,000	Static (variable)	Data BC	Total length of streams of stream orders 4 to 6
fwa_w	Freshwater Atlas - Wetlands	1:20,000	Static (variable)	Data BC	Total area of wetlands within 1.2 km circular radius of centroid point along 400m interval of transect
fwa_r	Freshwater Atlas - River	1:20,000	Static (variable)	Data BC	Total area of rivers within 1.2 km circular radius of centroid point along 400m interval of transect
aspect	Compass direction	1:20,000	Static (2011)	Data BC	Average aspect within 400 x 400 m areal interval of strip transect
slope	Topographic slope	1:20,000	Static (2011)	Data BC	Average slope within 400 x 400 m areal interval of strip transect
alr	Agricultural Land Reserve	1:20,000	Static (2014)	Data BC	Total area within 1.2 km circular radius of centroid point along 400m interval of transect

pa	Protected Areas	1:20,000	Static (2018)	CWS Conservation Areas DB	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
dra_u	Digital Road Atlas, Unpaved Roads	1:20,000	Static (2014)	Data BC	Total density within 1.2 km circular radius of centroid point along 400m interval of transect
cec_urban	Land cover - urban	30 m	Static (2010)	Commission for Environmental Cooperation	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
cec_shrubland	Land cover - shrubland	30 m	Static (2010)	Commission for Environmental Cooperation	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
cec_mixed_forest	Land cover - mixed forest	30 m	Static (2010)	Commission for Environmental Cooperation	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
cec_broadleaf	Land cover - broadleaf (deciduous)	30 m	Static (2010)	Commission for Environmental Cooperation	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
cec_needleleaf	Land cover - needleleaf (coniferous)	30 m	Static (2010)	Commission for Environmental Cooperation	Total area within 1.2 km circular radius of centroid point along 400m interval of transect
bec_zn	Biogeoclimatic Zone	1:20,000	Static (2018)	Data BC	Majority area within 400 x 400 m areal interval of strip transect
norm_dd5	30 yr normal Growing Degree Days > 5°C	Scale-free 400 m	1980-2010	ClimateBC	Climatic measure at coordinate position and elevation along 400m interval of transect
norm_cmd	30 yr normal Cumulative Moisture Deficit	Scale-free 400 m	1980-2010	ClimateBC	Climatic measure at coordinate position and elevation along 400m interval of transect
pas_wt	Mean Precipitation as Snow in winter	Scale-free 400 m	Annual	ClimateBC	Climatic measure at coordinate position and elevation along 400m interval of transect averaged over survey period
tave04	Average April Temperature	Scale-free 400 m	Annual	ClimateBC	Climatic measure at coordinate position and elevation along 400m interval of transect averaged over survey period

Geoprocessing Methods

Spatial analyses were performed and mapping products were produced in ArcGIS Pro (versions 2.2 to 2.4, ESRI, 2019) and Python (version 3.6.5, Python Software Foundation, 2018). Predictor variables were extracted, projected, rasterized and generalized as required in BC Albers equal area coordinate system within a 1 km buffer of the study area to eliminate edge effects. The location uncertainty of point observations determined the finest scale of the analysis to be a resolution of 400m. Conceptually, survey strip transects were segmented into 400m intervals forming 400m x 400m (16 ha) grid cells—16, 540 in total. Topographic values of slope and aspect were generalized to the mean average within each grid cell. BEC zone classifications were generalized by majority area within the cell and remained categorical. All remaining predictors were represented by continuous values and generalized to a 1.2 km radius of the interval centroid to capture landscape level effects (Figure 6). Predicted response values were projected to a fishnet grid of 400m cell centroid points with attributed predictor values and rasterized for display. Many of the steps required in the pre-processing of spatial data were automated in a Python Script Toolbox (Appendix 3).

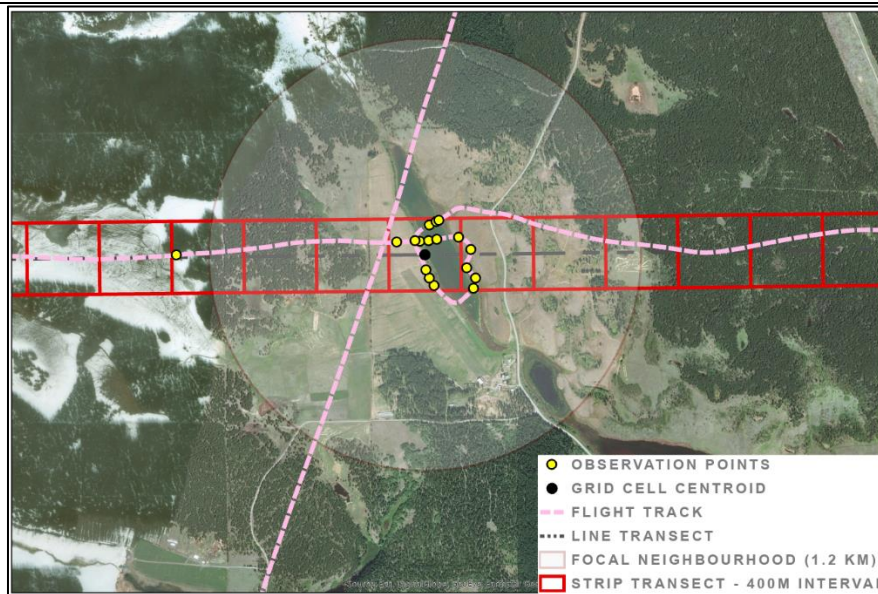


Figure 6. Representative schematic of the survey methods incorporating survey data from 2017. Observation points (yellow dots) are collected along the meandering flight tracklog (dashed pink line) within the transect. The strip transect was spliced into 400m wide intervals (red squares) with a circular focal neighbourhood of 1.2 km (pale circle) of the 400x400m grid cell centroid (black dot) used to characterize landscape level effects of environmental variables.

Statistical Methods

Random forest is an ensemble machine learning algorithm that creates a series of decision trees based on the principles of bagging (or bootstrapped aggregation—the drawing of a large number of data samples by random sampling with replacement) and random permutation. Each individual decision tree is based on a random subset of the data and at each node of the tree the data is partitioned into two branches based on a randomly selected but predetermined number of predictor variables evaluated by the algorithm to produce the best split. As individual trees are highly susceptible to noise in the data and sensitive to local optima, each tree is considered a ‘weak learner’ (Guisan, Wilfried, and Zimmermann 2017). But by combining and averaging the results of several regression trees, a ‘strong learner’ is created in the final ensemble prediction.

A random forest-based approach was selected for its predictive accuracy, resistance to overfitting, ability to account for imbalanced classes, ability to handle both continuous and categorical variables, and its independence from requirements of feature scaling and centering as well as assumptions of normality (Cutler, Cutler, and Stevens 2012; Guisan, Wilfried, and Zimmermann 2017). The observation frequency distribution of bird counts reflected a zero-inflated negative binomial distribution typical of ecological count data (Qian 2010) but not amenable to standard regression-based approaches. Preliminary explorations of zero-inflated generalized mixed models indicated it is a promising approach for future explanatory model building.

All statistical modeling and data manipulation was performed in R (version 3.5.3, R Core Team, 2018). The R ‘party’ package (version 1.3-3) was selected for its implementation of the random forest and bagging algorithm ‘cforest_unbiased’ function which utilizes conditional inference trees that account for correlation structures between variables in the permutation scheme of variable selection; additionally, the function implements a permutation importance measure, function ‘varimp’, that is immune to erroneous calculations due to correlated responses and is not biased towards continuous data or categorical variables with many classifications unlike the Gini accuracy of traditional random forest implementations (Strobl et al. 2008; Strobl, Hothorn, and Zeileis 2009). Slight differences in selected predictor variables between ecoregion models were due to zero or near-zero variance, correlated data structures and/or mismatched factor variables in ecoregion-based data inputs for model training and prediction.

Preliminary trial results of model inputs of annual survey data indicated low variable importance rankings for the dynamic climate variables. As all other environmental data was static the model input values were based on mean averaged counts and climate measures. Due to high zero-inflation (average of 93.6% frequency of zeroes for the top ten most common species) the data was not subset into training, validation, and test sets to evaluate model performance, instead the internal out-of-bag (OOB) error measures were determined. As each tree is based on a random subset of the training data, a collection of datasets which do not contain a particular record can be ensembled for each record. This collection forms the out-of-bag examples which are used as an unbiased test set to assess prediction accuracy by averaging the error rate. The predetermined number of candidate variables for each node split ('mtry' parameter of 'cforest') was left at the default value of 5 which resulted in better OOB estimates than 8 which was tested using Briemann's rule of thumb to divide the number of candidate variables by three for regression trees (Guisan, Wilfried, and Zimmermann 2017). The stability of 'varimp' ranks helped to inform the number of trees generated for each model which was set to 5,000.

Separate models for each species or species group were developed for each ecosection. Preliminary trials of generalized models on the entire study area indicated significant ecosection differences in predictor variables. Additionally, the computational intensity of the algorithm required for the entire study area was greater than available resources.

The conditional inference trees utilized by 'party' package are insensitive to highly correlated data structures but in order to reduce processing time, data preparation included addressing correlation and multicollinearity by step-wise elimination of correlated variables with threshold measures of $r = 0.8$ followed by elimination of variance inflation factors of 5 and greater corresponding to general thresholds recommended by Guisan et al (2017). The 'varimp' function to derive variable importance can be parameterized to produce unbiased importance measures of highly correlated data however preliminary trial results in Cariboo Basin reflected exaggerated processing times that restricted the application in this study. Neither correlation nor multicollinearity in predictor variables reduces predictive accuracy of random forests however the candidate predictors removed in the preprocessing step for the generation of 'varimp' values were not re-incorporated in the final prediction models. It is recommended these be included in future modeling exercises. The predictive models were re-run setting different seed values in order to confirm the stability of importance measures.

Random forest methods are widely recognized as fast and able to handle large amounts of data and model variables but the unbiased algorithm of the 'cforest' implementation is more computationally intensive than standard approaches. For example model training took approximately 10 minutes to process ~3,000 records and 27 variable inputs for mallards in Babine Upland, while model forecasting to the ecosection, an area ~40 times greater, took over 18 hours on a 64-bit OS workstation with 48.0 GB RAM and an Intel Xeon(R) CPU 3.60GHz. The R package 'caret' is designed specifically for data preprocessing and model generation and contains a number of machine learning methods including a more traditional random forest implementation and future studies are recommended these be explored.

The R scripts developed for statistical analyses as well as links to a Github repository of latest project updates and an interactive Jupyter Notebook documenting major processing steps are provided in Appendix 4.

RESULTS AND DISCUSSION

Variable Importance

Predictive modelling algorithms like random forest forsake the theoretical hypotheses of explanatory causal models for accurate forecasting (Shmueli 2011). The variable importance measures derived from recursive partitioning methods are unlike regression coefficients in that they do not provide a linear measure of the relationship between the predictor and response variables, rather the reported measure reflects the drop in prediction accuracy of the model by random permutation of the variable (Guisan, Wilfried, and Zimmermann 2017; Strobl et al. 2008). The most unambiguous application of these values is in variable selection for model

building. In summary, variable importance values are not by themselves interpretive however they may reveal causal mechanisms to inform the development of explanatory models (Shmueli, 2011). Predictors were ranked by their variable important measures and summaries are provided in Table # and Table #, respectively (see Appendix # for variable importance plots of each unique species within each ecosection). Note that the study is informed by a management framework and explores a place-based approach focusing on regional ecosections rather than the species perspective (e.g. Variable importance plots are grouped by ecosection not species).

Model Performance

Model performance was assessed with the out-of-bag (OOB) estimate. The coefficient of determination (R^2) and mean absolute error (MAE) are reported in Table #. R^2 represents the measure of variance in response values that is explained by the model and corresponds to the correlation between the observed and expected values. The MAE provides a measure of the difference between the observed and expected values and is less sensitive to outliers than the root mean square error (RMSE). In general terms, the lower the MAE and higher the R^2 the better the performance.

Table 2. Model performance of each species-ecosection model estimated by the coefficient of determination (R^2) and mean absolute error (MAE) derived from out-of-bag (OOB) estimates.

	Babine Upland		Bulkley Basin		Cariboo Basin		Chilcotin Plateau		Nazko Upland		Nechako Lowland		Quesnel Lowland		Western Chilcotin Lowland	
Species	R^2	MAE	R^2	MAE	R^2	MAE	R^2	MAE	R^2	MAE	R^2	MAE	R^2	MAE	R^2	MAE
AMWI	0.10	0.01	0.07	0.02	0.09	0.08	0.18	0.05	0.21	0.03	0.07	0.02	0.02	0.01	0.26	0.02
BAGO	0.26	0.05	0.20	0.04	0.17	0.05	0.11	0.04	0.27	0.04	0.13	0.03	0.09	0.05	0.13	0.03
BUFF	0.18	0.03	0.24	0.04	0.30	0.20	0.23	0.09	0.24	0.08	0.16	0.09	0.10	0.06	0.23	0.04
BWTE	0.04	0.01	0.05	0.01	0.09	0.05	0.14	0.02	0.13	0.01	0.13	0.03	0.02	0.00	0.14	0.01
CAGO	0.08	0.02	0.02	0.00	0.15	0.26	0.18	0.07	0.13	0.05	0.18	0.09	0.05	0.11	0.05	0.06
GWTE	0.11	0.03	0.16	0.05	0.17	0.11	0.19	0.10	0.19	0.05	0.13	0.07	0.04	0.04	0.21	0.07
MALL	0.15	0.06	0.15	0.10	0.24	0.26	0.26	0.17	0.24	0.12	0.20	0.14	0.10	0.14	0.28	0.13
NOSH	0.01	0.00	0.02	0.00	0.11	0.07	0.19	0.05	0.18	0.01	0.10	0.02	0.01	0.01	0.22	0.02
RNDU	0.18	0.05	0.20	0.06	0.20	0.16	0.23	0.09	0.20	0.09	0.21	0.12	0.06	0.07	0.12	0.05
SCAU	0.01	0.00	0.07	0.00	0.20	0.22	0.21	0.06	0.15	0.02	0.05	0.00	0.01	0.01	0.21	0.04
Dabblers	0.16	0.10	0.16	0.16	0.21	0.61	0.29	0.36	0.26	0.21	0.19	0.27	0.08	0.19	0.36	0.25
Divers	0.30	0.16	0.31	0.17	0.29	0.64	0.28	0.25	0.30	0.23	0.25	0.28	0.12	0.20	0.28	0.15
Cavity-Nesters	0.26	0.07	0.23	0.06	0.18	0.07	0.11	0.05	0.27	0.06	0.22	0.07	0.09	0.07	0.15	0.03
Species Diversity	0.29	0.09	0.35	0.12	0.37	0.34	0.37	0.20	0.39	0.14	0.28	0.17	0.18	0.15	0.43	0.11
All Species	0.27	0.24	0.22	0.36	0.27	1.37	0.33	0.63	0.33	0.43	0.24	0.55	0.10	0.43	0.36	0.40
Average	0.16	0.06	0.16	0.08	0.20	0.30	0.22	0.15	0.23	0.10	0.17	0.13	0.07	0.10	0.23	0.09

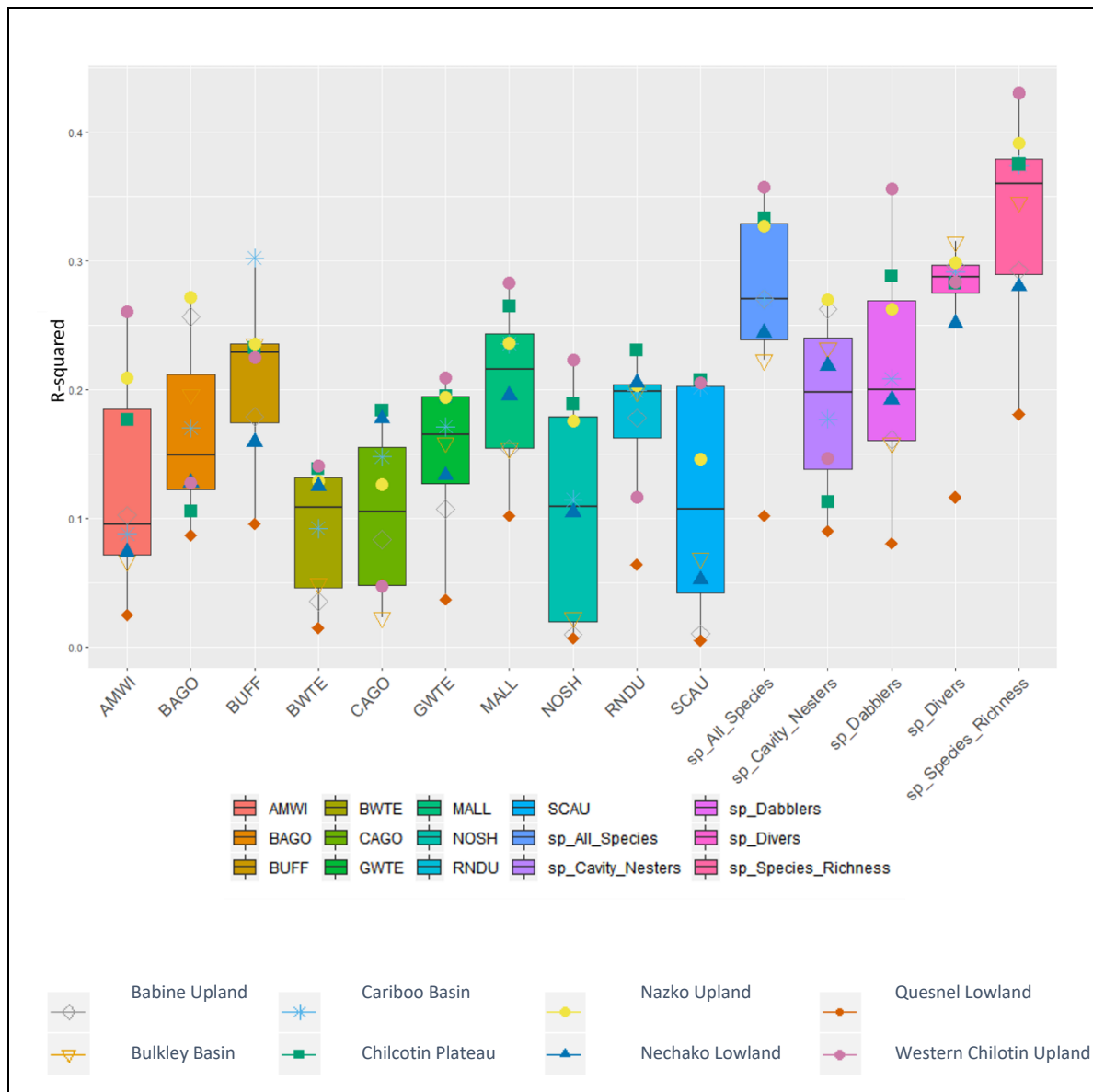


Figure 7. Boxplots of the coefficient of determination (R^2) of each species-ecosection specific model.

Overall, the models on average explained 18% of the variation in species distribution (Figure 7). The generalized groups representing all species ("sp_All_species") and species richness ("sp_Species_Richness") performed best followed by divers, dabblers and cavity nesters. The least variability in R^2 values was for divers. Diving ducks tend to prefer larger, deeper lakes that are likely to be better represented in the data than smaller wetlands. Models for Western Chilcotin Upland, Chilcotin Plateau and Nazko Upland performed best while Quesnel Lowland consistently scored poorly. Quesnel Lowland is the smallest ecosection in the study area and the predictors selected do not appear to have sufficient explanatory variability. While the models for Western Chilcotin Upland and Chilcotin Plateau performed best overall their performance for cavity-nesting species, Barrow's goldeneyes and Bufflehead, were relatively poor. Cavity-nesting duck species do not excavate their own nests and rely on abandoned (or natural) cavities within aspen or mixed aspen/coniferous forests (Baldassarre, 2014). Buffleheads as North America's smallest diving duck, prefer entrance holes excavated by northern flickers which are smaller than those made by pileated woodpeckers to which goldeneyes are restricted (Baldassarre, 2014). Model parameters for cavity-nesting species may be improved with species distributions of these nest cavity excavating land birds.

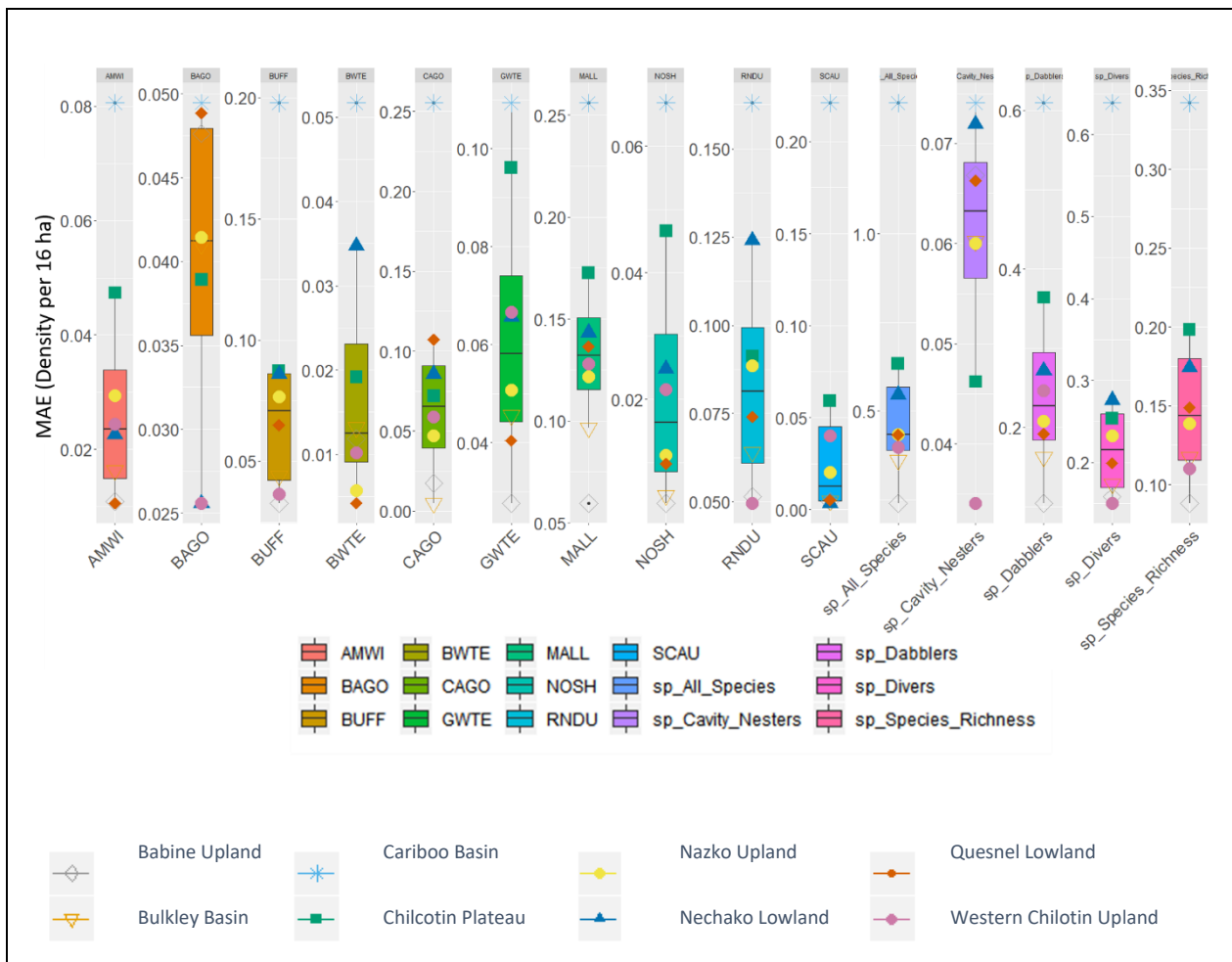


Figure 7. Boxplots of the mean absolute error (MAE) of each species-ecosection specific model (note the dynamic scale range values).

The overall average MAE was 13%, but this varied widely between species. The generalized group classifications excluding cavity-nesters had the largest values and greatest range in variability between ecosections. Cariboo Basin, consistently scored the highest error rate. The high error rates are likely due to the zero-inflation of observation frequencies—birds are patchily distributed throughout the landscape with zero observations in most cells punctuated by hotspots of high abundance.

Model Limitations

We recognize “[d]ucks like water” (Pimm 1994), but these waters have yet to be mapped in detail: Canada, unlike most industrialized nations, does not have a national wetland dataset (Canadian Wetland Inventory — Ducks Unlimited Canada, 2019). The delineation of highly productive wetlands, such as ephemeral wetlands due to increased nutrient mineralization by aerobic microbes (Schlesinger and Bernhardt 2013) and smaller wetlands due to increased light penetration at shallower depths and greater shoreline emergent vegetation, are difficult to capture with freely available, coarser-scale remote sensing imagery (e.g. Landsat imagery at 30m resolution). Techniques for finer-scale wetland feature extraction based on Landsat have been developed for open wetlands but have not yet been fully developed and tested on forested wetlands (Halabisky et al. 2018).

Relative to other provinces, BC has an abundance of fine-scale (1:20,000) base reference spatial data however the creation of much of these data has been driven by the forestry sector which is a significant component of the BC economy. Consequently, much of the mapping of environmental features has been focused on supporting forestry management practices and the delineation of wetlands (areas unsuited to logging) especially at higher elevations is poor (D. Filatow, personal communication April 28, 2018). Moreover, despite

mapping standards, BC TRIM data was produced on a mapsheet by mapsheet basis and variability exists between areas. There are ongoing efforts to develop methodologies for wetland mapping coincident with the May surveys utilizing Radarsat-2 technologies in a collaborative effort between the CWS and the Science and Technology branches of Environment and Climate Change Canada which are promising but results are still preliminary and the project is far from complete (K. Moore, personal communication, September 30, 2018). Additionally, the Canadian Wetland Inventory project spearheaded by Ducks Unlimited Canada aims to provide a comprehensive national wetland inventory but BC has yet to be mapped (Canadian Wetland Inventory — Ducks Unlimited Canada, 2019). Global wetland mapping projects include the European Space Agency's Climate Change Initiative which has a number of exciting projects and remote sensing products of varying temporal and spatial resolution and should be monitored for updates (European Space Agency, 2019). Model performance and predictive accuracy can be expected to improve with the incorporation of improved wetland cover products, but proactive management measures should not be delayed while waiting for these data.

Hydrological regimes that create and maintain wetland ecosystems are influenced by a host of factors such as the depth of snowpack, the rate of snowmelt, levels of groundwater, precipitation, glacial retreat, land management practices, and anthropogenic and natural disturbance (Adamus 2014; R. G. Pike et al. 2010). Such complexities are challenging to represent but future studies may be improved by incorporating snow basin, drainage and/or watershed data. Additionally, BC's forested ecosystems have been impacted by the mountain pine beetle outbreak from 1999 to 2015 followed by the extreme fire seasons of 2017 and 2018. The short and longer-term effects of these regional disturbances on forest hydrology are difficult to predict (R. Pike et al. 2010; R. G. Pike et al. 2010) but are worthy of monitoring and future investigation (Bunnell, Fred L, Wells, Ralph 2010; MacKenzie and Moran 2004; Snauffer, Hsieh, and Cannon 2016).

The population estimates reflect sampled observations over a limited period of time and therefore reflect only a snapshot of the species-habitat relationship assumed to be in pseudo-equilibrium (Guisan, Wilfried, and Zimmermann 2017). Moreover, the models did not account for density-dependence, breeding philopatry, site fidelity, territoriality, influence of breeding phenology, species nesting chronologies or lagged response to environmental shifts. A recent study on the breeding phenology of cavity-nesting birds identified observable impacts on nesting activities with critical temperature periods of local temperature as short as 4 days (Drake and Martin 2018). Daily temperature datasets from Natural Resources Canada at 1 km resolution (McKenney et al. 2011) were collated and extracted but not included in the generation of the models as these data were considered more useful as explanatory variables than predictive determinants. Preliminary trials indicated significant variable importance estimates for averaged weekly temperatures and future efforts are encouraged to explore the incorporation of these and other datasets as identified in Appendix 1.

Species Abundance and Distribution

<insert discussion of predicted distributions and abundance of mapped outputs>

Model Applications

This modeling study had two main, related objectives: first, develop the methods and techniques required to standardize the BC May Survey dataset for analysis and second, create SDMs of relative abundance and distribution of breeding waterfowl to support conservation planning and habitat management. The predicted distribution maps can be used to highlight hotspot areas of high abundance and diversity to evaluate and assess protection or mitigation measures, provide finer-scale population estimates for environmental impact assessments, and help guide adaptive management measures to prepare for climate change. Additionally, the results can inform future studies of ecological relationships, and serve as guidance further model development that addresses the models' limitations.

Changes in BC's hydrological regimes due to increased warming and drying trends are predicted to lead to wetland losses at low to mid-elevations. As higher elevations are less sensitive to temperature changes that

can affect snowpack accumulation, BC's higher elevation wetlands may buffer the impacts for waterfowl and other wetland species (Bunnell, Fred L, Wells, Ralph 2010; R. Pike et al. 2010; R. G. Pike et al. 2010). The breeding habitat within BC's Central Interior is by no means as productive as the Prairie Pothole Region (PPR), However the conservation value of our wetlands, especially at elevations greater than 1200 metres (Bunnell, Fred L, Wells, Ralph 2010), may rise with the present and predicted climate-related shifts in wetland productivity of the PPR (N. D. Niemuth, Fleming, and Reynolds 2014; N. Niemuth, Wangler, and Reynolds 2010; Zhao et al. 2016). Future climate impact studies should take into account the wide range in variability of projections between the global models available and employ ensemble methods that encompass this range of variability to account for uncertainty in impact assessments and adaptive management strategies (R. G. Pike et al. 2010; Spittlehouse and Wang 2016).

CONCLUSION

"The single story creates stereotypes, and the problem with stereotypes is not that they are untrue, but that they are incomplete. They make one story become the only story" (Adichie 2009).

With the quote above, the Nigerian author Chimamanda Ngozi Adichie was referring to how a limited perspective can lead to flawed conclusions and racial stereotyping; how any single observation however true is not representative. Models, like stories, must be developed and communicated in meaningful ways. A species distribution model is a single story: a simplified human construct of a complex phenomenon shared to represent and reveal processes and patterns through a single lens. Future studies are encouraged to validate and build upon these results by integrating expert opinion, employing best available methods and data, addressing uncertainty, and continuing to support systematic monitoring and ecological research. These models were created to assist the CWS, governmental and other partners in conservation to assess our efforts, guide action, and inspire us to ask more questions to better our understanding of fundamental biological and ecological theory (Sinclair et al, 2010) to inform planning and decision-making. This study is a single story but it is a story worth telling in support of waterfowl conservation in British Columbia.

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APPENDIX 1 – Dataset Sources

Environmental datasets collated and evaluated for the modeling study. The table describes each dataset and provides a brief description of variables and their assessment.

APPENDIX 2—Reclassification

<reclass tables for land cover and FWA>

APPENDIX 3 – Python Script Toolbox

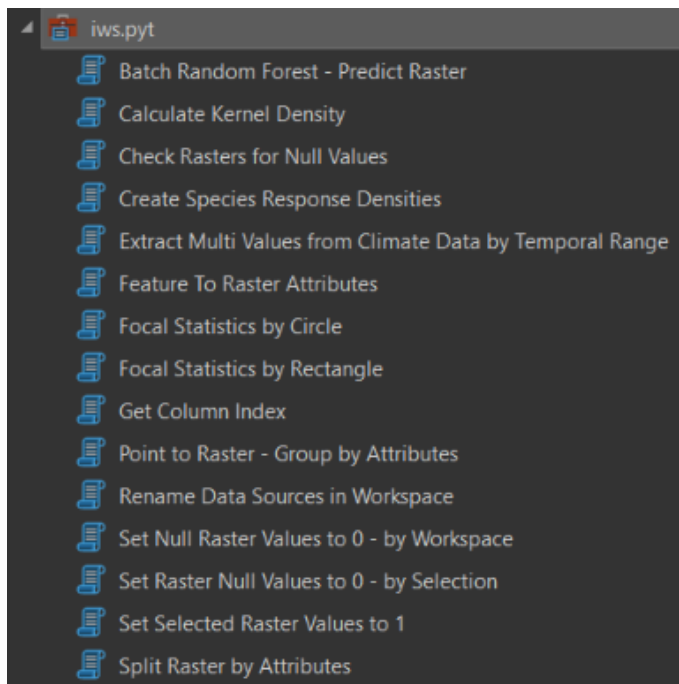


Figure 3. Python Script Toolbox as displayed in ArcGis Pro.

The code for the Python script toolbox is provided below.

```
# -*- coding: utf-8 -*-

import arcpy, os
from arcpy import env
arcpy.env.overwriteOutput = True
from arcpy.sa import *
arcpy.CheckOutExtension("Spatial")
arcpy.env.qualifiedFieldNames = False
# scratch_ws = arcpy.CreateScratchName(workspace=arcpy.env.scratchGDB)
arcpy.env.snapRaster = r"C:\Users\hashimotoy\Desktop\ws\base_alb.gdb\dem"
arcpy.env.mask = r"C:\Users\hashimotoy\Desktop\ws\base_alb.gdb\survey_mask"
scratch_ws = r"C:\Users\hashimotoy\Desktop\ws_prep\scratch.gdb"

def checkFieldExists(in_tbl, field_nm, field_type):
    fields = arcpy.ListFields(in_tbl)
    x = False
    for field in fields:
        if field.name == field_nm:
            x = True
    if x == False:
        arcpy.AddField_management(in_tbl, field_nm, field_type)

def getBaseName(in_fc):
    desc = arcpy.Describe(in_fc)
    basename = desc.basename
    return basename

def unique_values(table, field):
    with arcpy.da.SearchCursor(table, [field]) as cursor:
        return sorted({row[0] for row in cursor})

class Toolbox(object):
    def __init__(self):
        """Define the toolbox (the name of the toolbox is the name of the
        .pyt file)."""
        self.label = "IWS Data Tools"
        self.alias = ""

        # List of tool classes associated with this toolbox
        self.tools = [featureToRasterAttributes,
                      setRasterNullValuesTo0,
                      setRasterNullValuesTo0Workspace,
                      renameDataInWorkspace,
                      kernelDensityCalculations,
                      splitRasterByAttributes,
                      focalStatsByCircle,
                      focalStatsByRectangle,
                      setRasterValuesTo1,
                      pointToRasterGroupByAttributes,
                      getColumnIndex,
                      extractClimateValuesForRange,
                      checkRasterForNullValues,
                      batchRandomForest,
                      createPredictedDensitySurfaces]
```

```

class Tool(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Tool"
        self.description = ""
        self.canRunInBackground = False

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Features",
            name="in_features",
            datatype="GPFeatureLayer",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Sinuosity Field",
            name="sinuosity_field",
            datatype="Field",
            parameterType="Optional",
            direction="Input")

        param1.value = "sinuosity"

        # Third parameter
        param2 = arcpy.Parameter(
            displayName="Output Features",
            name="out_features",
            datatype="GPFeatureLayer",
            parameterType="Derived",
            direction="Output")

        param2.parameterDependencies = [param0.name]
        param2.schema.clone = True

        parameters = [param0, param1, param2]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        """The source code of the tool."""
        return

class batchRandomForest(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Batch Random Forest - Predict Raster"
        self.description = "Tool uses explanatory rasters to predict to raster. Specify the output workspace" \
            "for the four resulting outputs: prediction raster, variable importance table, trained " \
            "features and validation r2. The outputs will be named according to the name of the input feature class" \
            "and the species selected for prediction."
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""

        param0 = arcpy.Parameter(
            displayName="Input Training Features",
            name="in_fc",
            datatype="DEFeatureClass",
            parameterType="Required",
            direction="Input")

        param1 = arcpy.Parameter(
            displayName="Variables to Predict",
            name="sp_field",
            datatype="Field",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        param1.parameterDependencies = [param0.name]

        param2 = arcpy.Parameter(
            displayName="Output Workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        param3 = arcpy.Parameter(
            displayName="Output Files Prefix",
            name="prefix",
            datatype="GPString",
            parameterType="Required",
            direction="Input")

        param4 = arcpy.Parameter(
            displayName="Number of Trees",

```

```

        name="n_tree",
        datatype="GPLong",
        parameterType="Required",
        direction="Input")

param5 = arcpy.Parameter(
    displayName="# of Random Variables - mtry",
    name="m_try",
    datatype="GPLong",
    parameterType="Required",
    direction="Input")

param6 = arcpy.Parameter(
    displayName="Compensate for Sparse Categories",
    name="sparse",
    datatype="GPBoolean",
    parameterType="Required",
    direction="Input")
param6.value = True

param7 = arcpy.Parameter(
    displayName="Percent Excluded for Validation",
    name="pct_train",
    datatype="GPLong",
    parameterType="Required",
    direction="Input")
param7.filter.type = "ValueList"
param7.filter.list = [10, 20, 30]

param8 = arcpy.Parameter(
    displayName="Number of Validation Runs",
    name="n_validation",
    datatype="GPLong",
    parameterType="Required",
    direction="Input")

# Fifth parameter
param9 = arcpy.Parameter(
    displayName="Select Explanatory Rasters",
    name="in_rasters",
    datatype="DERasterDataset",
    parameterType="Required",
    direction="Input",
    multiValue=True)

parameters = [param0, param1, param2, param3, param4, param5,
              param6, param7, param8, param9]

return parameters

def isLicensed(self):
    """Set whether tool is licensed to execute."""
    return True

def updateParameters(self, parameters):
    """Modify the values and properties of parameters before internal
    validation is performed. This method is called whenever a parameter
    has been changed."""
    return

def updateMessages(self, parameters):
    return

def execute(self, parameters, messages):
    ws_fishnet = r"C:\Users\hashimotoy\Desktop\ws_prep\fishnet.gdb"

    in_fc = parameters[0].valueAsText
    lst_sp = parameters[1].valueAsText
    out_ws = parameters[2].valueAsText
    prefix = parameters[3].valueAsText
    n_tree = parameters[4].valueAsText
    m_try = parameters[5].valueAsText
    sparse = parameters[6].valueAsText
    pct_train = parameters[7].valueAsText
    n_validation = parameters[8].valueAsText
    in_rasters = parameters[9].valueAsText

    prediction_type = "PREDICT_RASTER"
    nm = getBaseName(in_fc)
    in_features = in_fc
    arcpy.env.mask = r"C:\Users\hashimotoy\Desktop\ws_prep\raster_attributes.gdb\\" + "eco_" + nm

    lst_rasters = []
    lst_matching = [] # Explanatory raster matching
    for raster in in_rasters.split(';'):
        lst_rasters.append(raster)
        sub_lst = [raster, raster]
        lst_matching.append(sub_lst)

    treat_variable_as_categorical = None
    explanatory_variables = None
    distance_features = None
    explanatory_rasters = lst_rasters
    features_to_predict = None
    explanatory_variable_matching = None
    explanatory_distance_matching = None
    explanatory_rasters_matching = lst_matching
    use_raster_values = True
    number_of_trees = n_tree
    minimum_leaf_size = None
    maximum_level = None
    sample_size = None
    random_sample = m_try

```



```

percentage_for_training = pct_train
output_classification_table = None
compensate_sparse_categories = True
number_validation_runs = n_validation

for sp in lst_sp.split(';'):
    arcpy.AddMessage("Running forest for " + sp)
    variable_predict = sp
    file_prefix = prefix + "_" + nm + "_" + sp + "_"
    output_features = os.path.join(out_ws, file_prefix + "_output_features")
    output_raster = os.path.join(out_ws, file_prefix + "_rtr")
    output_trained_features = os.path.join(out_ws, file_prefix + "_trained")
    output_importance_table = os.path.join(out_ws, file_prefix + "_varimp")
    output_validation_table = os.path.join(out_ws, file_prefix + "_validation")

    arcpy.stats.Forest(prediction_type,
                        in_features,
                        variable_predict,
                        treat_variable_as_categorical,
                        explanatory_variables,
                        distance_features,
                        explanatory_rasters,
                        features_to_predict,
                        output_features, output_raster,
                        explanatory_variable_matching,
                        explanatory_distance_matching,
                        explanatory_rasters_matching,
                        output_trained_features,
                        output_importance_table,
                        use_raster_values,
                        number_of_trees,
                        minimum_leaf_size,
                        maximum_level,
                        sample_size,
                        random_sample,
                        percentage_for_training,
                        output_classification_table,
                        output_validation_table,
                        compensate_sparse_categories,
                        number_validation_runs)

    return

class checkRasterForNullValues(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Check Rasters for Null Values"
        self.description = "Interrogates selected rasters for NULL values"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Select Rasters",
            name="in_rasters",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Output Workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        lst_rasters = parameters[0].valueAsText
        out_ws = parameters[1].valueAsText

        for raster in lst_rasters.split(';'):
            nm = getBaseName(raster)
            arcpy.AddMessage("Reading {}".format(raster))
            outras = IsNull(raster)
            outras.save("{}{}/{}".format(out_ws, nm))
            arcpy.AddMessage("Saving {}".format(raster))

        return

class setRasterNullValuesTo0Workspace(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Set Null Raster Values to 0 - by Workspace"

```

```

        self.description = "Interrogates rasters in a workspace and checks for null values. If present, NA values are set" \
            "to 0"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Raster Workspace",
            name="in_rasters",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Output Workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        in_ws = parameters[0].valueAsText
        out_ws = parameters[1].valueAsText
        arcpy.env.workspace = in_ws
        rasters = arcpy.ListRasters()

        for raster in rasters:
            nm = getBaseName(raster)
            arcpy.AddMessage("Reading {0}".format(raster))
            out_ras = Con(IsNull(raster), 0, raster)
            arcpy.AddMessage("Setting null for {0}".format(raster))
            out_ras.save("{0}/{1}".format(out_ws, nm))
            arcpy.AddMessage("Saving {0}".format(raster))
        return

class setRasterNullValuesTo0(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Set Raster Null Values to 0 - by Selection"
        self.description = "Sets all null raster values to 0 in new raster"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Rasters",
            name="in_rasters",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        param1 = arcpy.Parameter(
            displayName="Target workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        lst_rasters = parameters[0].valueAsText
        out_ws = parameters[1].valueAsText

        for raster in lst_rasters.split(';'):
            nm = getBaseName(raster)
            arcpy.AddMessage("Reading {0}".format(raster))

```

```

        out_raster = Con(IsNull(raster), 0, raster)
        arcpy.AddMessage("Setting null for {0}".format(raster))
        out_raster.save("{0}/{1}".format(out_ws, nm))
        arcpy.AddMessage("Saving {0}".format(raster))

    return

class featureToRasterAttributes(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Feature To Raster Attributes"
        self.description = ""
        self.canRunInBackground = True

    def getParameterInfo(self):
        # Define parameter definitions

        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Features",
            name="in_features",
            datatype="DEFeatureClass",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Attribute Field",
            name="field",
            datatype="Field",
            parameterType="Required",
            direction="Input")

        param1.filter.list = ['TEXT', 'LONG']
        param1.parameterDependencies = [param0.name]

        param2 = arcpy.Parameter(
            displayName="Output workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")
        param2.defaultEnvironmentName = "workspace"

        parameters = [param0, param1, param2]
        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        import os

        in_fc = parameters[0].valueAsText
        in_field = parameters[1].valueAsText
        out_ws = r"C:\Users\hashimoto\Desktop\ws_prep\raster.gdb"
        attributes_ws = r"C:\Users\hashimoto\Desktop\ws_prep\raster_attributes.gdb"
        out_raster = os.path.join(out_ws, os.path.basename(in_fc))
        # Converting to Raster
        arcpy.AddMessage("Converting to raster: " + out_raster + "...")
        raster = arcpy.FeatureToRaster_conversion(in_fc, in_field, os.path.join(out_ws, out_raster))
        # raster = r"C:\Users\hashimoto\Desktop\ws_prep\raster.gdb\{0}"
        values = unique_values(raster, in_field)
        # Extract By Attributes each unique value
        for value in values:
            if value == "":
                pass
            else:
                print("    Extracting " + value)
                where_clause = in_field + " = '" + value + "'"
                arcpy.AddMessage("    " + where_clause)
                extract = ExtractByAttributes(raster, where_clause)
                out_nm = (in_field + "_" + value).lower()
                extract.save(os.path.join(attributes_ws, out_nm))

        return

class renameDataInWorkspace(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Rename Data Sources in Workspace"
        self.description = "The tool will batch rename data within a workspace by one of three options: " \
            "replace, prefix or add suffix. if "
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Workspace",
            name="in_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")
        param0.filter.type = "Workspace"

        param1 = arcpy.Parameter(

```

```

        displayName="Select String Parsing Function",
        name="parse_function",
        datatype="GPString",
        parameterType="Required",
        direction="Input")

param1.filter.list = ["REPLACE SUBSTRING", "ADD PREFIX", "ADD SUFFIX"]

# Second parameter
param2 = arcpy.Parameter(
    displayName="Input string",
    name="in_string",
    datatype="GPString",
    parameterType="Required",
    direction="Input")

# Third parameter
param3 = arcpy.Parameter(
    displayName="Output string",
    name="out_string",
    datatype="GPString",
    parameterType="Optional",
    direction="Input")

parameters = [param0, param1, param2, param3]

return parameters

def isLicensed(self):
    """Set whether tool is licensed to execute."""
    return True

def updateParameters(self, parameters):
    parameters[3].enabled = False
    if parameters[1].value:
        if parameters[1].valueAsText == "REPLACE SUBSTRING":
            parameters[3].enabled = True
        else:
            parameters[3].enabled = False
    return

def updateMessages(self, parameters):
    """Modify the messages created by internal validation for each tool
    parameter. This method is called after internal validation."""
    return

def execute(self, parameters, messages):
    in_ws = parameters[0].valueAsText
    parse_function = parameters[1].valueAsText
    in_string = parameters[2].valueAsText
    out_string = parameters[3].valueAsText

    env.workspace = in_ws
    fcs = arcpy.ListFeatureClasses()
    rasters = arcpy.ListRasters()

    lst = fcs + rasters

    for data in lst:
        nm = getBaseName(data)
        if in_string in nm:
            pass
        elif parse_function == "ADD PREFIX":
            out_string = in_string + nm
        elif parse_function == "ADD SUFFIX":
            out_string = nm + out_string
        elif parse_function == "REPLACE SUBSTRING":
            if in_string not in nm:
                arcpy.AddMessage("\nThe substring " + in_string + " is not within data source names")
                pass
            else:
                arcpy.Rename_management(data, nm.replace(in_string, out_string))
                arcpy.AddMessage("\nRenamed " + nm + " to " + nm.replace(in_string, out_string))
                arcpy.Rename_management(data, out_string)
                arcpy.AddMessage("\nRenamed " + nm + " to " + out_string)
    return

class kernelDensityCalculations(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Calculate Kernel Density"
        self.description = "Tool to generalize vector point and line inputs (use the Focal Statistics tool for raster inputs)"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Feature Classes",
            name="lst_in_features",
            datatype="DEFeatureClass",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        param0.filter.list = ["Point", "Multipoint", "Polyline"]

        param1 = arcpy.Parameter(
            displayName="Search radius",
            name="search_radius",
            datatype="GPLong",
            parameterType="Required",
            direction="Input")
        param1.value = 564 # pi 'r' squared ~ 1sqkm

        param2 = arcpy.Parameter(

```

```

        displayName="Cell size",
        name="cell_size",
        datatype="GPIong",
        parameterType="Required",
        direction="Input")

    param2.value = 20 # Default

    param3 = arcpy.Parameter(
        displayName="Density unit value",
        name="area_unit_scale_factor",
        datatype="GPString",
        parameterType="Required",
        direction="Input")
    param3.filter.list = ["SQUARE_MAP_UNITS", "SQUARE_KILOMETERS", "HECTARES", "SQUARE_METERS"]

    param3.value = "SQUARE_METERS"

    param4 = arcpy.Parameter(
        displayName="Output workspace",
        name="out_ws",
        datatype="DEWorkspace",
        parameterType="Required",
        direction="Input")

    parameters = [param0, param1, param2, param3, param4]
    # parameters = [param0, param1, param2, param3]
    return parameters

def isLicensed(self):
    """Set whether tool is licensed to execute."""
    return True

def updateParameters(self, parameters):
    """Modify the values and properties of parameters before internal
    validation is performed. This method is called whenever a parameter
    has been changed."""
    return

def updateMessages(self, parameters):
    """Modify the messages created by internal validation for each tool
    parameter. This method is called after internal validation."""
    return

def execute(self, parameters, messages):
    1st_inputs = parameters[0].valueAsText
    search_radius = parameters[1].valueAsText
    cell_size = parameters[2].valueAsText
    area_unit_scale_factor = parameters[3].valueAsText
    out_ws = parameters[4].valueAsText

    for in_fc in 1st_inputs.split(';'):
        nm = getBaseName(in_fc)
        arcpy.AddMessage("\n\nProcessing " + nm)
        kd = KernelDensity(in_features=in_fc,
                           population_field="",
                           cell_size=cell_size,
                           search_radius=search_radius,
                           area_unit_scale_factor=area_unit_scale_factor,
                           out_cell_values="DENSITIES",
                           method="PLANAR")
        kd.save(os.path.join(out_ws, nm))

    return

class splitRasterByAttributes(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Split Raster by Attributes"
        self.description = "Output rasters are named according to the attribute field and value"
        self.canRunInBackground = False

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Raster",
            name="in_raster",
            datatype=["DERasterDataset", "GPRasterLayer"],
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Attribute Field",
            name="field",
            datatype="Field",
            parameterType="Required",
            direction="Input")

        param1.filter.list = ['TEXT', 'LONG']
        param1.parameterDependencies = [param0.name]

        param2 = arcpy.Parameter(
            displayName="Output workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        param2.defaultEnvironmentName = "workspace"

        parameters = [param0, param1, param2]
        return parameters

    def isLicensed(self):

```

```

        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        in_raster = parameters[0].valueAsText
        in_field = parameters[1].valueAsText
        out_ws = parameters[2].valueAsText

        values = unique_values(in_raster, in_field)
        # Extract By Attributes each unique value
        for value in values:
            if value == "":
                pass
            else:
                print("    Extracting " + value)
                where_clause = in_field + " = '" + value + "'"
                arcpy.AddMessage("    " + where_clause)
                extract = ExtractByAttributes(in_raster, where_clause)
                out_nm = (in_field + " " + value).lower()
                extract.save(os.path.join(out_ws, out_nm))

        return

class focalStatsByCircle(object):
    def __init__(self):
        self.label = "Focal Statistics by Circle"
        self.description = "Tool to generalize raster inputs (use the Kernel Density tool for vector points and lines)"
        self.canRunInBackground = True

    def getParameterInfo(self):

        param0 = arcpy.Parameter(
            displayName="Input Rasters",
            name="in_rasters",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        param1 = arcpy.Parameter(
            displayName="Neighbourhood in map units",
            name="neighbourhood",
            datatype="GPLong",
            parameterType="Required",
            direction="Input")
        param1.value = 1200 # Circular neighbourhood of 1.2km to account for center of 400m cell grid

        param2 = arcpy.Parameter(
            displayName="Statistics type",
            name="stats_type",
            datatype="GPString",
            parameterType="Required",
            direction="Input",
            multiValue=False)
        param2.filter.list = ["MEAN", "MAJORITY", "MAXIMUM", "MEDIAN",
                              "MINIMUM", "MINORITY", "RANGE", "STD",
                              "SUM", "VARIETY"]
        param2.value = "SUM"

        param3 = arcpy.Parameter(
            displayName="Output workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1, param2, param3]
        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):

        rasters = parameters[0].valueAsText
        neighbourhood = parameters[1].valueAsText
        stats_type = parameters[2].valueAsText
        out_ws = parameters[3].valueAsText

        for in_raster in rasters.split(';'):
            arcpy.AddMessage(in_raster)
            nm = getBaseName(in_raster)
            arcpy.AddMessage("\nProcessing focal statistics for " + nm)
            fs = FocalStatistics(in_raster, NbrCircle(neighbourhood, "MAP"),

```



```

        stats_type,"DATA")
        fs.save(os.path.join(out_ws, nm))

    return

class focalStatsByRectangle(object):
    def __init__(self):
        self.label = 'Focal Statistics by Rectangle'
        self.description = "Tool to generalize raster inputs (use the Kernel Density tool for vector points and lines)"
        self.canRunInBackground = True

    def getParameterInfo(self):

        param0 = arcpy.Parameter(
            displayName="Input Rasters",
            name="in_rasters",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input",
            multiValue=True)

        param1 = arcpy.Parameter(
            displayName="Neighbourhood in map units",
            name="neighbourhood",
            datatype="GPLong",
            parameterType="Required",
            direction="Input")
        param1.value = 1000 # Rectangular neighbourhood 1km x 1km

        param2 = arcpy.Parameter(
            displayName="Statistics type",
            name="stats_type",
            datatype="GPString",
            parameterType="Required",
            direction="Input",
            multiValue=True)
        param2.filter.list = ["MEAN", "MAJORITY", "MAXIMUM", "MEDIAN",
                              "MINIMUM", "MINORITY", "RANGE", "STD",
                              "SUM", "VARIETY"]
        param2.value = "SUM"

        param3 = arcpy.Parameter(
            displayName="Output workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1, param2, param3]
        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):

        rasters = parameters[0].valueAsText
        neighbourhood = parameters[1].valueAsText
        stats_type = parameters[2].valueAsText
        out_ws = parameters[3].valueAsText

        for in_raster in rasters.split(';'):
            arcpy.AddMessage(in_raster)
            nm = getBaseName(in_raster)
            arcpy.AddMessage("\nProcessing focal statistics for " + nm)
            fs = FocalStatistics(in_raster, NbrRectangle(neighbourhood, neighbourhood, "MAP"),
                                stats_type,"DATA") #
            fs.save(os.path.join(out_ws, nm))

        return

class setRasterValuesTo1(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Set Selected Raster Values to 1"
        self.description = "Sets all raster values to 1 within a specified workspace. For categorical (factor) variables."
        self.canRunInBackground = False

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Rasters",
            name="in_rasters",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input",
            multiValue=False)

        param1 = arcpy.Parameter(
            displayName="Output workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",

```

```

        direction="Input")

    parameters = [param0, param1]
    return parameters

def isLicensed(self):
    """Set whether tool is licensed to execute."""
    return True

def updateParameters(self, parameters):
    """Modify the values and properties of parameters before internal
    validation is performed. This method is called whenever a parameter
    has been changed."""
    return

def updateMessages(self, parameters):
    """Modify the messages created by internal validation for each tool
    parameter. This method is called after internal validation."""
    return

def execute(self, parameters, messages):
    lst_rasters = parameters[0].valueAsText
    out_ws = parameters[1].valueAsText

    for in_raster in lst_rasters.split(';'):
        nm = getBaseName(in_raster)
        arcpy.AddMessage("\n" + nm)
        out_con = Con(~IsNull(in_raster), 1, 0)
        out_con.save(os.path.join(out_ws, nm))

    return

class pointToRasterGroupByAttributes(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Point to Raster - Group by Attributes"
        self.description = "Create raster surfaces from one or more attributes in an input point feature class." \
            " Output rasters will be prefixed by user defined string" \
            "and appended with the field value. The optional 'group by' parameter will output individual rasters" \
            "based on attribute."
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Point Feature Class",
            name="in_pts",
            datatype="GPFeatureLayer",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Attribute fields",
            name="fields",
            datatype="Field",
            parameterType="Required",
            direction="Input",
            multiValue=True)
        param1.parameterDependencies = [param0.name]

        # Third parameter
        param2 = arcpy.Parameter(
            displayName="Output Workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")
        param2.defaultEnvironmentName = "workspace"
        # param2.filter.list = ["Local Database"]

        # Fourth parameter
        param3 = arcpy.Parameter(
            displayName="Prefix for out raster name",
            name="prefix",
            datatype="GPString",
            parameterType="Required",
            direction="Input")

        # Fifth parameter
        param4 = arcpy.Parameter(
            displayName="Cell Assignment",
            name="assignment_type",
            datatype="GPString",
            parameterType="Required",
            direction="Input")
        param4.filter.type = 'ValueList'
        param4.filter.list = ["MEAN", "MAXIMUM", "MOST_FREQUENT",
            "MINIMUM", "RANGE", "STANDARD_DEVIATION",
            "SUM", "COUNT"]
        param4.value = "MEAN"

        # Sixth parameter
        param5 = arcpy.Parameter(
            displayName="Cell Size",
            name="cell_size",
            datatype="GPIlong",
            parameterType="Input",
            direction="Input")
        param5.value = 400

        # Seventh Optional parameter
        param6 = arcpy.Parameter(
            displayName="Optional - Group By attribute",
            name="groupby",

```

```

        datatype="Field",
        parameterType="Optional",
        direction="Input",
        multiValue = False)

    param6.parameterDependencies = [param0.name]

    parameters = [param0, param1, param2, param3, param4, param5, param6]

    return parameters

def isLicensed(self):
    """Set whether tool is licensed to execute."""
    return True

def updateParameters(self, parameters):
    """Modify the values and properties of parameters before internal
    validation is performed. This method is called whenever a parameter
    has been changed."""
    return

def updateMessages(self, parameters):
    """Modify the messages created by internal validation for each tool
    parameter. This method is called after internal validation."""
    return

def execute(self, parameters, messages):
    # Set environment settings

    in_pts = parameters[0].valueAsText
    fields = parameters[1].valueAsText
    out_ws = parameters[2].valueAsText
    prefix = parameters[3].valueAsText
    assignment_type = parameters[4].valueAsText
    cell_size = parameters[5].valueAsText
    groupby = parameters[6].valueAsText

    env.workspace = out_ws

    arcpy.AddMessage("Running Point to Raster on: " + in_pts)

    for field in fields.split(';'):
        valField = field

        if groupby is None:
            arcpy.AddMessage("\n    Processing " + field)
            inFeatures = in_pts
            outRaster = (prefix + "_" + field).lower()
            arcpy.PointToRaster_conversion(inFeatures, valField, outRaster,
                                           assignment_type, "", cell_size)

        else:
            values = unique_values(in_pts, groupby)
            for value in values:
                arcpy.AddMessage("\n    Processing " + field + " for " + str(value))
                nm = getBaseName(in_pts)
                out_nm = nm + "_" + str(value)
                where_clause = groupby + " = '" + str(value) + "'"
                inFeatures = arcpy.Select_analysis(in_pts, out_nm, where_clause)
                outRaster = (prefix + "_" + field + "_" + str(value)).lower()
                arcpy.PointToRaster_conversion(inFeatures, valField, outRaster,
                                               assignment_type, "", cell_size)

    return

class getColumnIndex(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Get Column Index"
        self.description = "Using pandas module, read a csv file and get the index of selected columns"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input CSV",
            name="csv",
            datatype="DEFile",
            parameterType="Required",
            direction="Input")
        param0.filter.list = ['txt', 'csv']

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Fields",
            name="fields",
            datatype="Field",
            parameterType="Required",
            direction="Input",
            multiValue=True)
        param1.parameterDependencies = [param0.name]

        parameters = [param0, param1]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

```

```

def updateMessages(self, parameters):
    """Modify the messages created by internal validation for each tool
    parameter. This method is called after internal validation."""
    return

def execute(self, parameters, messages):
    import pandas as pd

    in_csv = parameters[0].valueAsText
    fields = parameters[1].valueAsText

    arcpy.AddMessage("\n\nGetting indices for selected columns...\n\n")
    csv = pd.read_csv(in_csv)

    for field in fields.split(';'):
        index = csv.columns.get_loc(field)
        arcpy.AddMessage("\n      " + field + " : " + str(index) + "\n")

    return

class extractClimateValuesForRange(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Extract Multi Values from Climate Data by Temporal Range"
        self.description = "The tool will extract the values of selected climate variables for" \
            "the input points for each year in the study range 2007-2017. Basename of filename" \
            "will be appended with _annual_clim. Note intermediate files will be output to the 'Output" \
            "workspace"
        self.canRunInBackground = True

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Features",
            name="in_features",
            datatype="GPFeatureLayer",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Output Workspace",
            name="out_ws",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        # Third parameter
        param2 = arcpy.Parameter(
            displayName="Select climate variables",
            name="clim_var",
            datatype="GPString",
            parameterType="Input",
            direction="Input",
            multiValue=True)
        param2.filter.type = 'ValueList'
        param2.filter.list = ["ahm", "bfff", "cmd", "dd5", "dd18", "effp", "mat", "map",
            "ppt", "pas_sp", "pas_wt", "shm", "tave_sp", "tave_wt", "tave04"]

        # Fourth parameter
        param3 = arcpy.Parameter(
            displayName="Workspace containing climate rasters",
            name="clim_ws",
            datatype="DEWorkspace",
            parameterType="Input",
            direction="Input")

        parameters = [param0, param1, param2, param3]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        pts = parameters[0].valueAsText
        out_ws = parameters[1].valueAsText
        clim_var = parameters[2].valueAsText
        ws_clim = parameters[3].valueAsText

        base_nm = getBaseName(pts)

        lst_merge = []
        for i in range(2007, 2018):
            out_fc = os.path.join(out_ws, base_nm + "clim_" + str(i))
            arcpy.AddMessage("\nRunning value extraction for " + out_fc)
            in_pts = arcpy.CopyFeatures_management(pts, out_fc)
            checkFieldExists(in_pts, "year_txt", "TEXT")
            lst_clim = []
            for var in clim_var.split(';'):
                clim_raster = os.path.join(ws_clim, "clim_" + var + "_" + str(i))
                arcpy.AddMessage("      " + clim_raster)
                lst_clim.append([clim_raster, var])

```

```

        arcpy.CalculateField_management(out_fc, "year_txt", "" + str(i) + "")
        ExtractMultiValuesToPoints(out_fc, lst_clim)
        lst_merge.append(out_fc)
    arcpy.AddMessage("\n\nCompleted extractions by year. \n\nMerging into final dataset...")
    arcpy.Merge_management(lst_merge, os.path.join(out_ws, base_nm + "_annual_clim"))
    return

class createPredictedDensitySurfaces(object):
    def __init__(self):
        """Define the tool (tool name is the name of the class)."""
        self.label = "Create Species Response Densities"
        self.description = "This tool will create density surfaces for predicted SDMs output from 'cforest'"
        self.canRunInBackground = False

    def getParameterInfo(self):
        """Define parameter definitions"""
        # First parameter
        param0 = arcpy.Parameter(
            displayName="Input Directory of CSV response files",
            name="in_csv",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        # Second parameter
        param1 = arcpy.Parameter(
            displayName="Geodatabase of fishnets for each ecosection",
            name="ws_fishnet",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        # Third parameter
        param2 = arcpy.Parameter(
            displayName="Output Workspace",
            name="ws_out",
            datatype="DEWorkspace",
            parameterType="Required",
            direction="Input")

        # Fourth parameter
        param3 = arcpy.Parameter(
            displayName="Snap Raster",
            name="snap_raster",
            datatype="DERasterDataset",
            parameterType="Required",
            direction="Input")

        parameters = [param0, param1, param2, param3]

        return parameters

    def isLicensed(self):
        """Set whether tool is licensed to execute."""
        return True

    def updateParameters(self, parameters):
        """Modify the values and properties of parameters before internal
        validation is performed. This method is called whenever a parameter
        has been changed."""
        return

    def updateMessages(self, parameters):
        """Modify the messages created by internal validation for each tool
        parameter. This method is called after internal validation."""
        return

    def execute(self, parameters, messages):
        ws_response = parameters[0].valueAsText
        ws_fishnet = parameters[1].valueAsText
        ws_output = parameters[2].valueAsText
        snap_raster = parameters[3].valueAsText

        # Loop through the CSV files of predicted densities
        # For each CSV file, get the basename, join it to the appropriate ecosection fishnet
        # Output a raster
        env.workspace = ws_response
        arcpy.env.snapRaster = snap_raster
        files = arcpy.ListFiles("*.csv")
        for f in files:
            f_nm = getBaseName(f)
            arcpy.AddMessage(f_nm)
            eco = f_nm[7:10]
            sp = f_nm[11:len(f_nm)]
            arcpy.AddMessage("Preparing " + sp.upper() + " for " + eco + "...")
            fishnet_lyr = arcpy.MakeFeatureLayer_management(os.path.join(ws_fishnet, eco), "fishnet_lyr")
            joined = arcpy.AddJoin_management(fishnet_lyr, "id_fishnet", f, "id_fishnet")
            arcpy.FeatureToRaster_conversion(joined, sp, os.path.join(ws_output, eco + "_" + sp), cell_size=400)
            arcpy.AddMessage("\n\nCompleted rasterized densities. Check results in " + ws_output)
        return

```

APPENDIX 4 – R Scripts – Project Repository

Latest updates to the project will be uploaded to <https://github.com/Yuhash/iws>. The repository contains the base survey data inputs as well as an interactive [Jupyter notebook](#) running the R-kernel that documents the major script processes in the workflow. For optimal viewing (without interactive code functionality) in Notebook Viewer go to https://nbviewer.jupyter.org/github/Yuhash/iws/blob/master/IWS_Notebook.ipynb.

Workflow Model

```
# For data pre-processing steps please refer to the Github repository and the Jupyter Notebook

# https://journal.r-project.org/archive/2009/RJ-2009-013/RJ-2009-013.pdf
#=====
# cforest model script loops through ecosections and species/species group
# mclapply is a parallelizing function available only on MAC OS. On Windows change 'mclapply' to 'lapply'

useMaxCoreCount <- 2
nTree <- 5000
mTry <- 5
seed <- 42
PREDICT <- TRUE

gitHubRoot <- "/Volumes/Black/Yuri/iws/inputs/by_location/"

outputRoot <- "/Users/hashimotoy/Desktop/iws-results/"

fgcRequire <- function(pkg) {
  if(pkg %in% rownames(installed.packages()) == FALSE) {
    install.packages(pkg)
  }
  # library(pkg)
}

fgcRequire("ggplot2")
fgcRequire("icesTAF")
fgcRequire("party")
fgcRequire("Hmisc")
fgcRequire("lattice")
fgcRequire("beepr")

#install.packages("parallel") # is base, should not be updated (MacOS / R 3.6.0 / RStudio Version
1.2.1335 )
#install.packages("tools") # is base, should not be updated (MacOS / R 3.6.0 / RStudio Version 1.2.1335
)

library(parallel)
library(lattice)
library(Hmisc)
library(party)
library(tools)
library(icesTAF)
library(beepr)

wd <- gitHubRoot
outwd <- paste0(outputRoot,paste0("results-seed-",seed,"-year-studyarea/"))

set.seed(seed)
mkdir(outwd)
setwd(wd)
getwd()

locList <- c("BAU", "NAU", "NEL", "CHP", "BUB", "CAB", "WCU", "QUL")

spList
c("amwi", "buff", "bago", "bwte", "cago", "gwte", "mall", "nsho", "rndu", "scau", "dabblers", "divers", "cavity", "
sp_div", "sp_tot") <-

mclapply(spList, function(sp) {
  lapply(locList, function(loc) {
    setwd(wd)
    mydata <- read.csv(paste0(wd,"id1_years_",loc,".csv"))
```

```

mydata[ 2:ncol(mydata) ] <- lapply(mydata[2:ncol(mydata)], as.numeric)
#sum(is.na(mydata))

fishnet <- read.csv(paste0(gitHubRoot,"fishnet_",loc,".csv"))
fishnet[ 2:ncol(fishnet) ] <- lapply(fishnet[2:ncol(fishnet)], as.numeric)
setwd(outwd) # DOING OUTPUT NOW

rdsFilename <- paste0("cf_", sp, "_", loc, ".rds")
vi_fn <- paste0("VI-",sp,"_",loc,".csv")

print(paste("START Processing cforest for:", sp))

cf <- if (
  !file.exists(paste0(outwd, rdsFilename))
) {
  #colnames(mydata)[colnames(mydata)==sp] <- "sp" RENAME HACK

  cf <- cforest(
    eval(parse(text = paste0(sp,
      "~ aspect + slope + alr + pa + cec_urban + cec_shrubland + ",
      " cec_mixed_forest + cec_grassland + cec_broadleaf + cec_needleleaf +
",
      " fwa_1 + fwa_2 + fwa_3 + fwa_4 + fwa_10ha_more + str_s + str_m + ",
      " fwa_r + fwa_w + dra_u + ",
      # bec_zn + # removed because: model used for CAB on the eco section
basis
      #eco + # removed because we have bined by eco
      "norm_dd5 + norm_cmd + pas_wt + tave04 +",
      "shorecx_10plus_100000 + shorecx_10less_100000"
    )))
    ,
    data = mydata,
    controls = cforest_unbiased(ntree = nTree, mtry = mTry)
  )
  print(paste("cforest done:", sp))
  saveRDS(cf, paste0(outwd, rdsFilename))
  cf
} else {
  readRDS(paste0(outwd, rdsFilename))
}

if (!file.exists(paste0(outwd, vi_fn))
) {
  vi <- varimp(cf, conditional = FALSE, OOB = TRUE)
  # write.csv(vi, paste(fn, ".csv", sep = ""), row.names = FALSE)
  df_vi <- as.data.frame(vi)
  write.csv(df_vi,vi_fn);
}

#### Not incorporated in batch: deriving OOB, Response, Probability
if (PREDICT) {
  ofResp <- paste0(outwd,sp,"-response_",loc,".csv")
  cf_response <- predict(cf, newdata = fishnet, OOB = TRUE, type = 'response')
  df_result <- data.frame(fishnet$id_fishnet, cf_response)
  write.csv(df_result, ofResp)
}

print(paste("COMPLETED Anaylsis of:", sp))
})
}
, mc.cores = min(useMaxCoreCount,detectCores())
)
#####
# Ranking and Plots for varimp
# Written if RDS has to be loaded

setwd(wd)

rdss <- list.files(wd, pattern ="*rds$")
lapply(rdss, function(f){
  cf <- readRDS(f)

```



```

fn <- substr(basename(f), 4, nchar(basename(f)) - 4)
eco <- substr(fn, nchar(fn) - 2, nchar(fn))
sp <- sub(paste0("_", eco), "", fn)
vi_fn <- paste0(wd, "vi_", fn, ".csv")
if (!file.exists(vi_fn)) {
  vi <- varimp(cf, conditional = FALSE, OOB = TRUE)
  df_vi <- as.data.frame(vi)
  v <- as.vector(df_vi$vi)

  vi <- varimp(cf, conditional = FALSE, OOB = TRUE)
  df_vi <- as.data.frame(vi)
  df_vi$X <- names(vi)
  df_vi$eco <- eco
  df_vi$sp <- sp

  # Add metadata fields
  df_vi <- as.data.frame(vi)
  df_vi$X <- names(vi)
  df_vi$eco <- eco
  df_vi$sp <- sp
  write.csv(df_vi, vi_fn, row.names = FALSE)

  # Rank
  df_vi <- df_vi %>%
    mutate(rank = dense_rank(desc(df_vi$vi)))
  colnames(df_vi)[colnames(df_vi) == "rank"] <- paste(eco, sp, sep = "_")
  rank_vi <- subset(df_vi, select = -c(vi, eco, sp))
  write.csv(df_vi, vi_fn, row.names = FALSE)
}
})
# =====
## Create plots

library(tools)
setwd(wd)
varimpFiles <- list.files(wd, pattern = "^vi.*csv$")
lapply(varimpFiles, function(f) {
  fn <- substr(basename(f), 4, nchar(basename(f)) - 4)
  print(fn)
  eco <- substr(fn, nchar(fn) - 2, nchar(fn))
  sp <- sub(paste0("_", eco), "", fn)

  print(paste("Starting plot", f))
  fn <- file_path_sans_ext(basename(f))
  title <- paste(toupper(sp), eco)
  print(title)
  df_vi <- read.csv(f)
  v <- as.vector(df_vi$vi)
  names(v) <- as.vector(df_vi$X)
  print(names(v))
  dotchart(v[order(v)], cex = 0.9, pch = 19,
    color = "darkblue",
    xlab = "varImp", main = title)
  dev.copy(png, paste(wd, paste("varimp_", title, ".png", sep = ""), sep = "/"))
  dev.off()
  print(paste("plot done:", fn))
})

print("ALL DONE")

```

R Snippets - Data Manipulation

```

# Create a data frame from a list of csv files converted to a list of data frames merged by common column
values
lst <- list.files(wd, pattern = "^rank.*csv$" )
merged <- do.call("cbind", lapply(rankeds, read.csv))

# =====
# Flat correlation matrix with P and r values

library(tidyr)
library(tibble)
library(Hmisc)

```

```

flat_cor_mat <- function(cor_r, cor_p){
  #This function provides a simple formatting of a correlation matrix
  #into a table with 4 columns containing :
  # Column 1 : row names (variable 1 for the correlation test)
  # Column 2 : column names (variable 2 for the correlation test)
  # Column 3 : the correlation coefficients
  # Column 4 : the p-values of the correlations
  library(tidyr)
  library(tibble)
  cor_r <- rownames_to_column(as.data.frame(cor_r), var = "row")
  cor_r <- gather(cor_r, column, cor, -1)
  cor_p <- rownames_to_column(as.data.frame(cor_p), var = "row")
  cor_p <- gather(cor_p, column, p, -1)
  cor_p_matrix <- left_join(cor_r, cor_p, by = c("row", "column"))
  cor_p_matrix
}

library(corrplot)
cor <- rcorr(as.matrix(mtcars[, 1:7]))

my_cor_matrix <- flat_cor_mat(cor$r, cor$p)
head(my_cor_matrix)

corr <- rcorr(as.matrix(df))
corrplot(corr$r, method='number', number.cex= 12/ncol(df_sub))#To alter font size

# =====

# Check for NA values

df %>%
  select_if(function(x) any(is.na(x))) %>%
  summarise_each(funs(sum(is.na(.)))) -> extra_NA

# =====
# Set NA values to 0
df[is.na(df)] <- 0

# =====
# The function complete.cases() returns a logical vector indicating which cases are complete.
# list rows of data that have missing values

df[!complete.cases(df),]

# =====
# Check which version of R is running
Sys.getenv("R_ARCH")
# "/i386" or "/x64"

# =====
# UPDATE PACKAGES
update.packages(checkBuilt=TRUE, ask=FALSE)

# =====
mypath <- path

multmerge = function(mypath){
  filenames=list.files(path=mypath, full.names=TRUE)
  datalist = lapply(filenames, function(x){read.csv(file=x,header=T)})
  Reduce(function(x,y) {merge(x,y)}, datalist)}

mymergeddata = multmerge(path)

# =====
# UPDATE R Version

# installing/loading the package:
if(!require(installr)) {
  install.packages("installr"); require(installr)} #load / install+load installr

library(installr)
# using the package:
updateR()

```

```
# =====
# # Rename a column in R
colnames(data)[colnames(data)=="old_name"] <- "new_name"

sp_start <- grep("dabblers", colnames(df))
sp_end <- grep("tot_sp", colnames(df))

print(sp_start)
print(sp_end)

sp <- colnames(df)[sp_start:sp_end]

var_start <- sp_end + 1
var_end <- ncol(df)
print(var_start)
print(var_end)

int_eco <- grep("eco", colnames(df))
int_trans <- grep("trans_id", colnames(df))
int_bec_zn <- grep("bec_zone", colnames(df))
int_bec_sz <- grep("bec_sz", colnames(df))

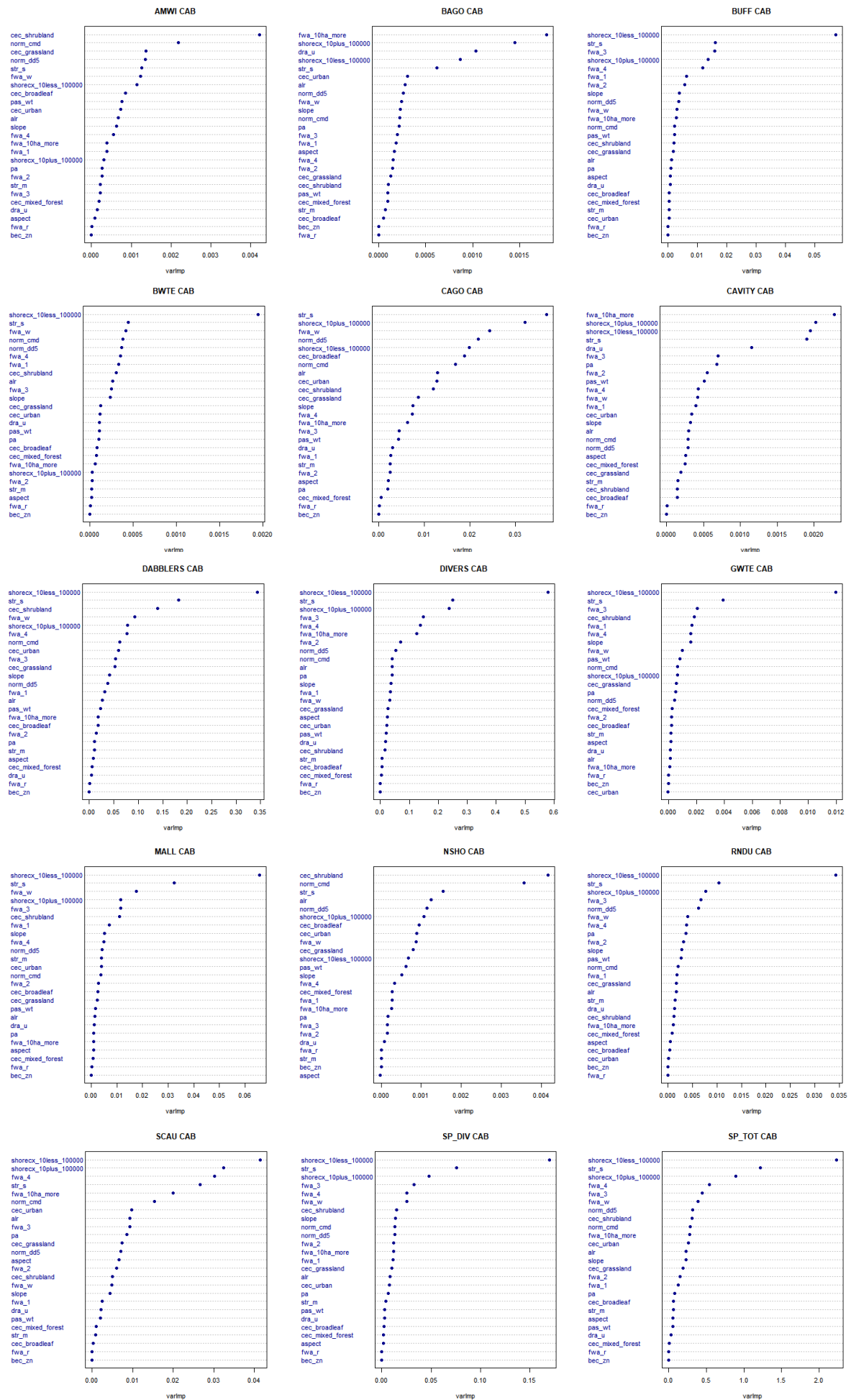
for (i in 1:length(sp)){
  nm <- sp[i]
  print(nm)
  int = grep(nm, colnames(df))
  data <- df[c(int,int_eco,int_trans,int_bec_zn, int_bec_sz,var_start:var_end)]
  colnames(data)[1]<- "sp"
  write.csv(data, paste(outwd, paste("rf_",scale, "_",nm,".csv", sep = ""), sep = "/"), row.names =
FALSE)
}
```

APPENDIX 5 – Variable Importance Plots

Babine Upland

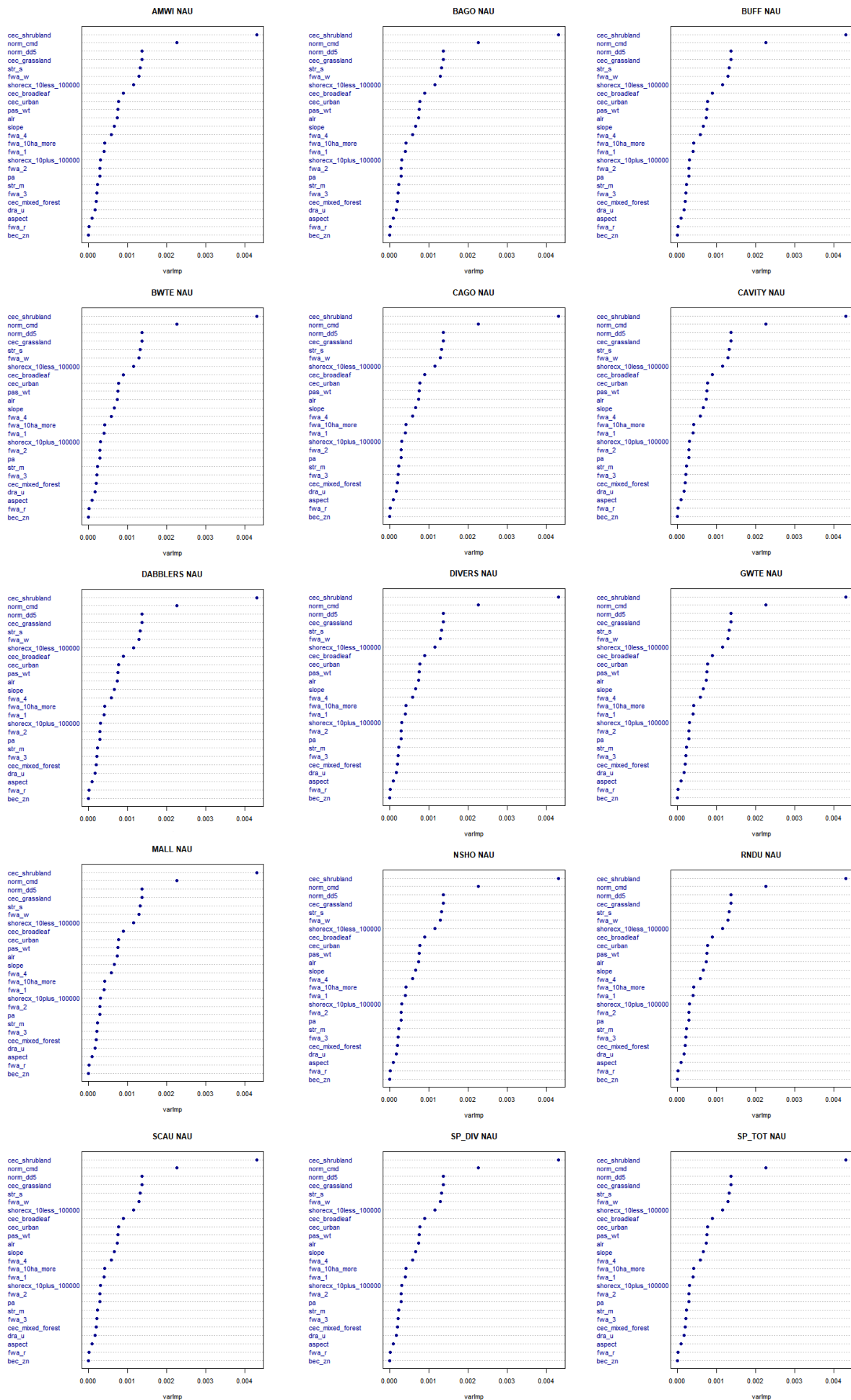
Bulkley Basin

Cariboo Basin



Chilcotin Plateau

Nazko Upland



Nechako Lowland

Quesnel Lowland

Western Chilcotin Uupland

APPENDIX 6 – Species Distribution Maps

American Wigeon

Barrow's Goldeneye

Bufflehead

Canda Goose

Green-winged Teal

