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Predicting environmental mitigation requirements for hydropower projects through the integration of biophysical and socio-political geographies☆

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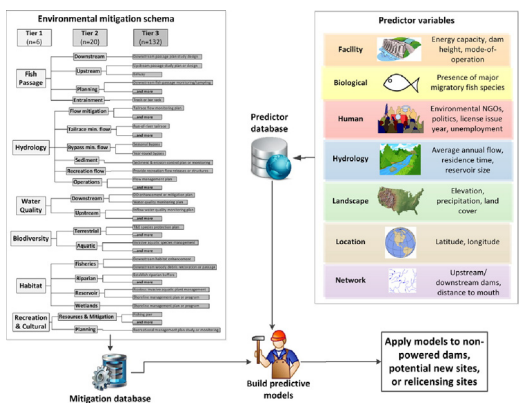
HIGHLIGHTS

- Statistical models were built to predict required mitigation at hydropower sites.
- Predictors describe biosphere, lithosphere, hydrosphere, and anthroposphere.
- BRT model results show that biophysical and sociopolitical factors influence mitigation.
- Hydropower developers can use models to reduce cost and inform design decisions.
- Resource managers can use models to identify likely environmental issues.

GRAPHICAL ABSTRACT



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ABSTRACT

Uncertainty about environmental mitigation needs at existing and proposed hydropower projects makes it difficult for stakeholders to minimize environmental impacts. Hydropower developers and operators desire tools to better anticipate mitigation requirements, while natural resource managers and regulators need tools to evaluate different mitigation scenarios and order effective mitigation. Here we sought to examine the feasibility of using a suite of multi-faceted explanatory variables within a spatially explicit modeling framework to fit predictive models for future environmental mitigation requirements at hydropower projects across the conterminous U.S. Using a database comprised of mitigation requirements from more than 300 hydropower project licenses, we were able to successfully fit models for nearly 50 types of environmental mitigation and to apply the predictive models to a set of more than 500 non-powered dams identified as having hydropower potential. The results demonstrate that mitigation requirements are functions of a range of factors, from biophysical to socio-political. Project developers can use these models to inform cost projections and design considerations, while regulators can use the models to more quickly identify likely environmental issues and potential solutions, hopefully resulting in more timely and more effective decisions on environmental mitigation.

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1. Introduction

Hydroelectric power is currently the largest of the renewable energy resources worldwide, contributing to electricity generation in 160 countries (Manzano-Agugliaro et al., 2013). The environmental impacts of hydropower are well established (Liermann et al., 2012; Nilsson et al., 2005; Poff et al., 1997, 2007), and are mitigated with mixed success (Trussart et al., 2002). In the United States (U.S.), the authority to issue 30–50 year licenses for the operation of non-federal hydropower facilities belongs to the U.S. Federal Energy Regulatory Commission (FERC). The passage of the Electric Consumers Protection Act of 1986 (ECPA) substantially changed FERC's consideration of environmental impacts with the requirement that equal consideration be given to the protection and enhancement of, and mitigation of damage to, wildlife, environmental quality, and recreational opportunity. Furthermore, a string of court rulings eroded FERC's singular authority to prescribe environmental mitigation by requiring FERC to include fishway prescriptions from the National Marine Fisheries Service or U.S. Fish and Wildlife Service, as well as minimum streamflow requirements included as part of state water quality certificates (Blumm and Nadol, 2001; Tarlock, 2012). The result was a significant increase in the number of mitigation requirements included in FERC licenses and a growing role of other federal and state agencies in the licensing process (Blumm and Nadol, 2001; Deshazo and Freeman, 2005; Kosnik, 2010).

FERC and the hydropower industry have suggested that this instable policy context and increased regulatory plurality have resulted in increased licensing time and increased uncertainty in mitigation requirements (FERC, 2001; U.S.-Congress, 2012). Original licenses for new projects and relicensing of existing projects provide a once in every 30 to 50 year opportunity to address environmental concerns at hydropower projects. FERC addresses potential environmental impacts by incorporating license conditions (mitigation requirements) where evidence shows project operations will impact environmental or recreational resources. With over 300 relicense applications anticipated between 2016 and 2026 (FERC, 2015), there is new urgency to integrate sustainability practices into future hydropower development by evaluating and balancing the environmental and social costs of hydropower projects with the variety of potential benefits hydropower projects provide.

Hydropower developers and owners desire some certainty and ability to better anticipate mitigation requirements. Similarly, resource managers and regulators must be able to evaluate likely mitigation scenarios and determine the relative effectiveness of mitigation implemented at similar projects. While each hydropower project is unique, Yu and Xu (2016) recommend development of common approaches and principles for designing ecological and social compensation mechanisms for hydropower development. The authors of this manuscript recently developed a database of environmental mitigation requirements in FERC licenses (Schramm et al., 2016) that presents new opportunities for analyzing past environmental mitigation requirements and predicting future mitigation requirements.

In this study we sought to examine the feasibility of using a suite of multidisciplinary explanatory variables to fit predictive models for environmental mitigation requirements at hydropower projects across the conterminous U.S. We developed a spatially explicit framework (applying niche modeling concepts common in landscape ecology) to predict nearly 50 types of environmental mitigation requirements using biological, facility, human, hydrologic, landscape, locational, and stream network characteristics. Our primary goal was to build statistical models to predict future mitigation requirements at hydropower project sites, while the secondary goal was to gain some understanding into potential key environmental and social drivers of these requirements that may warrant additional future research. As an example of how the models can be applied, we made predictions to a set of non-powered dams (NPDs) across the U.S. that were previously identified as having considerable energy potential.

2. Materials and methods

The conterminous United States (Fig. 1) is environmentally and culturally heterogeneous (Fig. 2), containing diverse physiographic regions ranging from mountains to inland and coastal plains, and encompassing examples of nearly every global climate. There is also considerable geographic variation in socio-political, economic, and cultural characteristics.

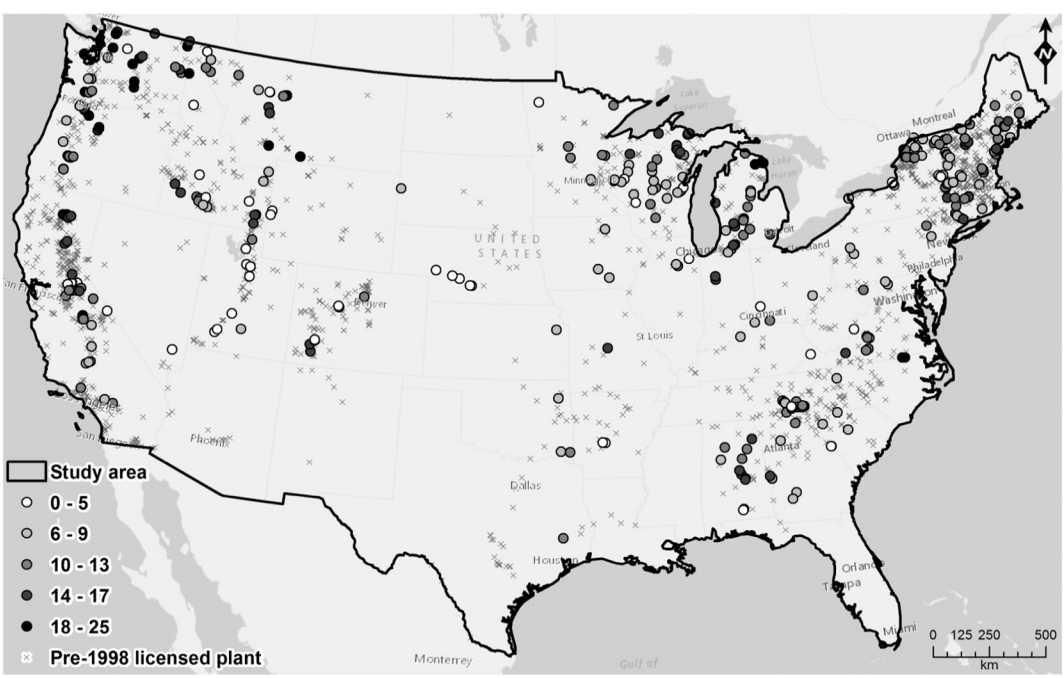


Fig. 1. Study area showing location of 463 hydropower plants licensed from 1998 through September 2015. Color of plant locations indicates number of mitigation requirements for mitigation categories selected for statistical modeling.

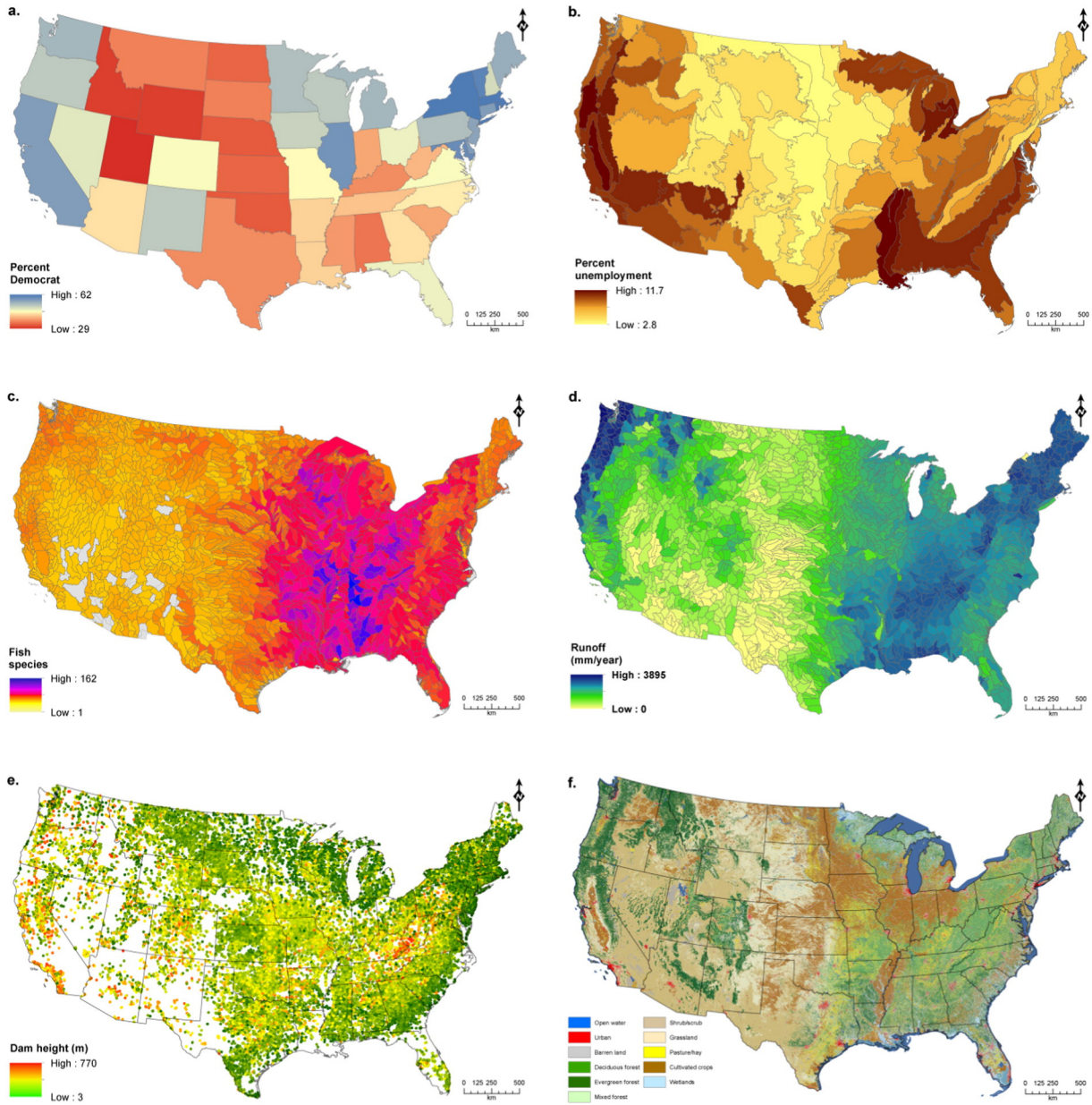


Fig. 2. a. Average percent democratic votes cast in U.S. presidential elections from 1996 to 2012. b. Percent unemployment from 2010 U.S. census, aggregated to physiographic region. c. Number of freshwater fish species per HUC8 watershed. d. Average annual runoff per HUC8 watershed. e. Dam locations symbolized by height. f. 2011 land cover.

2.1. Mitigation database and response variables

A database of environmental mitigation requirements was compiled for FERC licenses issued from 1998 through September 2015 (Schramm et al., 2016). Since our goal is prediction of future mitigation requirements, the manual review of licenses was limited to those issued from 1998 through 2015 with an assumption that more recently issued licenses would better reflect future mitigation requirements. The database includes Bernoulli distributed presence–absence mitigation data at 463 hydropower plants in the study area from 316 licenses. Six broad categories (Tier 1) of mitigation (biodiversity, fish passage, habitat, hydrology, recreation, and water quality) and 20 subcategories (Tier 2) were used to classify specific mitigation types in the hierarchical database. A full list of each of the mitigation types catalogued in the database and the percent of times each was required, including each of the 132 Tier 3 categories, is presented in Appendix A. Descriptions of each of the Tier 3 categories are provided in Appendix A of Schramm et al. (2016). Predictive models were built only if a mitigation type was required for at least 5% (Rickbeil et al., 2014) of the plants in the mitigation database. Models were not built for the very broad Tier 1 categories.

2.2. Explanatory variables

Given that hydropower project licensing is influenced by a suite of biophysical and socio-economic factors, the candidate predictor variables (Table 1) employed here were selected based on expert opinion and on previous research by Kosnik (2010) and Trussart et al (2002) as broad-scale measures of biological, facility, human, hydrologic, landscape, locational, and stream network characteristics thought to have some bearing on mitigation requirements. The models that each candidate predictor was included in are indicated in Table 1. We used expert opinion to identify candidate predictors for each of the six Tier 1 categories, and these six predictor sets were then used to build models

Table 1
Summary and description of input variables for the boosted regression tree models. Variables or units in bold and underlined indicate remaining predictor variables after collinearity analysis.

Variable	Description	Units	Spatial scale	Source	Models
		Biological			
bigPlyrSum	Major migratory fish species	Count	HUC8 watershed	NatureServe fish distributions, expert opinion	P, H, B, A, R
		Facility			
Height	Dam height	Feet	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
HY_MW	Generation capacity	Megawatts	Hydropower dam	ORNL NHAAP database	––
HY_MWh	Generation	Megawatt-hours	Hydropower plant	ORNL NHAAP database	––
Length	Dam length	Feet	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
Mode	Dam mode-of-operation	Categorical	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
owner	Ownership type	Categorical	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
PrmyPurps	Dam primary purpose	Categorical	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
		Human			
birdG_xx	National Audubon Society chapters	Count, PA, PC	State	National Audubon Society	––
damR_xx	Dam removals	**Count**, PA, PC	State	American Rivers	P, H, W, B, A, R
education	Education attainment - percent bachelor's degree or higher	Percent	USEPA Level 3 Ecoregion	US Census	P, H, W, B, A, R
FishG_xx	TU and CCA chapters	**Count**, PA, **PC**	State	TU, CCA	P, H, B, A, R
hshldincm	Mean household income	US dollars	USEPA Level 3 Ecoregion	US Census	––
IssueYear	FERC hydropower project license issue year	Year	Hydropower plant	ORNL NHAAP database	P, H, W, B, A, R
LandG_xx	Land trusts	Count, PA, PC	State	Land Trust Alliance	––
politics	See note*	Difference	State	US Federal Election Commission	P, H, W, B, A, R
xx_POPDENS	2000 population density	Individuals/km^2 (L and N)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W, B, A, R
q12_avg	Survey response on environmental impact of dams	Rank	Geographic region	MIT Energy Survey, 2008	P, H, W, B, A, R
q16_avg	Survey response on increasing or decreasing hydro power	Rank	Geographic region	MIT Energy Survey, 2008	P, H, W, B, A, R
SierG_xx	Sierra Club chapters	Count, **PA**, **PC**	State	Sierra Club	P, H, W, B, A, R
unemplymnt	Unemployment	Percent	USEPA Level 3 Ecoregion	US Census	P, H, W, B, A, R
usHouse	LCV US House of Rep. mean scorecard for 1998 to 2013	Percent	State	League of Conservation Voters	––
usSenate	LCV US Senate mean scorecard for 1998 to 2013	Percent	State	League of Conservation Voters	––
wshed_xx	Local watershed associations	**Count, PA, PC**	State	USEPA	P, H, W, B, A, R
		Hydrology			
ADRAIN	Total artificial drainage area	Square meters	NHD Plus V1 Catchment	USGS	H, W, A
BFI_MEAN	Mean base-flow index for GW discharge into streams	Percent	NHD Plus V1 Catchment	USGS	H, W, A
CNTC_MEAN	Baseflow residence time in the subsurface	Days	NHD Plus V1 Catchment	USGS	H, W, A
DITCHES	Estimated area subject to the practice of ditches	Square meters	NHD Plus V1 Catchment	USGS	––
FlowYr	Average annual flow	Cubic feet per second	NHD Plus V1 Flowline	NHD Plus V1	P, H, W, B, A, R
IRRIG	Estimated area subject to the practice of irrigation	Square meters	NHD Plus V1 Catchment	USGS	––
KFACT	Soil erodibility factor	Dimensionless	NHD Plus V1 Catchment	USGS	H, W, A
MAVELU	Mean Annual Velocity (fps) at bottom of flowline	Cubic feet per second	NHD Plus V1 Flowline	NHD Plus V1	P, H, W, B, A, R
MEAN_IEOF	Mean value for infiltration-excess overland flow	Percent	NHD Plus V1 Catchment	USGS	H, W, A
MEAN_RCHRG	Mean annual natural groundwater recharge	Millimeters	NHD Plus V1 Catchment	USGS	––
nidStorSum	Accumulated upstream storage	Acre-feet	Hydropower dam	National Anthropogenic Barriers Dataset	H, W, A
ResDay	Reservoir residence time	Days	Hydropower dam	ORNL NHAAP database	P, H, W, B, A, R
SATOF_MEAN	Average value of saturation overland flow	Percent	NHD Plus V1 Catchment	USGS	H, W, A
SfArea	Reservoir surface area	Acres	Hydropower dam	National Inventory of Dams	P, H, W, B, A, R
Stor	Reservoir storage	Acre-feet	Hydropower dam	National Inventory of Dams	––
TILES	Estimated area of tile drains	Square meters	NHD Plus V1 Catchment	USGS	––
		Landscape			
xx_CROPS	Land cover classified as cultivated crops	Percent (**L and N**)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W, B, A
xx_NPDES	Number of NPDES sites	Count (**L** and N)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W
xx_PASTURE	Land cover classified as pasture/hay	Percent (**L and N**)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W, B, A
xx_ROADCRC	Road-stream crossings	Count (L and N)	NHD Plus V1 Catchment	USGS, National Fish Habitat Partnership	––
xx_URBANHC	Land cover classified as high intensity urban	Percent (L and N)	NHD Plus V1 Catchment	National Fish Habitat Partnership	––
xx_URBANL	Land cover classified as low intensity urban	Percent (**L and N**)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W, B, A
xx_URBANM	Land cover classified as medium intensity urban	Percent (**L** and N)	NHD Plus V1 Catchment	National Fish Habitat Partnership	H, W, B, A
CNPY_MEAN	Mean canopy cover	Percent	NHD Plus V1 Catchment	USGS	H, W, B, A
CROP_AREA	Total crop area for fertilizer/manure derived from land use	Square meters	NHD Plus V1 Catchment	USGS	H, W, B, A
d303_count	Impaired or threatened waters	Count	NHD Plus V1 Catchment	USEPA 303(d) list	H, W, B, A
IMPV_MEAN	Mean impervious surface	Percent	NHD Plus V1 Catchment	USGS	––
L_MINES	Number of mines or mineral processing plants	Count	NHD Plus V1 Catchment	National Fish Habitat Partnership	W
L_ROADLEN	Length of roads	Meters	NHD Plus V1 Catchment	National Fish Habitat Partnership	P, H, W, B, A
MAXELEVSMO	Maximum elevation	Meters	NHD Plus V1 Flowline	NHD Plus V1	P, H, W, B, A, R
PPT30MEAN	30-year (1971-2000) average annual precipitation	Millimeters	NHD Plus V1 Catchment	USGS	P, H, W, B, A, R
SLOPE	Slope of stream reach	Unitless	NHD Plus V1 Flowline	NHD Plus V1	P, H, W, B, A, R
SLP_PERC	Landscape slope	Percent	NHD Plus V1 Catchment	USGS	P, H, W, B, A, R
TMAX30_MEA	30–year (1971–2000) average annual maximum temperature	Celsius	NHD Plus V1 Catchment	USGS	––
		Location			
POINT_X	Longitude	Decimal degrees	Hydropower dam	National Anthropogenic Barriers Dataset	P, H, W, B, A, R
POINT_Y	Latitude	Decimal degrees	Hydropower dam	National Anthropogenic Barriers Dataset	P, H, W, B, A, R
		Stream network			
dist2Mouth	Stream network distance to network mouth	Meters	Entire downstream flow path	Calculated from NHD Plus V1 flowlines	P, H, W, B, A, R
DrArea	Drainage area upstream of dam	Square miles	Hydropower dam	National Inventory of Dams	––
dsDams	Downstream dams on flow path to network mouth	Count	Entire downstream flow path	Calculated from NHD Plus V1 and NABD	P, H, W, B, A, R
N_DAMSC	Number of dams within network catchment	Count	NHD Plus V1 Catchment	National Fish Habitat Partnership	P, H, W, B, A, R
SO	Strahler stream order	Strahler number	NHD Plus V1 Flowline	NHD Plus V1	P, H, W, B, A, R

PA = per area; PC = per capita; L = local catchment; N = entire network catchment; xx indicates variable derived for multiple units; P = fish passage; H = hydrology; W = water quality; B = biodiversity; A = habitat; R = recreation; *politics is the difference between mean percent democrat and republican from 1996 to 2012 presidential elections; LCV = League of Conservation Voters; TU = Trout Unlimited; CCA = Coastal Conservation Association.

for each Tier 2 and Tier 3 model nested within the Tier I categories. Given that our goal was prediction and not explanation, we did not delve into the exact causal role of each potential predictor. Instead, we selected predictors based on hypothesized quality of association between the predictor and the response, data quality, and data availability (Shmueli, 2010).

2.2.1. Biological

The presence or absence of important fish species can influence not only fish passage mitigation requirements but also other measures related to biological conservation (Cada, 1998; Fraley et al., 1989; Renofalt et al., 2010). We used conservation status in concert with expert opinion to compile a list of high profile migratory fish species supported by policy protections (McManamay et al., 2015). We then mapped distributions of each of these species using the NatureServe (2010) database of current distributions of freshwater fishes of the U.S. at the 8-digit hydrologic unit code (HUC8) scale to allow for analysis of interactions between these high profile species and hydropower project locations. The biological explanatory variable is a count of the number of key fish species per HUC8 (McManamay et al., 2015).

2.2.2. Facility characteristics

The Oak Ridge National Laboratory (ORNL) National Hydropower Asset Assessment Program (NHAAP) is an integrated energy, water, and ecosystem research effort for sustainable hydroelectricity generation and water management. The ORNL NHAAP database (http://nhaap.ornl.gov/) integrates data from multiple data sources and provides the most current, detailed, and spatially comprehensive information for analyzing and visualizing existing U.S. hydropower assets. We included hydropower facility characteristics from the NHAAP database thought to be important drivers of prescribed mitigation such as dam height, generation capacity, dam mode-of-operation, and geographic location (Kosnik, 2010).

2.2.3. Human dimensions

The convergence of different anthropogenic characteristics such as presence of environmental interest groups, political climate, population demographics, and regulatory tendencies can be impactful on mitigation requirements (Kosnik, 2010). Consistent with the interest group theory of regulation (Peltzman, 1976), Knittel (2006) concluded that electricity industry regulators respond to lobbying from interest groups. In research focused on explaining drivers of environmental mitigation requirements at hydropower projects, Kosnik (2010) found the largest influences on FERC's regulatory decisions to be congressional politics and regulatory tendencies. In an attempt to capture the socio-political and regulatory landscape, we included numerous anthropogenic predictors that serve as direct measures or proxies for local, state, or regional political tendencies, environmental awareness, regulatory trends, and public attitudes toward dams. Candidate predictors aimed at capturing political tendencies include presidential election voting averaged over time and congressional politics. Different aspects of environmental awareness were estimated at a state-scale using prevalence of non-profit organizations, including protection of birds and their habitats (using National Audubon Society chapters), fish and their habitats (using Trout Unlimited chapters for freshwater and Coastal Conservation Association chapters for marine), land conservation (using land trusts), water quality conservation (using local watershed associations), and general environmental awareness (using Sierra Club chapters). Regulatory trends were estimated using the issue year of the license. Prevalence of dam removals and citizen survey responses on energy and environmental impacts from dams were used as estimates of public attitudes toward dams.

2.2.4. Hydrology

Operation of a hydropower facility typically involves modifications to hydrologic regimes both upstream and downstream of dams, reservoirs, or river diversions (Fraley et al., 1989; Ligon et al., 1995; Poff et al., 1997). The magnitude of these flow disturbances can be minimized by discharge management, and there is increasing pressure from regulatory agencies to incorporate ecological flow requirements in licenses and operational plans for hydropower projects (Bunn and Arthington, 2002; Renofalt et al., 2010; Trussart et al., 2002). We included a suite of explanatory variables derived at the stream reach and watershed scale that describe different aspects of the hydrologic regime of a given area, including surface water, groundwater, and reservoir storage characteristics.

2.2.5. Landscape

Broad-scale landscape descriptors such as land cover, terrain, and climate can influence prescribed mitigation in all six of the Tier 1 mitigation categories, either directly or indirectly. Thus we included numerous land cover metrics derived at multiple scales (Tong and Chen, 2002; Wang et al., 2001), topographic variables such as slope and elevation (Moore et al., 1991), and the core climatic variables of average annual precipitation and air temperature (Grimm et al., 2008).

2.2.6. Location

In the U.S., there are tangible trends and patterns in environmental, economic, cultural, and social conditions from east to west and north to south. We included latitude and longitude to account for spatial effects and capture spatial patterns across the large study area that may be insufficiently represented in the other predictors (Fink et al., 2010; Oppel et al., 2012).

2.2.7. Stream network

Stream network position and the prevalence of upstream and downstream dams are important descriptors of network fragmentation/connectivity (Kuby et al., 2005). Where a hydropower project falls on the stream network in relation to other barriers and the network mouth can have a strong influence on the nature and magnitude of ordered mitigation (Fraley et al., 1989; Kosnik, 2010).

2.3. Statistical analyses

Model development was carried out in R version 3.2.2 (R-Core-Team, 2015). Boosted regression trees (a machine-learning technique) were used to develop the predictive models, as this method has been demonstrated to have high predictive performance with presence–absence response variables, allows for complex regression analyses of complex responses, and can handle continuous and categorical explanatory variables (Abram et al., 2015; Arganaraz et al., 2015; Elith et al., 2006, 2008). Before running the models, all predictor variables were assessed for collinearity using Pearson's correlation coefficients (r). When r values exceeded 0.7 (Dormann et al., 2013), the variable deemed more functionally applicable to hydropower mitigation (Arganaraz et al., 2015; Rickbeil et al., 2014) or that was derived at a higher spatial resolution was retained (Table 1). The data were split into training (80%) and validation (20%) data using the caret package in R, which creates random splits within each class so that the overall class distribution is preserved as well as possible (Kuhn, 2008).

Given the novelty of the mitigation database, we were unable to obtain an independent validation dataset as recommended by Araujo and Guisan (2006). The optimal number of trees was determined using 10-fold cross validation (CV), with the bag fraction set to 0.5 and the learning rate set to 0.001 to ensure that each model had at least 1000 trees (Elith et al., 2008). The area under the receiver-operating characteristic curve (ROC) calculated on the validation dataset was used to assess predictive performance. We implemented the ROC interpretation presented by Hosmer et al. (2013) where an ROC value of 0.7–0.8 is considered an acceptable prediction, 0.8–0.9 is excellent, and >0.9 is outstanding. For a model to be deemed acceptable, both the internal CV ROC and the validation ROC had to be ≥0.7. We

generated partial dependence plots to examine the nature of the models and to interpret the effect of a variable on the response after accounting for the average effects of all other variables in the model (Elith et al., 2008). Spatial autocorrelation of model residuals was evaluated using Moran's *I* statistics (Dormann et al., 2007) calculated with the Spatial Autocorrelation tool in ArcGIS version 10.2.2 (ESRI).

2.4. Example model application at non-powered dams

While approximately 2500 dams in the U.S. provide 78 gigawatts (GW) of conventional and 22 GW of pumped-storage hydropower, there are hundreds of NPDs originally built for other purposes that may be retrofitted for hydropower to produce an additional 12 GW of estimated renewable energy for the U.S. (Hadjerioua et al., 2012). While many of the monetary costs and environmental impacts have already been incurred at these sites, our models can be used as a tool to assess potential environmental mitigation requirements that may arise during the hydropower licensing process. As an example of how the modeling can be applied, we made predictions for each of the acceptable models to 568 NPDs estimated by Hadjerioua et al. (2012) to have >1 MW (MW) in potential capacity. We used the optimal threshold function in the R package SDMtools (VanDerWal et al., 2012) to identify the value on the ROC curve that is closest to a perfect model fit, and then we applied that value as the predicted present/absent threshold when making predictions to the NPDs.

3. Results

3.1. BRT models

Predictive models were built only if a mitigation type was required for at least 5% (Rickbeil et al., 2014) of the plants in the mitigation database, resulting in 57 Tier 3 mitigation types being modelled and all 20 of the Tier 2 mitigations being modelled (see Table 2 for modeling results). Eight of the 57 Tier 3 models were rejected due to either a CV ROC or validation ROC < 0.7, leaving 49 Tier 3 models with at least an acceptable fit. All 20 of the Tier 2 models had an ROC ≥ 0.7. Significant spatial autocorrelation of model residuals was detected in 4 of 20 Tier 2 models and 11 of 49 Tier 3 models.

3.2. Explanatory variables

The three variables with the highest relative influence in each model are presented in Table 2, and partial dependence plots for these variables are presented in Appendix B. Overall, we considered a variable important if its relative influence was ≥5% (Parisien et al., 2011). A summary of the important variables for the Tier 3 models (Fig. 3) shows that nearly all the categories of variables (i.e. biological, facility, human, hydrologic, landscape, locational, and stream network) were influential within each Tier 1 category.

Across all Tier 3 models (Fig. 4), the most important variables were longitude (location), reservoir surface area (hydrology), average annual flow (hydrology), precipitation (landscape), and latitude (location). Stream network, facility, human, and biological variables were also important but exceeded the ≥5% relative influence threshold less frequently.

To identify potential key environmental and social drivers of mitigation that may warrant additional future research, we examined important variables across all of our Tier 3 models based on frequency of importance and average relative influence. We grouped important variables into the potential future research areas of socio-political conditions, regional trends, network/landscape position, hydrology/site design, regulatory tendencies, and fisheries (Table 3).

3.3. Predictions to NPDs

We made predictions to 568 NPDs with >1 MW potential capacity for each of the 49 acceptable Tier 3 models (Fig. 5). The optimal present/absent threshold for each model is presented in Table 2. The number of predicted mitigation requirements ranged from 9 to 34.

4. Discussion

The spatial modeling approach developed here integrates GIS techniques, novel data, machine-learning algorithms, and niche modeling concepts common in landscape ecology (see Guisan and Thuiller, 2005) to predict environmental mitigation requirements at hydropower project sites. Given the multifaceted, complex nature of demonstrated (Kosnik, 2010) and hypothesized (FERC, 2001) drivers of environmental mitigation requirements, we were uncertain of their predictability. However, we have demonstrated that a broad-scale, multidisciplinary geographical predictor dataset can effectively predict many environmental mitigation requirements across an environmentally and culturally heterogeneous study area.

We summarized and evaluated the influence of the important (relative influence ≥5%) explanatory variables at several different levels of aggregation (Table 2, Figs. 3, and 4). Since nearly all the categories (e.g. biological, facility, etc.) of variables were influential within each Tier 1 category (Fig. 3) and every Tier 3 model had at least two variable categories represented in the top 3 influential variables (Table 2), it appears that the multi-faceted nature of the predictor dataset we compiled was a key to our modeling success.

Based on our analysis of the top predictor variables across all of the Tier 3 models (Fig. 4), the most common important predictors include metrics of project location (latitude and longitude), project size (annual flow, reservoir size, dam height, and dam length), stream network position (distance along the stream network to network mouth), and climate (precipitation). Elevation above mean sea level, statewide prevalence of local watershed associations, local population density, license issue year, dam length, and dam mode-of-operation were the predictors with the highest average relative influence (Fig. 4) among the most important predictors. Given that the study area is large, environmentally and culturally heterogeneous, and comprised of many diverse physiographic regions, we anticipated that latitude and longitude would be valuable predictors that capture regional trends across the U.S. For example, the inclusion of latitude and longitude in models predicting fish passage are related to the fact that most mitigation for passage occurs in the U.S. northeast and northwest. We expected variables related to project size, facility characteristics, and hydrology to be important, given that larger projects are likely to have a higher impact to the environmental and social landscape than smaller projects. Elevation is a proxy for head and a measure of landscape position, and is a very powerful descriptor of landscape context. Stream network position, such as distance to river mouth, can explain the presence of diadromous fish species, network connectivity, and existing hydrologic alteration, all of which can heavily influence decisions on mitigation requirements. It is well known in the U.S. that environmental stakeholder groups can be influential in ordered mitigation, so it was not surprising that anthropogenic variables, such as the prevalence of environmental groups, were important. Previous research (Kosnik, 2010) has shown that regulatory trends can influence hydropower mitigation requirements, and the license issue year proved to be an important variable in several models.

Examination of partial dependence plots to assess the direction of variable influence (Appendix B) seems to show that, while there appears to be some consistent direction of influence for important predictors, particularly in the fish passage and water quality models, there are as many examples of contrasting direction of influence within the six broad mitigation categories. This underscores the complexity of the interplay of the nature and magnitude of a given mitigation

Table 2
Model results summary.

Tier 1	Tier 2	Tier 3	ModelID	Trees	CV ROC	V ROC	OT	MI	Influential Variable 1	Influential Variable 2	Influential Variable 3
Fish Passage	DS	NA (see Tier 2 category)	F101	5550	0.867	0.916	0.36	-0.165	POINT_Y (13)	dist2Mouth (10.7)	FlowYr (8)
	Fish Passage	DS Passage Plan Study Design	F101010	5300	0.892	0.829	0.30	-0.309	POINT_Y (11.1)	dist2Mouth (9.9)	MAXELEVSMO (9.1)
	US	NA (see Tier 2 category)	F102	5250	0.899	0.896	0.29	-0.436	MAXELEVSMO (14.5)	POINT_Y (13)	bigPlyrSum (8.3)
	Fish Passage	Eelway	F102017	4350	0.956	0.966	0.33	*-1.178*	MAXELEVSMO (36.5)	POINT_X (11.9)	bigPlyrSum (7.7)
		US passage study plan or design	F102023	5000	0.909	0.854	0.29	*-0.703*	MAXELEVSMO (12.3)	POINT_X (10.5)	POINT_Y (9.7)
	Passage	NA (see Tier 2 category)	F103	2850	0.780	0.856	0.27	*-0.467*	POINT_Y (9.3)	dsDams (8.1)	MAXELEVSMO (7.5)
	Planning	DS fish passage mon. sampling	F103029	3200	0.888	0.924	0.22	*-0.908*	MAXELEVSMO (18.2)	Height (10)	POINT_X (8.9)
		Fish passage & operations plan	F103031	1050	0.739	0.749	0.08	-0.246	wshed_PC (11.8)	L_ROADLEN (10.5)	dsDams (9.9)
		Fish stranding plan mon. evaluation	F103033	1100	0.712	0.605	——		——	——	——
		US fish passage mon. sampling	F103036	3050	0.891	0.865	0.18	*-0.504*	MAXELEVSMO (16.2)	Height (11.9)	POINT_Y (8.7)
	Entrainment	NA (see Tier 2 category)	F104	3450	0.849	0.756	0.29	-0.222	ResDay (9.8)	SierG_PC (7.8)	politics (7)
		Trash or bar rack	F104043	3700	0.917	0.833	0.22	0.147	POINT_X (10.4)	SierG_PC (9.6)	fishGroups (8.8)
Hydrology	Flow	NA (see Tier 2 category)	F205	4700	0.785	0.787	0.56	*-1.413*	PrmryPurps (7.7)	N_URBANLC (5.3)	Height (5.1)
	Mitigation	Tailrace flow mon. plan	F205045	5850	0.822	0.920	0.39	-0.076	POINT_X (8.5)	IssueYear (4.8)	politics (4.7)
		Tailrace flow or stage mon. equipment	F205048	2650	0.784	0.867	0.17	-0.191	N_CROPSC (9)	Length (7.3)	dist2Mouth (4.7)
		Tailrace ramping rate restriction	F205050	2400	0.790	0.834	0.19	-0.333	SfArea (8.3)	CNPY_MEAN (5.9)	nidStorSum (5.8)
		Bypass flow mon. plan	F205052	2900	0.802	0.853	0.20	*-0.522*	politics (6.9)	Length (6.7)	SfArea (5.6)
		Bypass flushing or flood flow	F205054	3750	0.890	0.951	0.15	0.187	POINT_X (24.6)	N_PASTUREC (6.8)	PPT30MEAN (6.2)
		Bypass flow or stage mon. equipment	F205055	1500	0.735	0.779	0.13	*-0.679*	SLP_PERC (18)	POINT_X (7)	bigPlyrSum (5.2)
		Bypass ramping rate restriction	F205057	2900	0.878	0.802	0.16	0.170	POINT_X (28.6)	BFI_MEAN (6.7)	CNTC_MEAN (6.5)
	Tailrace	NA (see Tier 2 category)	F206	3800	0.863	0.845	0.63	-0.198	POINT_X (10.4)	Mode (10.3)	SLP_PERC (7.2)
	Minimum	Run-of-river Tailrace	F206058	3700	0.904	0.911	0.37	-0.349	Mode (39.2)	Height (7.8)	POINT_X (4.8)
	Flow	Seasonal Tailrace	F206059	2700	0.850	0.846	0.20	0.087	Mode (24.6)	POINT_Y (9.2)	N_PASTUREC (5.7)
		Year-round Tailrace	F206061	1500	0.787	0.899	0.19	-0.312	Mode (22.7)	owner (9.2)	Length (4.3)
	Bypass	NA (see Tier 2 category)	F207	3250	0.808	0.771	0.46	*-0.676*	SfArea (16.3)	MAXELEVSMO (6.6)	MAVELU (4.7)
	Minimum	Seasonal Bypass	F207063	1450	0.678	0.668	——		——	——	——
	Flow	Year-round Bypass	F207065	1200	0.720	0.805	0.23	-0.339	SfArea (15.6)	Height (10.2)	Length (6.9)
	Sediment	NA (see Tier 2 category)	F208	4850	0.767	0.851	0.49	-0.364	IssueYear (6.1)	CNPY_MEAN (5.3)	unemplymnt (4.6)
		Sediment & erosion control plan or mon.	F208066	4100	0.778	0.838	0.47	-0.257	IssueYear (6.6)	CNPY_MEAN (5)	dist2Mouth (4.9)
	Recreation	NA (see Tier 2 category)	F209	1550	0.733	0.796	0.17	-0.127	POINT_X (12.3)	Height (6.8)	SierG_PA (6.8)
	Flow	Provide recreational flow releases	F209071	700	0.655	0.713	——		——	——	——
	Operations	NA (see Tier 2 category)	F210	3050	0.734	0.819	0.53	0.040	FlowYr (8.6)	q16_avg (4.5)	N_URBANLC (4.5)
		Flow mgmt. plan	F210073	3350	0.893	0.985	0.09	-0.399	Length (13)	wshedG_PA (11.4)	IssueYear (8.6)
		Operations compliance mon. plan	F210074	5150	0.807	0.913	0.41	0.146	politics (8.8)	PrmryPurps (4.8)	FlowYr (4.7)
		Provide flow or lake levels electronically	F210075	1750	0.795	0.917	0.14	-0.282	SierG_PA (18.8)	POINT_X (6.2)	Mode (6.1)
Water Quality	DS	NA (see Tier 2 category)	F311	4300	0.838	0.887	0.55	-0.240	ResDay (12.3)	SfArea (6.8)	wshedG_PA (4.6)
	Water	Benthic macroinvertebrate mon.	F311077	1500	0.724	0.938	0.12	-0.396	BFI_MEAN (16.9)	unemplymnt (8.3)	POINT_X (7.8)
	Quality	DO enhancement or mitigation plan	F311078	2200	0.832	0.676	——		——	——	——
		Water quality mon. plan	F311086	6000	0.852	0.873	0.50	-0.375	ResDay (7.7)	SfArea (6.9)	IssueYear (5.1)
	US	NA (see Tier 2 category)	F312	4000	0.831	0.860	0.23	-0.320	unemplymnt (7.6)	POINT_Y (6.8)	N_PASTUREC (6.8)
	Water	Fish tissue sampling & analysis	F312087	4500	0.965	0.823	0.39	*-1.704*	unemplymnt (13.4)	wshedG_PA (9.7)	dist2Mouth (8.8)
	Quality	Impoundment sediment analysis	F312088	4100	0.993	0.999	0.19	0.334	wshedG_PA (21)	dist2Mouth (13.3)	unemplymnt (11.8)
		Inflow water quality mon. plan	F312090	1650	0.831	0.904	0.11	0.106	wshedG_PA (12.1)	KFACT (9.3)	Length (6)
		Impoundment water quaity mon. plan	F312091	4100	0.828	0.805	0.22	-0.166	N_PASTUREC (10)	unemplymnt (6.5)	CNTC_MEAN (5.6)
Biodiversity	Terrestrial	NA (see Tier 2 category)	F413	4150	0.847	0.832	0.64	*-0.638*	POINT_X (17.8)	SfArea (8.7)	Height (6.4)
		Noxious weed & invasive plant mgmt.	F413094	6650	0.912	0.901	0.39	0.068	POINT_X (13.8)	IssueYear (10.4)	PPT30MEAN (6.2)
		Species conservation mgmt. mon.	F413095	5850	0.832	0.899	0.40	-0.265	damRmvls (8.9)	Length (8.5)	Mode (6.7)
		T&E species protection plan	F413096	3950	0.879	0.905	0.21	*0.965*	L_POPDENS (12.5)	SLP_PERC (6.8)	SfArea (5.8)
		Transmission related avian & bat protection	F413097	6250	0.936	0.941	0.19	-0.109	PPT30MEAN (10.3)	POINT_X (9.7)	dsDams (7.5)
		Wildlife terrestrial habitat mgmt.	F413098	4100	0.844	0.937	0.27	0.146	FlowYr (6.3)	SfArea (5.6)	SierG_PC (5.2)
	Aquatic	NA (see Tier 2 category)	F414	3500	0.791	0.859	0.35	-0.271	FlowYr (11.1)	CNPY_MEAN (6.2)	PPT30MEAN (5.7)
		Aquatic species conservation mgmt. mon.	F414100	3400	0.807	0.869	0.34	-0.336	FlowYr (7.9)	POINT_X (7.1)	dist2Mouth (5.4)
		Diadromous species mgmt. mon.	F414101	3000	0.871	0.901	0.26	0.124	POINT_Y (22.1)	FlowYr (11.2)	PPT30MEAN (8.4)
		Invasive aquatic species mgmt.	F414102	2800	0.800	0.881	0.19	*0.552*	FlowYr (15.3)	L_POPDENS (6.4)	POINT_Y (6.2)
Habitat	Fisheries	NA (see Tier 2 category)	F515	2650	0.776	0.730	0.27	-0.038	POINT_X (8.5)	PPT30MEAN (7.4)	Length (5.6)
		DS habitat enhancement	F515105	1200	0.687	0.680	——		——	——	——
		DS woody debris restoration or passage	F515106	2850	0.863	0.879	0.25	0.071	POINT_Y (7.3)	Length (6.2)	damRmvls (5.5)
	Riparian	NA (see Tier 2 category)	F516	2600	0.771	0.869	0.28	0.084	L_POPDENS (8.6)	BFI_MEAN (7.8)	POINT_X (7.4)
		Establish riparian buffers	F516108	3100	0.866	0.864	0.25	*0.673*	Mode (10)	IssueYear (9)	MAVELU (6.5)
		Riparian habitat mon. or planning	F516110	2300	0.793	0.912	0.22	-0.368	L_POPDENS (8.1)	SierG_PA (7.4)	PPT30MEAN (7)
	Reservoir	NA (see Tier 2 category)	F517	6100	0.858	0.905	0.40	-0.082	ResDay (6.4)	IssueYear (5.8)	SfArea (5.4)
		Noxious invasive aquatic plant mgmt.	F517111	6950	0.928	0.952	0.25	*-0.348*	fishGroups (9.2)	IssueYear (7.6)	Length (4.9)
		Shoreline mgmt. plan or program	F517112	4800	0.856	0.952	0.27	0.192	POINT_Y (10.2)	SfArea (8.4)	Height (7.5)
	Wetlands	NA (see Tier 2 category)	F518	3800	0.828	0.874	0.19	0.207	SierG_PA (10.5)	POINT_Y (10.4)	L_POPDENS (5.4)
		Wetland protection	F518116	3500	0.878	0.875	0.14	0.082	POINT_Y (12.4)	Mode (8.5)	PPT30MEAN (6.6)
Recreation	Resources	NA (see Tier 2 category)	F619	3200	0.741	0.744	0.65	0.089	SfArea (10.6)	FlowYr (7.6)	Length (6.9)
	and	Boating facilities	F619118	1200	0.625	0.660	——		——	——	——
	Mitigation	Canoe portage launch	F619119	5000	0.859	0.773	0.37	-0.161	POINT_X (10.2)	dsDams (8)	N_DAMSC (6.7)
		Fishing pier	F619120	1700	0.797	0.869	0.13	0.055	N_DAMSC (18.3)	SfArea (10)	POINT_Y (8.2)
		Interpretive education sign & displays	F619123	1900	0.720	0.731	0.20	-0.192	MAVELU (7.3)	PPT30MEAN (7.3)	dist2Mouth (6.7)
		Parking	F619125	3550	0.715	0.722	0.32	0.441	MAXELEVSMO (13)	FlowYr (8.2)	ResDay (6.5)
		Shoreline access	F619128	750	0.623	0.759	——		——	——	——
		Stocking recreational fish species	F619129	1250	0.756	0.796	0.09	0.069	FlowYr (14)	PPT30MEAN (9.8)	Height (9.7)
		Trail trailhead or camping areas	F619130	3200	0.781	0.601	——		——	——	——
		Other day use area improvements	F619132	4900	0.750	0.781	0.44	-0.430	ResDay (8.5)	IssueYear (7.3)	PPT30MEAN (6.3)
	Planning	NA (see Tier 2 category)	F620	2450	0.753	0.883	0.74	-0.001	PrmryPurps (15.8)	SfArea (10.6)	Length (9.6)
		Recreational mgmt. plan study or mon.	F620131	2450	0.753	0.883	0.74	-0.001	PrmryPurps (15.8)	SfArea (10.6)	Length (9.6)

See Table 1 for variable descriptions; if no influential variables are shown, model rejected due to poor fit; mgmt. = management; DS = downstream; US = upstream; T&E = threatened and endangered, mon. = monitoring; NA = not applicable; CV ROC = internal cross-validation ROC; V ROC = validation ROC; OT = optimal threshold; MI = Moran's Index; italics indicates spatial autocorrelation detected in training data; color scheme for influential variables corresponds to Table 1 color scheme.

Fish passage (n=7)		
Variable	F	Inf
POINT_X	7	0.63
MAXELEVSMO	6	0.92
POINT_Y	4	0.67
bigPlyrSum	4	0.41
Height	3	0.58
dist2Mouth	3	0.57
dsDams	2	0.74
fishG_PC	2	0.39
FlowYr	2	0.33
wshed_PC	1	1.00
SierG_PC	1	0.92
L_ROADLEN	1	0.89
fishGroups	1	0.84
politics	1	0.74
PrmryPurps	1	0.62
SfArea	1	0.50
SLOPE	1	0.43
MAVELU	1	0.43

Hydrology (n=15)		
Variable	F	Inf
Mode	5	0.79
POINT_X	5	0.74
Length	4	0.81
SfArea	3	0.94
nidStorSum	3	0.64
Height	3	0.45
politics	2	1.00
IssueYear	2	0.83
CNPY_MEAN	2	0.73
N_PASTUREC	2	0.25
unemplymnt	2	0.22
SierG_PA	1	1.00
N_CROPSC	1	1.00
SLP_PERC	1	1.00
wshedG_PA	1	0.88
fishG_PC	1	0.63
owner	1	0.40
POINT_Y	1	0.37
FlowYr	1	0.33
bigPlyrSum	1	0.29
dist2Mouth	1	0.29
PPT30MEAN	1	0.25
BFI_MEAN	1	0.24
CNTC_MEAN	1	0.23
MAVELU	1	0.21
SierG_PC	1	0.19

Water quality (n=7)		
Variable	F	Inf
unemplymnt	4	0.68
wshedG_PA	3	0.91
BFI_MEAN	3	0.61
dist2Mouth	3	0.57
SierG_PC	3	0.41
SfArea	2	0.87
IssueYear	2	0.56
POINT_X	2	0.44
N_PASTUREC	1	1.00
N_DAMSC	1	1.00
ResDay	1	1.00
KFACT	1	0.76
POINT_Y	1	0.67
CNTC_MEAN	1	0.55
Length	1	0.50
damRmvls	1	0.44
Height	1	0.35

Biodiversity (n=8)		
Variable	F	Inf
FlowYr	4	0.88
PPT30MEAN	4	0.66
POINT_X	3	0.95
SfArea	3	0.57
L_POPDENS	2	0.71
POINT_Y	2	0.70
SLP_PERC	2	0.55
damRmvls	1	1.00
Length	1	0.95
SierG_PC	1	0.82
Mode	1	0.75
IssueYear	1	0.75
dsDams	1	0.73
PrmryPurps	1	0.70
dist2Mouth	1	0.69
Height	1	0.38

Habitat (n=6)		
Variable	F	Inf
POINT_Y	3	1.00
Mode	3	0.74
PPT30MEAN	3	0.64
IssueYear	2	0.86
fishG_PC	2	0.59
L_POPDENS	1	1.00
fishGroups	1	1.00
SierG_PA	1	0.91
Length	1	0.85
SfArea	1	0.82
damRmvls	1	0.75
Height	1	0.73
MAVELU	1	0.65
education	1	0.59
wshedG_PA	1	0.42
PrmryPurps	1	0.41

Recreation (n=10)		
Variable	F	Inf
FlowYr	7	0.72
PPT30MEAN	6	0.72
ResDay	5	0.59
MAXELEVSMO	4	0.80
Height	4	0.66
Length	4	0.66
dist2Mouth	4	0.65
SfArea	4	0.56
L_POPDENS	3	0.73
dsDams	3	0.54
MAVELU	2	0.84
N_DAMSC	2	0.83
IssueYear	2	0.77
SLOPE	2	0.72
POINT_X	2	0.70
POINT_Y	2	0.54
PrmryPurps	1	1.00
unemplymnt	1	0.48
Mode	1	0.47

Fig. 3. Explanatory variables with relative influence ≥5 for Tier 3 models, broken down by Tier 1 category. Relative influence normalized to 0 to 1 scale for each model; Inf = mean relative influence for a variable across all models in which relative influence ≥5; F = frequency, or number of times a variable had Inf ≥5; color scheme corresponds to Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

requirement with the environmental, economic, political, cultural, and social conditions that coalesce at a project and also underscores the need for further investigation into the causality of different drivers of mitigation.

While it is impractical to research causality for all specific mitigation requirements given the sheer number of different types, we identified several potential future research areas (Table 3) that warrant further investigation. One approach to prioritizing future research into mitigation requirement causality would be to delve further into the socio-political and environmental concerns of non-governmental organizations and environmental resource agencies regarding hydropower development, and how those concerns are manifest in prescribed mitigation. These

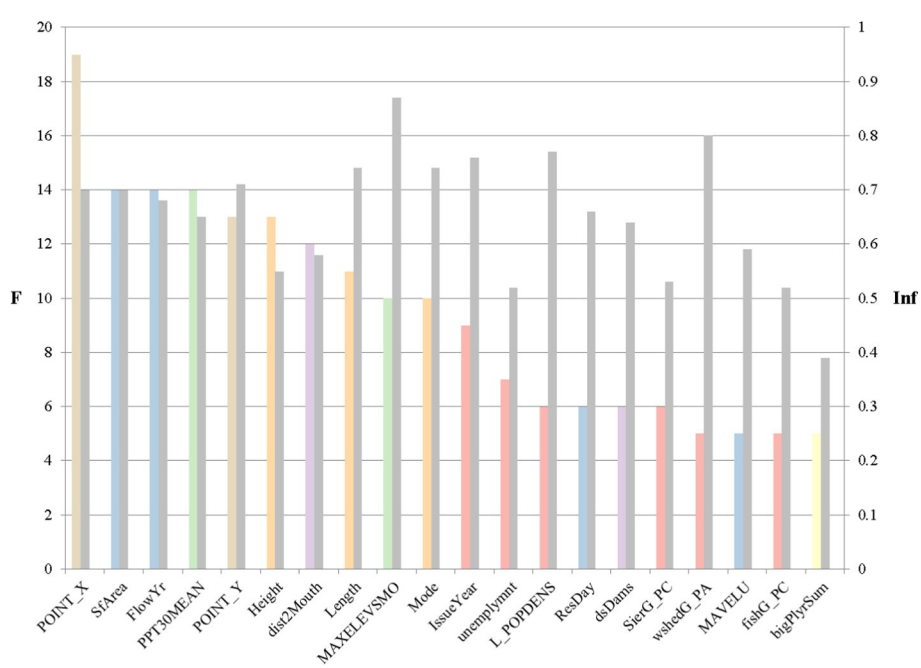


Fig. 4. The 20 most frequently occurring important variables across all Tier 3 models, sorted in descending order from left to right by frequency of occurrence. Colored bars present frequency, while grey bars present the normalized average relative influence for the variable across all of the models in which it was important. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
The 20 most frequently occurring important variables across all Tier 3 models, with potential future research areas that correspond to each variable. F = frequency; Inf = normalized average relative influence.

Variable	Category	F	Inf	Future research area
POINT_X	Location	19	0.70	Regional trends
SfArea	Hydrology	14	0.70	Hydrology/site design
FlowYr	Hydrology	14	0.68	Hydrology/site design
PPT30MEAN	Landscape	14	0.65	Hydrology/site design
POINT_Y	Location	13	0.71	Regional trends
Height	Facility	13	0.55	Hydrology/site design
dist2Mouth	Stream network	12	0.58	Network/landscape position
Length	Facility	11	0.74	Hydrology/site design
MAXELEVSMO	Landscape	10	0.87	Network/landscape position
Mode	Facility	10	0.74	Hydrology/site design
IssueYear	Human	9	0.76	Regulatory tendencies
unemplymnt	Human	7	0.52	Socio-political conditions
L_POPDENS	Human	6	0.77	Socio-political conditions
ResDay	Hydrology	6	0.66	Hydrology/site design
dsDams	Stream network	6	0.64	Network/landscape position
SierG_PC	Human	6	0.53	Socio-political conditions
wshedG_PA	Human	5	0.80	Socio-political conditions
MAVELU	Hydrology	5	0.59	Hydrology/site design
fishG_PC	Human	5	0.52	Socio-political conditions
bigPlyrSum	Biological	5	0.39	Fisheries

stakeholder groups have a powerful voice and are important to engage early and throughout the project development process if hydropower's contribution to the U.S. renewable energy portfolio is going to be optimized (Fu et al., 2014). A high-level review of The Nature Conservancy's Hydropower by Design strategy (The Nature Conservancy, 2015) and American Rivers Hydropower Reform Coalition platform (Hydropower Reform Coalition, 2016) reveals a common theme of maximizing hydropower sustainability through 1) careful selection of dam location within river networks to optimize both hydropower and conservation objectives, 2) implementing cumulative watershed-scale mitigation strategies, 3) reducing uncertainty and risk associated with project development by directing dam development away from environmentally and socially sensitive areas, and 4) improved outcomes for ecosystem services. Future research into the interplay between socio-political demographics, stream connectivity, ecosystem services, and watershed-scale mitigation approaches and their influence on project siting and ultimate success or failure could serve to catalyze future sustainable hydropower development in the 21st century (Crook et al., 2015; Fu et al., 2014; Karjalainen and Jarvikoski, 2010; Yu et al., 2016).

Another future direction of this research space is the inclusion of cost estimates for different mitigations, which could inform a cost-based approach for identifying priority mitigation types for future investigation of causality. Cost data would also provide a useful constraint for model predictions. Hydropower projects included in the mitigation database (Fig. 1) have a maximum number of 25 mitigation requirements (of the 49 that we modelled), while the model predictions to NPDs included as many as 34 mitigation requirements. Incorporating cost data would allow for additional realism to be integrated into the predictions by sequentially predicting mitigation types from most to least costly with a control on cost.

Our results should be interpreted with caution given that several models showed significant spatial autocorrelation. Since one of our goals was spatial prediction beyond the spatial extent of our dataset, we did not implement methods for accounting for spatial autocorrelation because previously developed methods do not allow for prediction beyond the dataset (Dormann et al., 2007; Rickbeil et al., 2014). We recognize that our models did not use an independent validation dataset, but rather a split of our original dataset. Since there is no comparable dataset available, we argue that our data split combined with tenfold internal cross-validation allowed for reliable evaluation of model performance to be made (Rickbeil et al., 2014).

The BRT models could potentially be improved by improving some of the more coarse resolution predictors – such as those derived at the state-scale – to represent a more refined local scale. A disconnect may exist between the spatial scale at which mitigation requirements are

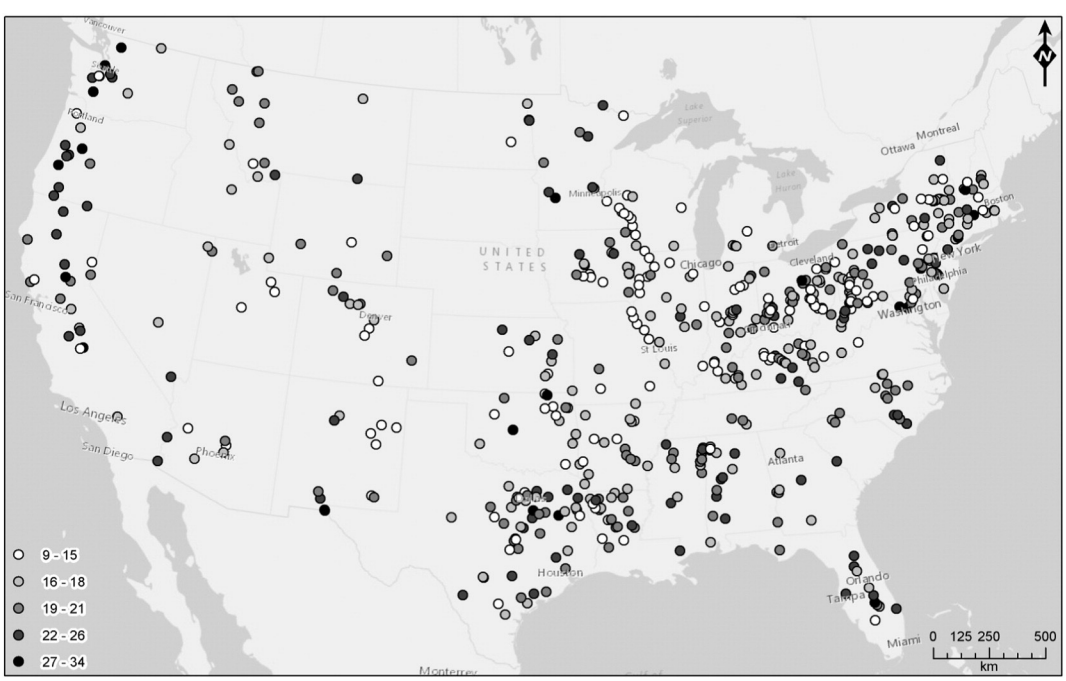


Fig. 5. Number of predicted Tier 3 mitigation requirements at NPDs with >1 MW energy potential.

ordered and the scale at which some of our explanatory variables are derived. This disparity of scales and varying resolution of predictors can affect the apparent importance of a predictor variable (Brewer et al., 2007). Schramm et al. (2016)described several possible limitations to the development of the mitigation database, which was limited to a review of mitigation prescribed explicitly in FERC licenses issued from 1998 to 2015. More specifically, some of the reviewed licenses were for relicensing of existing projects and thus may not include previously required mitigation under the original license. Also, FERC encourages the use of settlement agreements (legal agreements developed between hydropower developers, agencies, and other stakeholders on project operations and environmental conditions) that may include mitigation not included in the final license.

5. Conclusion

We demonstrated in this study an approach including specific statistical models that can be used by developers and regulators alike to identify and anticipate likely environmental mitigation at existing and proposed hydropower projects in the U.S. The results demonstrate that mitigation requirements in existing licenses have been a result of a range of factors from biological and hydrological to political and cultural. That such a range of variable types is needed to predict mitigation requirements explains much of the difficulty and uncertainty that surrounds the development of effective environmental mitigation during the licensing process in the U.S. Further research is needed to establish robust links between specific explanatory variables, mitigation requirements, and mitigation strategies. However, use of these models by developers can reduce uncertainty with regards to cost projections and inform decisions about project design. Regulators will be able to use the models to more quickly identify likely environmental issues and potential solutions, hopefully resulting in more timely and more effective decisions on environmental mitigation.

Acknowledgements

We would like to thank R. McManamay for statistical advice, suggestions for predictor variables, and valuable comments on this manuscript. We also thank S.C. Kao for assistance with the NHAAP database and FERC licenses. This study was funded by the U.S. Department of Energy (DOE) Energy Efficiency and Renewable Energy Office, Wind and Water Power Technologies Program through Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, for the DOE under contract DE-AC05-00OR22725.

Appendix A. Mitigation categories in the hierarchical database and percent of times each was required. Bold indicates that the model was fit for mitigation category

Tier 1	Tier 2	Tier 3	Model ID	Percent required
Fish passage	**–**	**–**	**FT**	**48.8%**
	Downstream fish passage	**–**	**FI01**	**24.9%**
		Surface collector	**FT01001**	**1.9%**
		Trap and transport	**FI01002**	**1.4%**
		Modification of spill or gate operation	**FT01003**	**3.3%**
		Sluiceway	**FI01004**	**0.4%**
		Bypass facility	**FT01005**	**2.1%**
		Conduit	**FI01006**	**1.2%**
		Fish friendly turbine	**F101007**	**0.2%**
		Generation shut down	**F101008**	**2.1%**
		Flashboard removal or modification	**FI01009**	**0.2%**
		Downstream passage plan study design	**F101010**	**15.5%**
		Modify spill or gate design	**F101011**	**2.7%**
		Modify sluiceway	**F101012**	**1.6%**
		Modify bypass facility	**F101013**	**0.2%**
		Modify intake	**F101014**	**0.2%**
	Upstream fish passage	**–**	**F102**	**19.4%**
		Adult fishway	**F102015**	**0.4%**
		Conduit	**F102016**	**0.2%**
		Eelway	**F102017**	**7.4%**
		Fish ladder	**FI02018**	**3.3%**
		Lock or elevator	**FI 02019**	**2.3%**
		Modify spill or gate operation	**FI02020**	**0.2%**
		Tailrace exclusion device	**FI02021**	**2.5%**
		Trap and transport	**FI02022**	**4.3%**
		Upstream passage study plan or design	**FI02023**	**12,2%**
		Modify adult fishway	**FI02024**	**0.2%**
		Modify fish ladder	**FI02025**	**0,8%**
		Modify lock or lift	**FI02026**	**0.2%**
		Modify trap and transport	**FI02027**	**0.6%**
	Passage planning	**–**	**F103**	**26.2%**
		Design plan entrainment avoidance system	**FI03028**	**1.6%**
		Downstream fish passage monitoring sampling	**F103029**	**13.6%**
		Entrainment or turbine mortality monitoring	**F103030**	**3.7%**
		Fish passage and operations plan	**FI03031**	**7.4%**
		Fish passage feasibility assessment	**FI03032**	**3.1%**
		Fish stranding plan monitoring evaluation	**FI03033**	**7.2%**
		Fisheries disease management	**FI03034**	**0.6%**
		Hatchery operations and management	**FI03035**	**1.9%**
		Upstream fish passage monitoring sampling	**FI03036**	**10.7%**
	Entrainment	**–**	**F104**	**23.9%**
		Barrier or guidance net	**FI04037**	**1.6%**
		Fish screen	**FI04038**	**4.3%**

(continued on next page)

Appendix A. *(continued)*

Tier 1	Tier 2	Tier 3	Model ID	Percent required
		Gatewell exclusion screen	FI04039	0.4%
		Perforated plate	FI04040	0.2%
		Solid panel and bar rack	FI04041	0.4%
		Strobe light	FI04042	0.2%
			FI 04043	17.1%
Hydrology	–	–	F2	95.1%
	Flow mitigation	–	F205	61.9%
		Tailrace adaptive flow management	F205044	1.6%
		Tailrace flow monitoring plan	F205045	34.0%
		Tailrace flow studies	F205046	3.5%
		Tailrace flushing or flood flows	F205047	1.9%
		Tailrace flow or stage monitoring equipment	F205048	14.2%
		Tailrace flow control device	F205049	2.7%
		Tailrace ramping rate restriction	F205050	11.1%
		Bypass adaptive flow management	F205051	1.9%
		Bypass flow monitoring plan	F205052	12.8%
		Bypass flow study	F205053	2.5%
		Bypass flushing or flood flow	F205054	5.6%
		Bypass flow or stage monitoring equipment	F205055	7.2%
		Bypass flow control device	F205056	0.8%
		Bypass ramping rate restriction	F205057	6.2%
	Tailrace minimum flow	–	F206	64.5%
		Run-of-river tailrace	F206058	39.0%
		Seasonal tailrace	F206059	13.6%
		Seasonal and type of year tailrace	F206060	1.6%
		Year-round tailrace	F206061	10.3%
	Bypass minimum flow	–	F207	41.9%
		Seasonal bypass	F207063	17.1%
		Seasonal and type of year bypass	F207064	4.5%
		Year-round bypass	F207065	20.2%
	Sediment	–	F208	42.9%
		Sediment and erosion control plan or monitoring	F208066	41.6%
		Dredging	F208067	0.2%
		Install or operate gate to flush sediment	F208068	0.8%
		Sediment flushing flows	F208069	0.8%
	Recreation flow	–	F209	13.2%
		Maintain recreational lake levels	F209070	3.3%
		Provide recreational flow releases or structures	F209071	9.7%
		Recreational flow studies	F209072	4.1%
	Operations	–	F210	54.8%
		Flow management plan	F210073	6.6%
		Operations compliance monitoring plan	F210074	40.6%
		Provide flow or lake levels electronically	F210075	10.7%
Water quality	–	–	F3	53.7%
	Downstream water quality	–	F311	54.0%
		Adaptive water quality management	F3I1076	3.7%
		Benthic macroinvertebrate monitoring	F3I1077	5.4%
		DO enhancement or mitigation plan	F3I1078	5.4%
		Establish or fund water quality stations and stream gages	F311079	3.3%
		Forebay aeration	F311080	0.2%
		Operational changes	F311081	2.7%
		Powerhouse aeration	F311082	2.1%
		Tailrace structures for aeration	F311083	0.2%
		Temperature regulating device or structure	F311084	0.6%
		Temperature regulation or mitigation plan	F3U085	0.4%
		Water quality monitoring plan	F311086	50.3%
	Upstream water quality	–	F312	24.5%
		Fish tissue sampling and analysis	F312087	8.2%
		Impoundment sediment analysis	F312088	6.4%
		Macroinvertebrate monitoring	F312089	0.6%
		Inflow water quality monitoring plan	F312090	8.9%
		Impoundment water quality monitoring plan	F3I2091	17.3%
Biodiversity	–	–	*F4*	71.4%
	Terrestrial	–	F4I3	66.6%
		Acquisition easements conservation or important habitat	F413092	4.1%
		Install upgrade monitor wildlife crossings	F413093	4.1%
		Noxious terrestrial weed and invasive plant management	F4I3094	25.6%
		Species conservation management monitoring	F4I3095	42.9%
		Threatened and endangered species protection plan	F4I3096	10.9%
		Transmission related avian and bat protection	F4I3097	15.5%
		Wildlife terrestrial habitat management	F4I3098	27.0%
	Aquatic	–	F4I4	35.5%
		Adaptive fishery management	F414099	3.9%
		Aquatic species conservation management monitoring	F4I4100	25.6%
		Diadromous species management monitoring	F4I4101	7.4%
		Invasive aquatic species management (fish and mollusks)	F414102	9,3%

Appendix A. *(continued)*

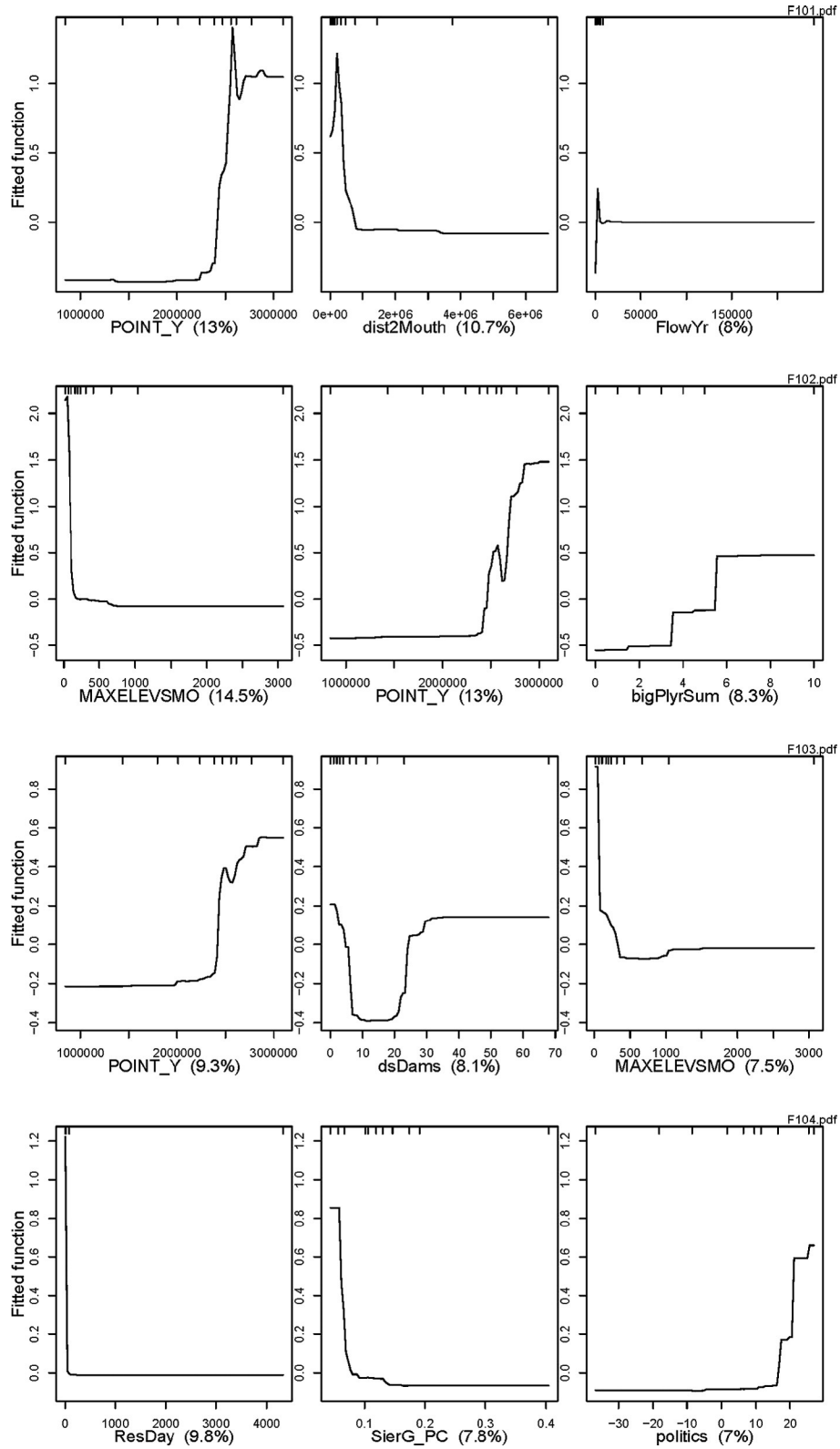
Tier 1	Tier 2	Tier 3	Model ID	Percent required
		Stocking fish species of concern	F414103	4.5%
Habitat	–	–	F5	57.1%
	Fisheries	–	F515	26.8%
		Downstream gravel and sediment restoration	F515104	4.5%
		Downstream habitat enhancement	F515105	8.7%
		Downstream woody debris restoration or passage	F515106	15.9%
		Reservoir fishery habitat enhancement	F515133	3.3%
	Riparian	–	F516	20.4%
		Dust control and abatement	F516107	0.6%
		Establish riparian buffers	F516108	7,2%
		Riparian habitat enhancement	F516109	4.7%
		Riparian habitat monitoring or planning	F516110	12,0%
	Reservoir	–	F517	31.8%
		Noxious invasive aquatic plant management	F517111	21.0%
		Shoreline management plan or program	F517112	16.1%
	Wetlands	–	F518	11.5%
		Wetland enhancement	F518113	0.8%
		Wetland mitigation	F518114	4.9%
		Wetland monitoring	F518115	2.9%
		Wetland protection	F518116	6.8%
Recreation	–	–	F6	82.3%
	Resources and mitigation	–	F619	66.2%
		Appoint historic cultural resource coordinator	F619117	0.4%
		Boating facilities	F619118	23.1%
		Canoe portage launch	F619119	24.1%
		Fishing pier	F619120	8.9%
		Floating debris removal	F619121	1.0%
		Install fish attracting structure for recreational fishing	F619122	2.7%
		Interpretive education sign and displays	F619123	15.5%
		Navigational aids and improvements	F619124	1.0%
		Parking	F619125	26.4%
		Protection of specific historic cultural resource sites	F619126	3.3%
		Public outreach education programs	F619127	0.6%
		Shoreline access	F619128	17.9%
		Stocking recreational fish species	F6I9129	6.6%
		Trail trailhead or camping areas	F619130	14.2%
		Other day use area improvements	F619132	35.3%
	Planning	–	F620	72.8%
		Recreational management plan study or monitoring	F620131	72.8%

Appendix B. Partial dependence plots for the three variables with the highest relative influence for each Tier 2 and Tier 3 model with an internal CV ROC and independent ROC ≥0.7

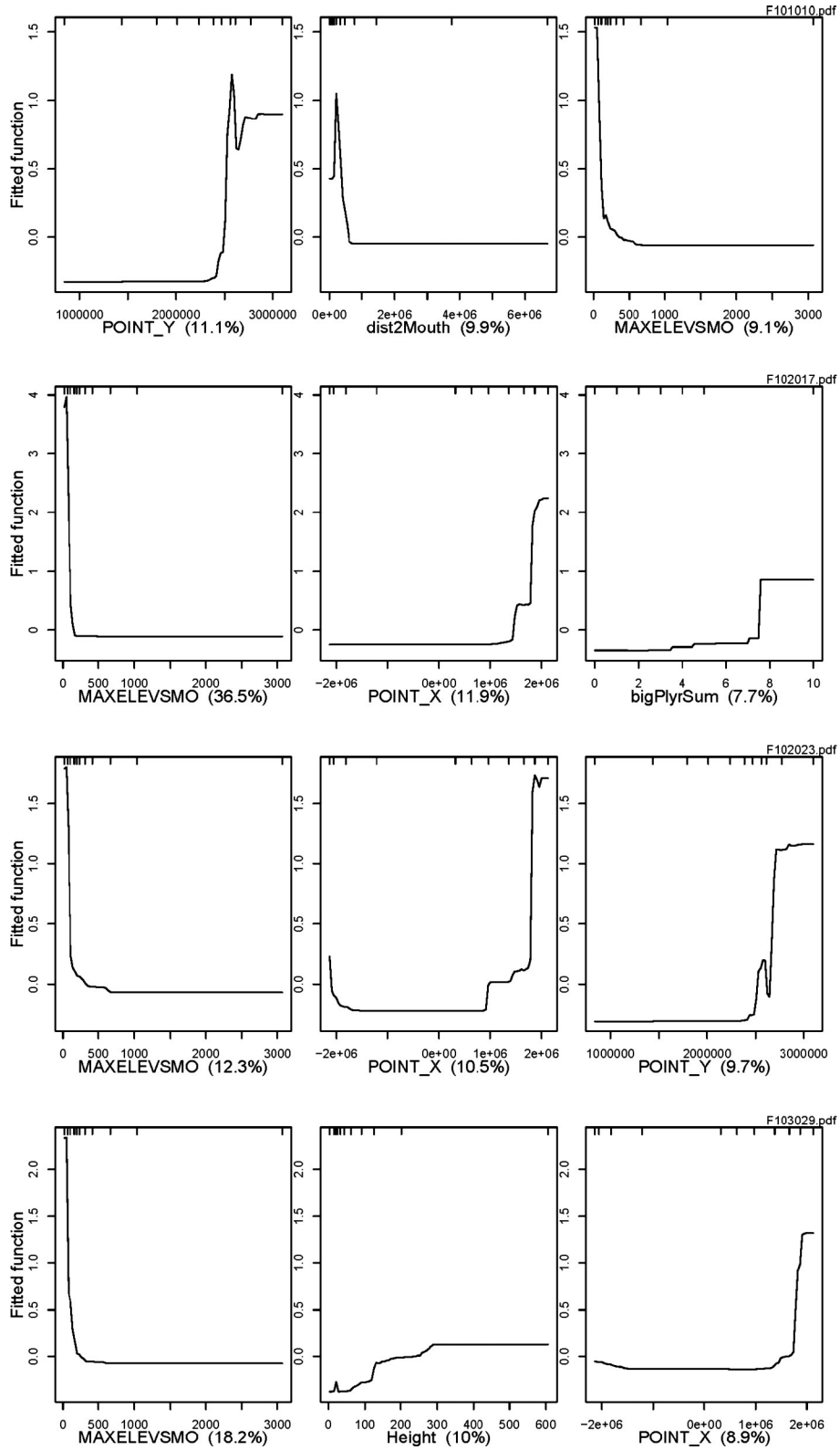
Notes: the Model ID for each model is shown in the upper-right hand corner of each set of three partial dependence plots; see Table 1 for variable descriptions; see Table 2 for details on mitigation types; ticks across the top of each plot show the distribution of deciles for each predictor variable.

Definitions for categorical variables

Mode	Value
Canal/conduit	C
Intermediate peaking	I
Peaking	P
Pumped storage	S
Reregulating	R
Run-of-river	O
Run-of-river/peaking	A
Run-of-river/upstream peaking	B
Owner	**Value**
Cooperative	C
Private	P
Public	U
Wholesale power marketer	W
PrmryPurps	**Value**
Flood control and stormwater management	C
Fish and wildlife pond	F
Hydroelectric	H
Irrigation	I
Navigation	N
Other	O
Recreation	R
Water supply	S



Tier 2. Fish passage.



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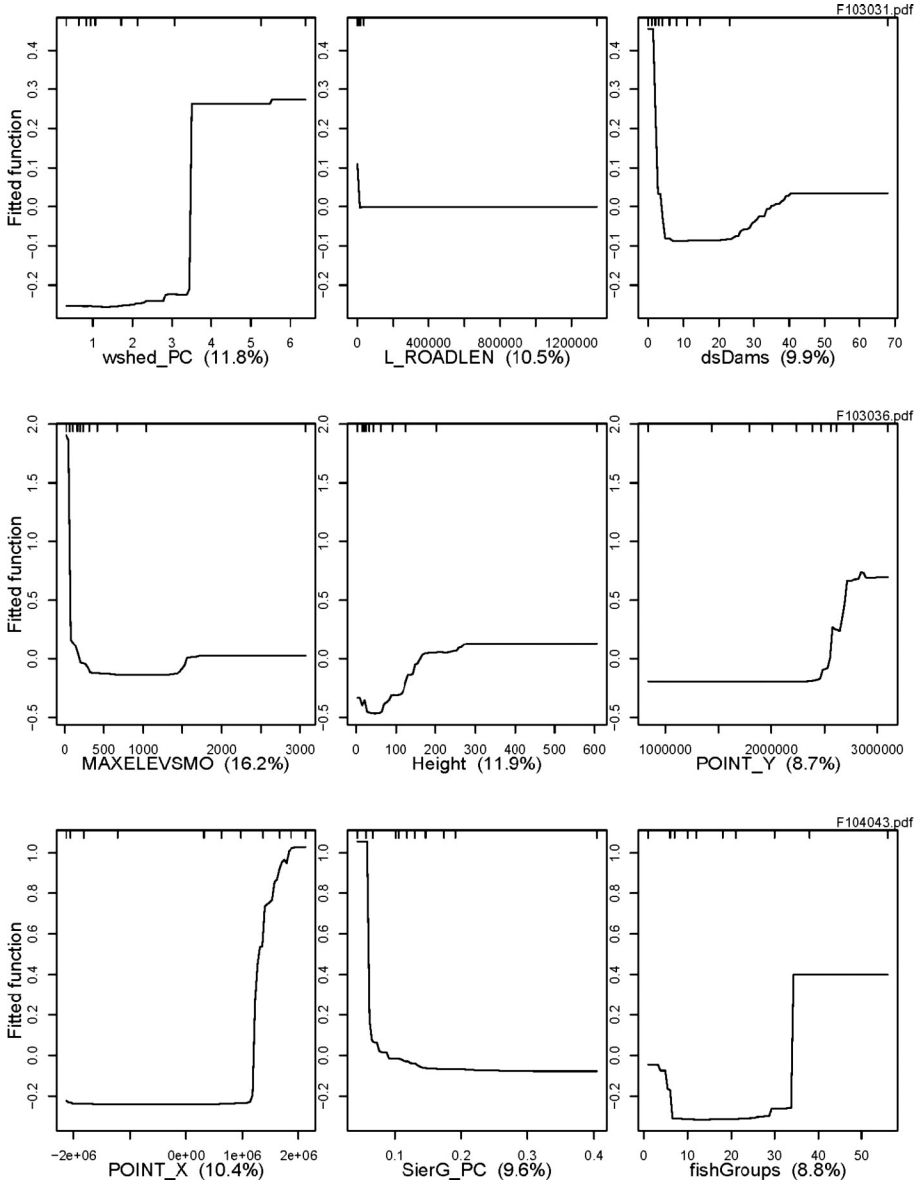

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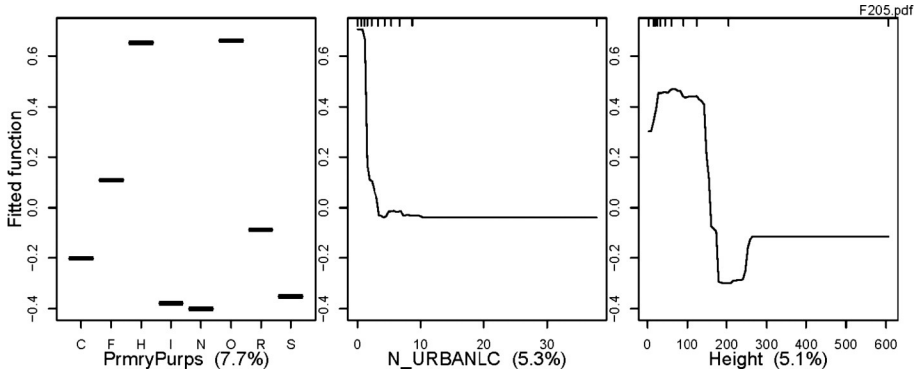
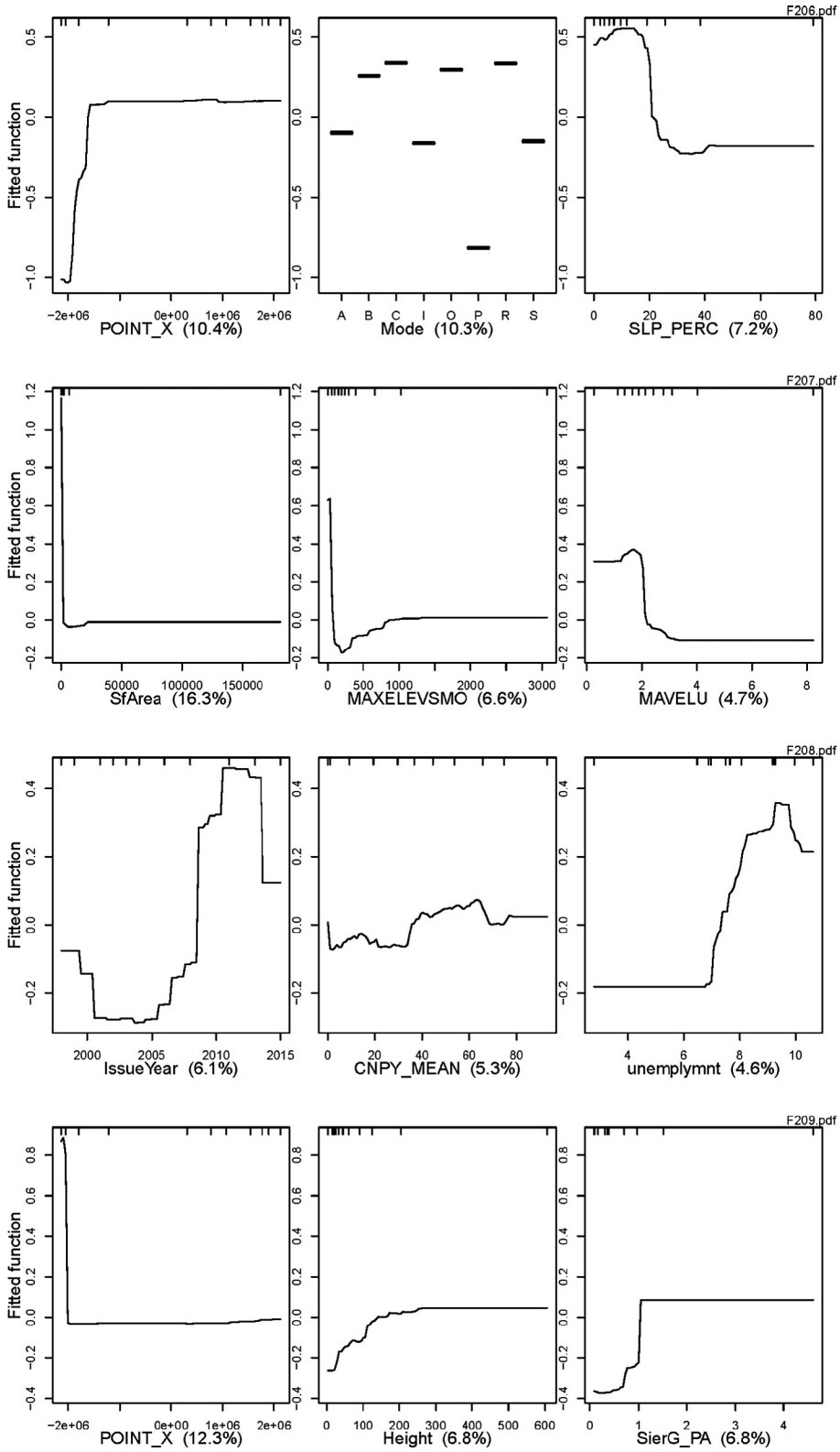


Tier 2. Hydrology.



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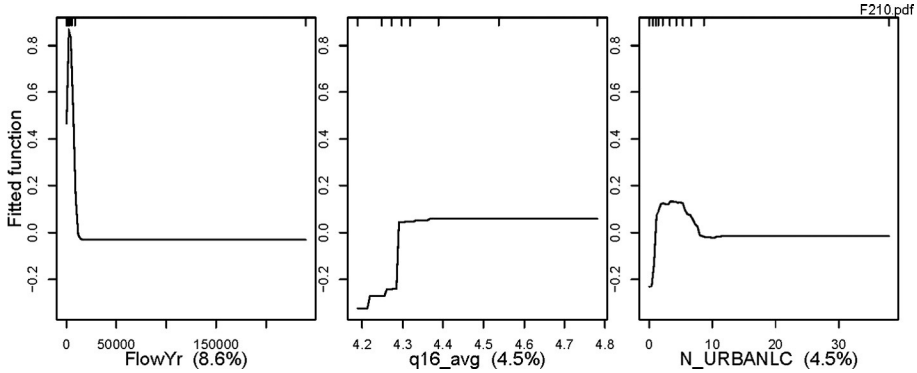

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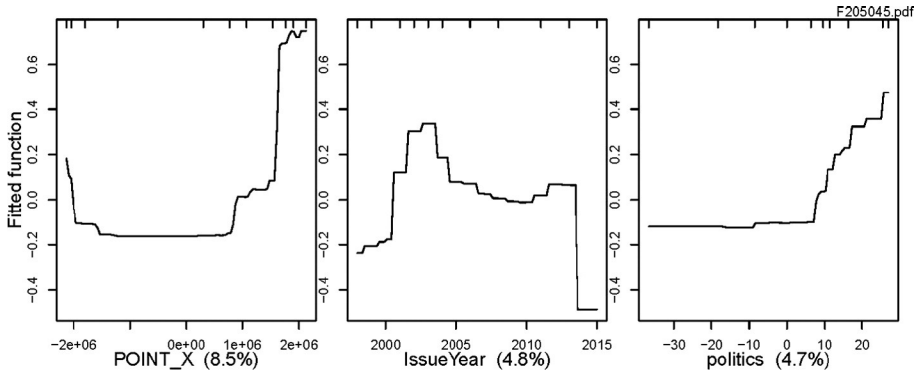

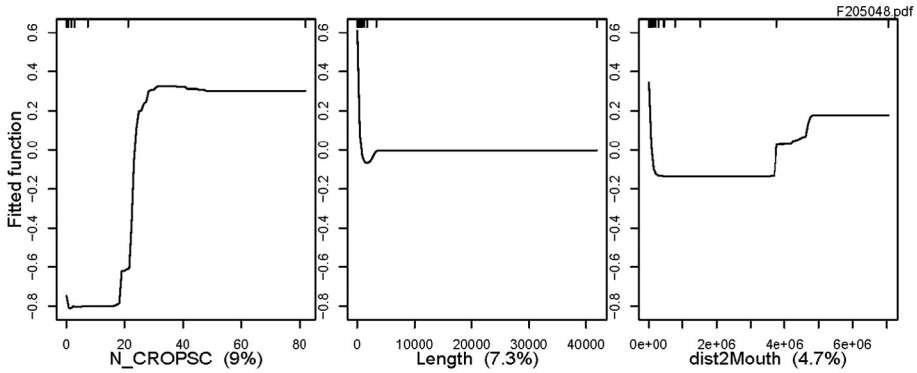

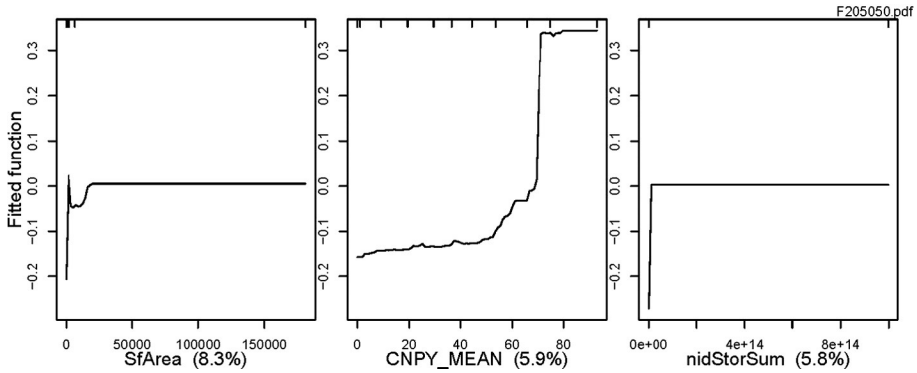

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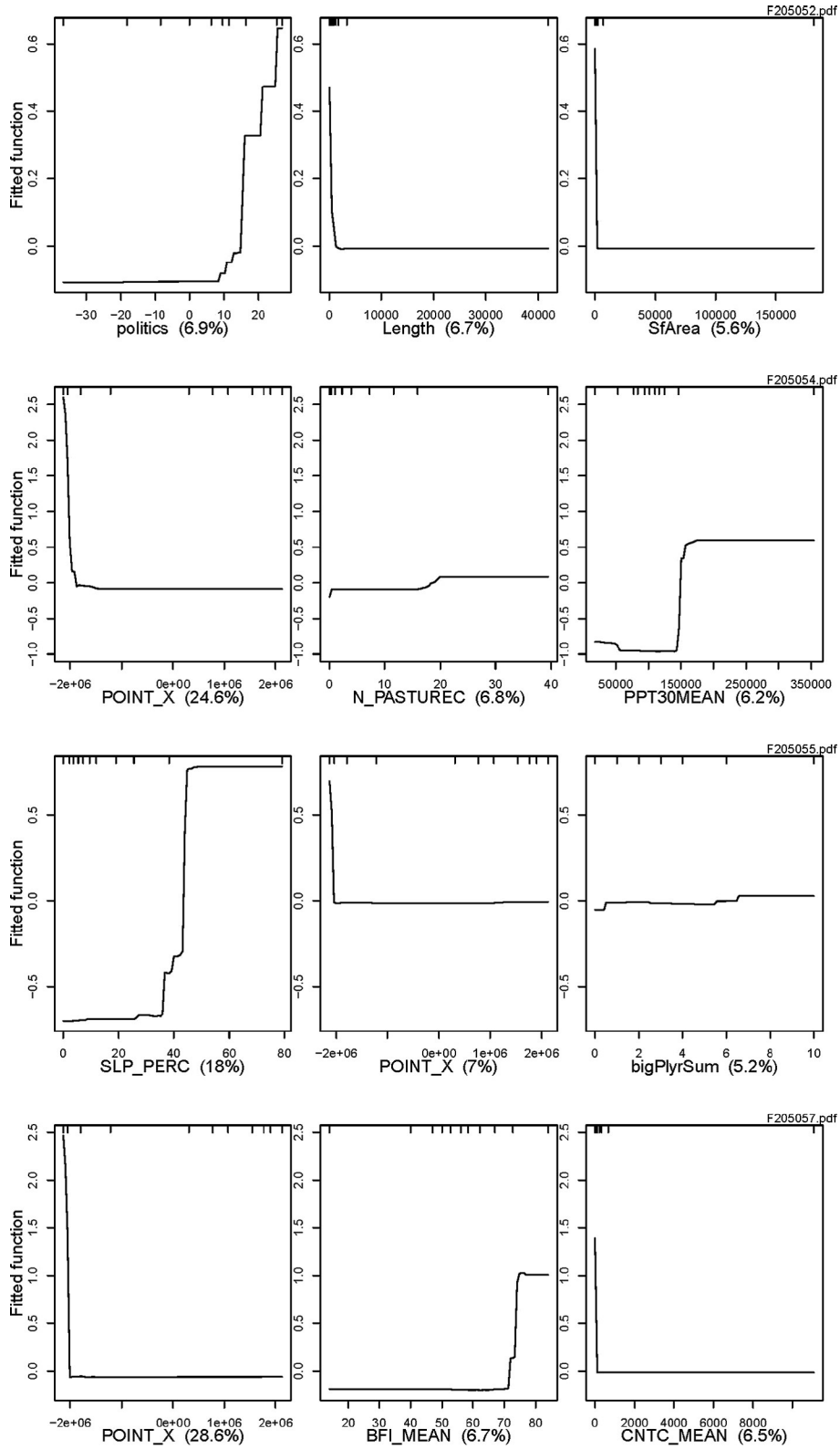

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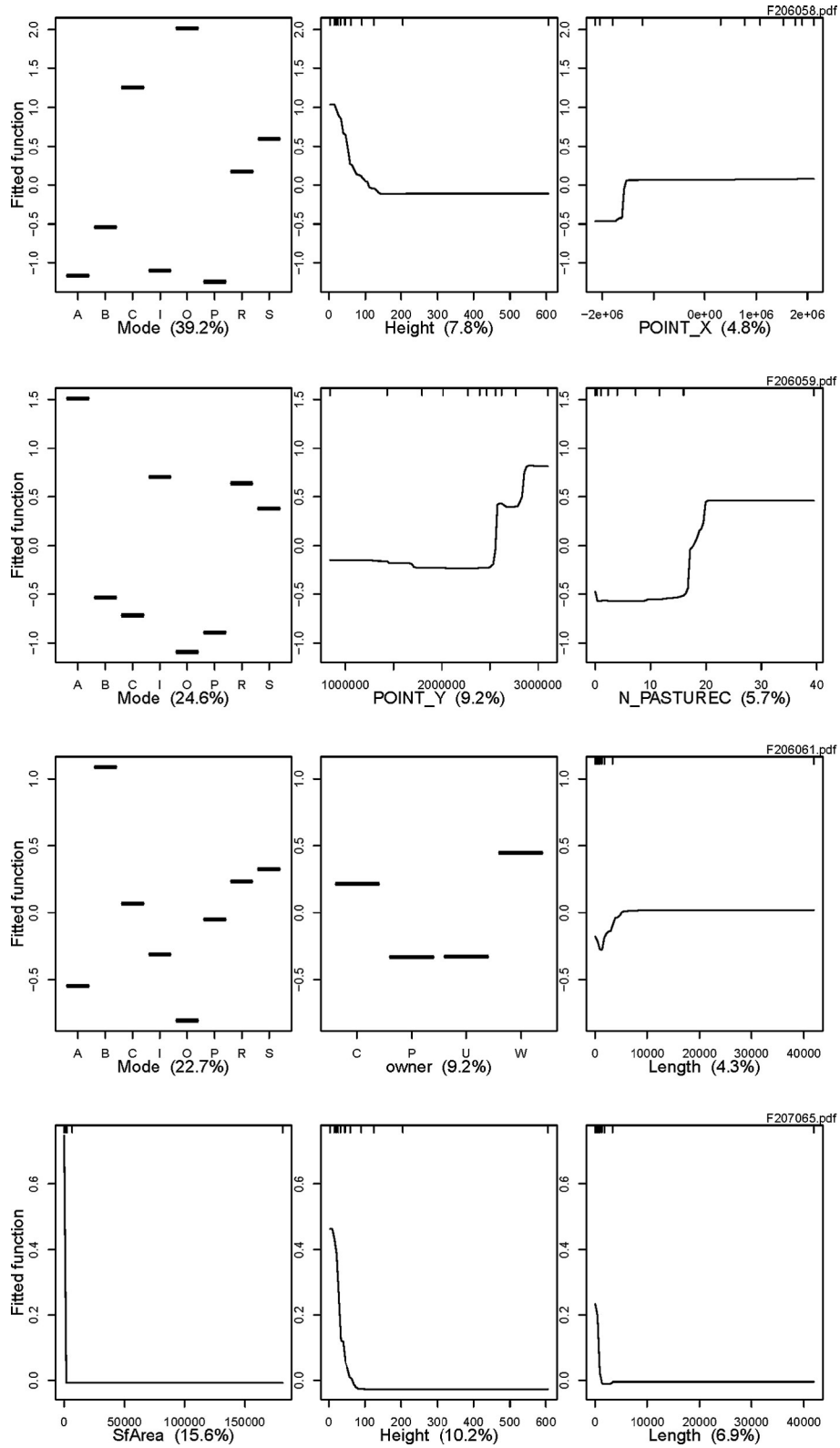

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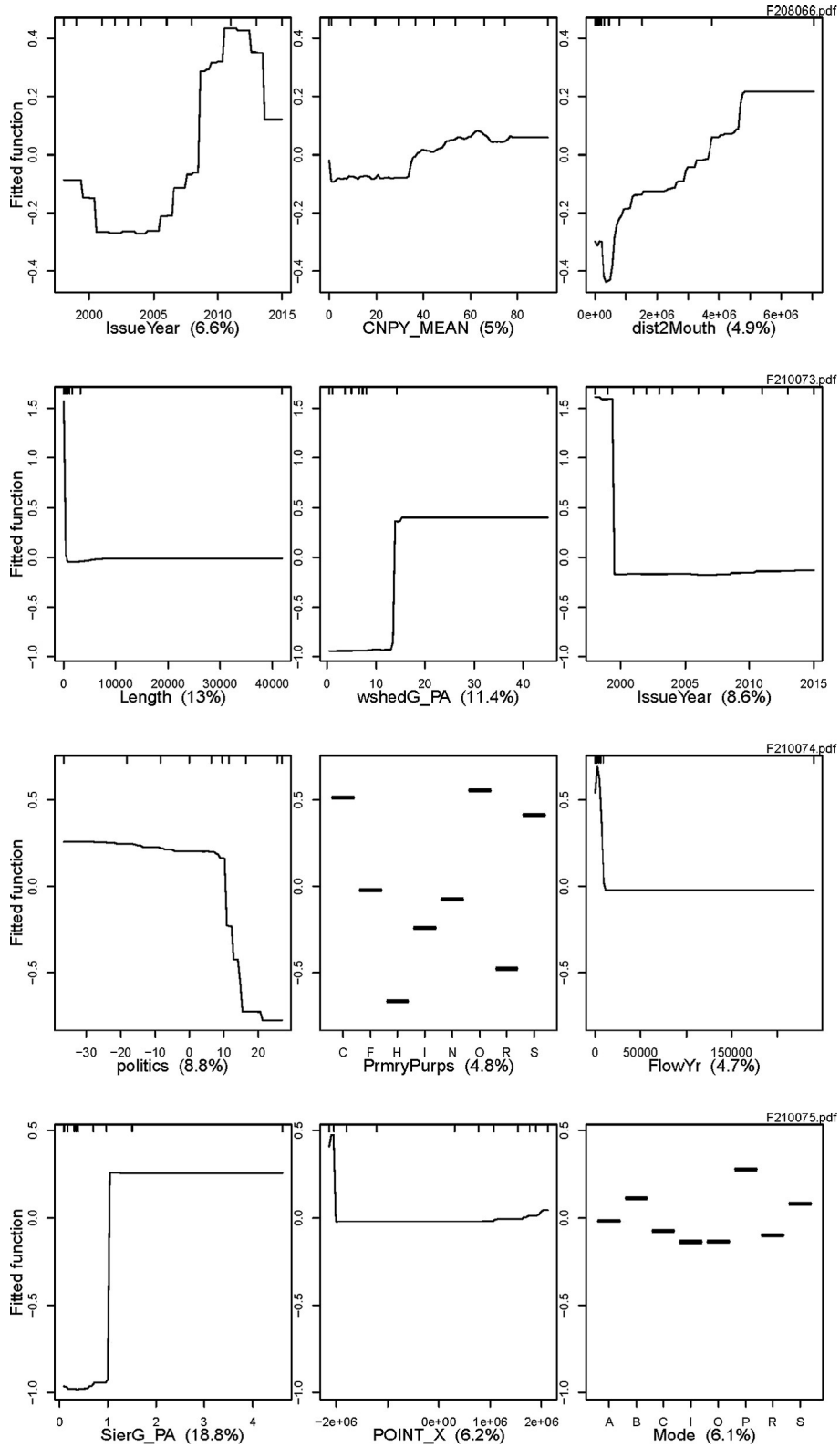

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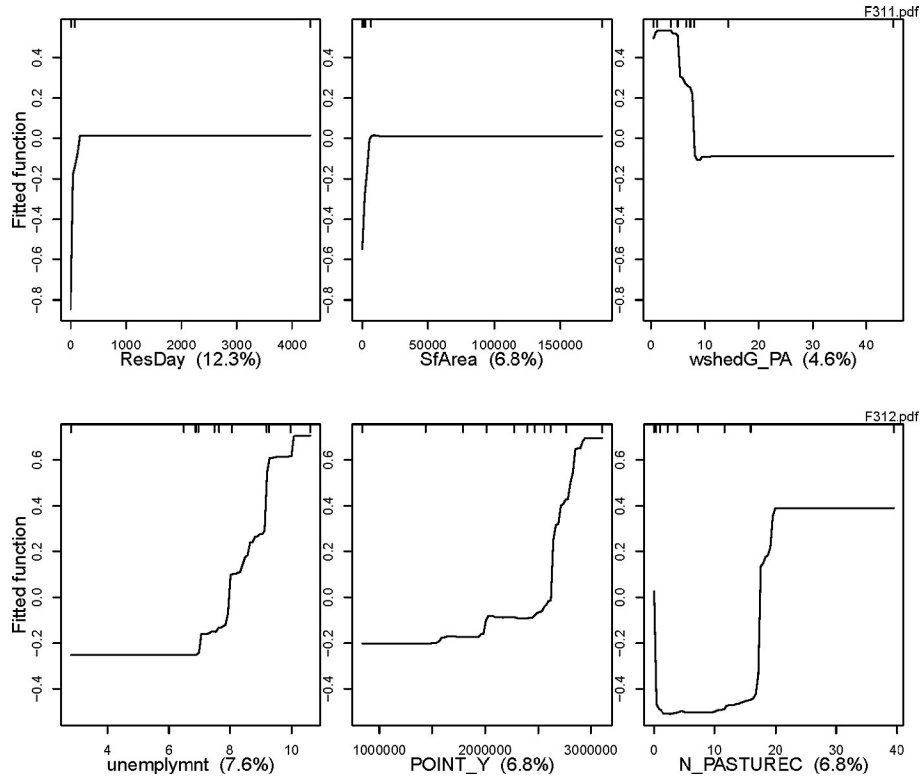

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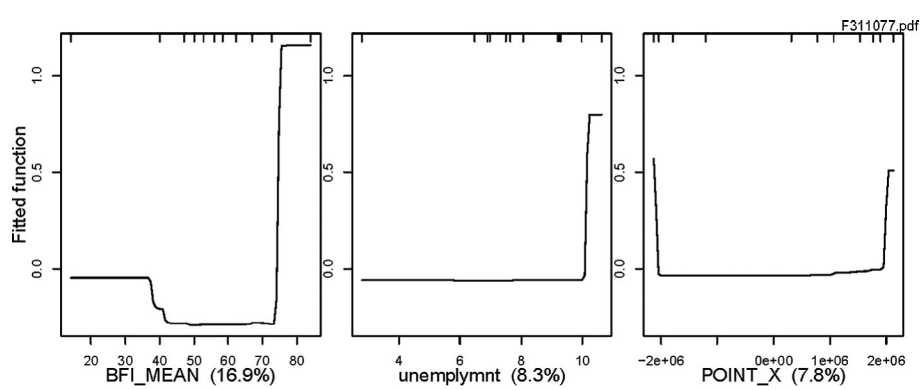

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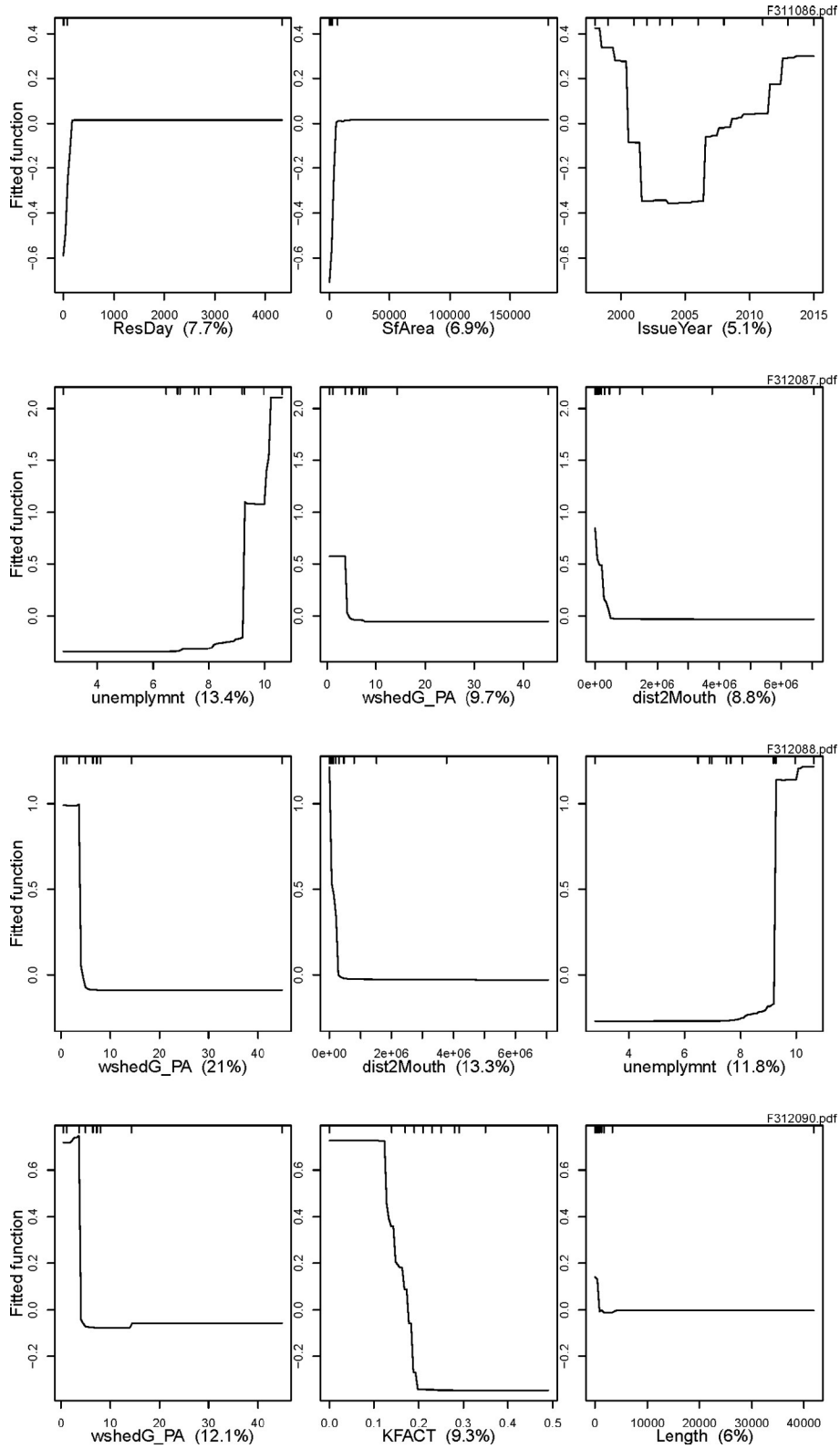

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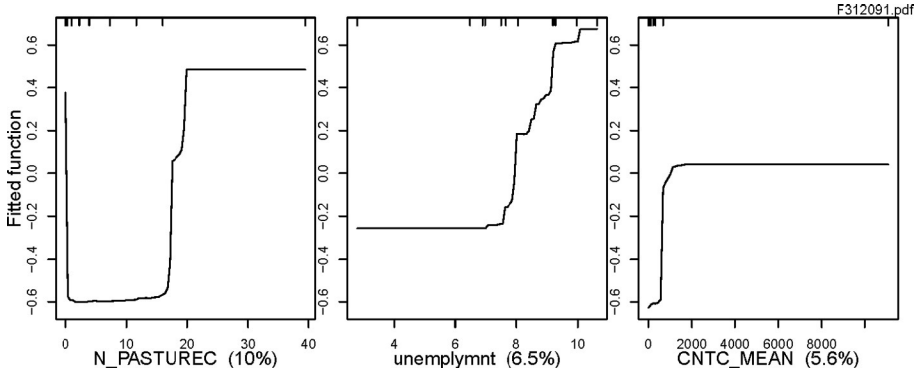

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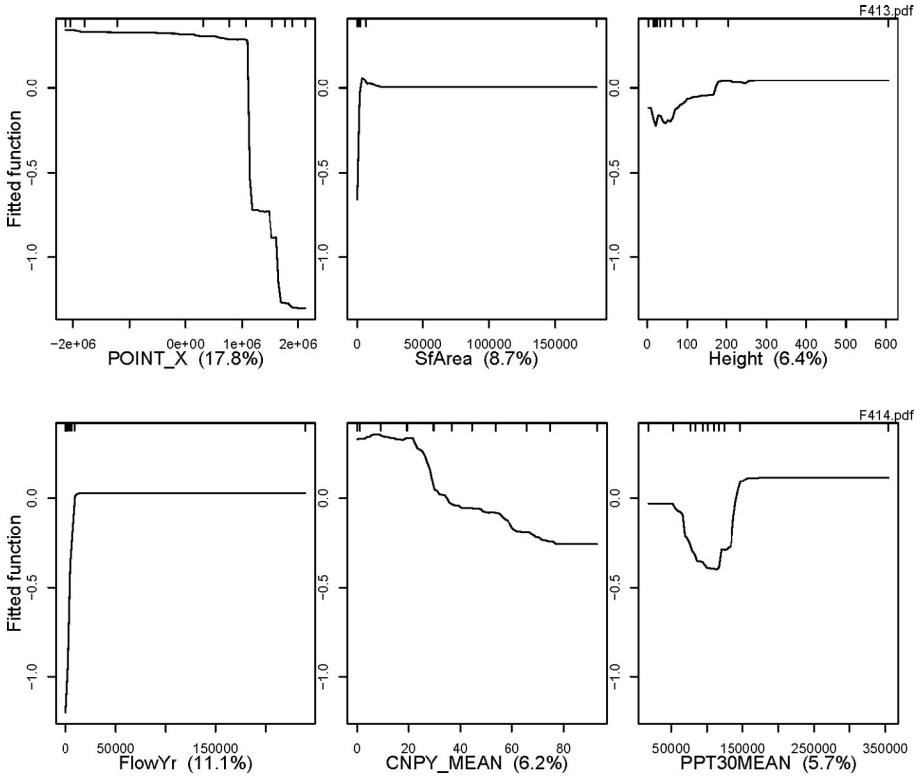

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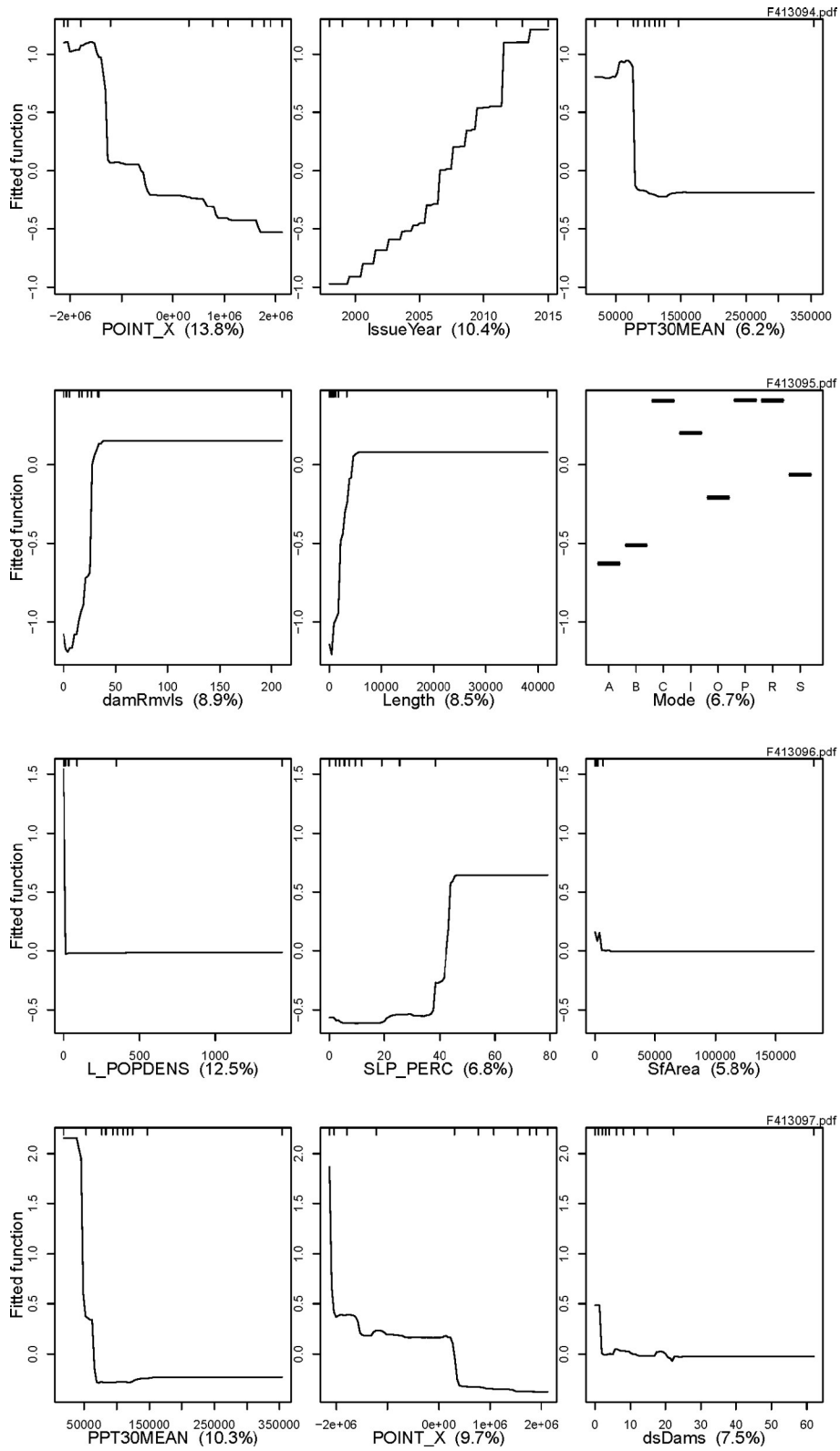

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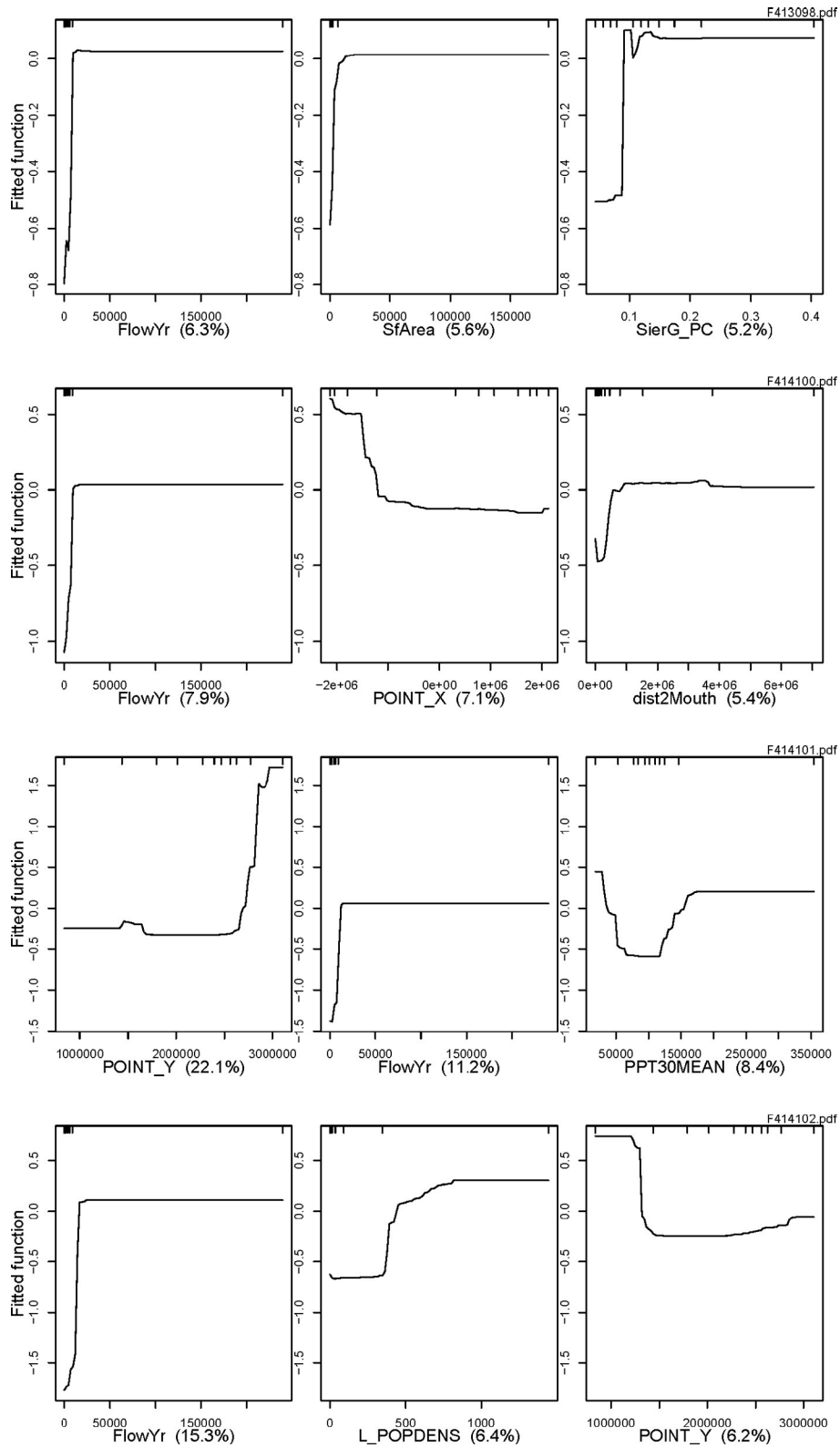

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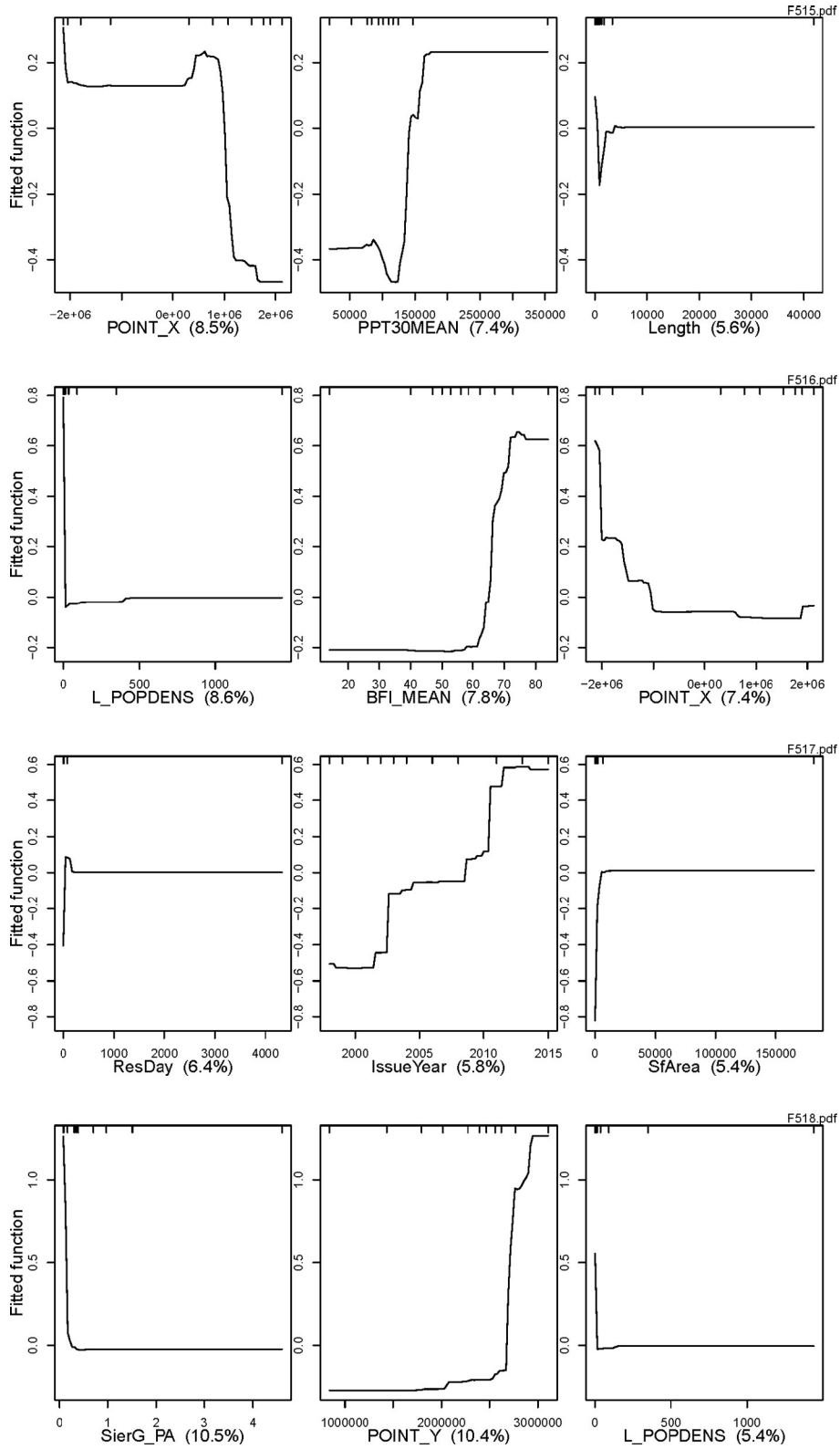

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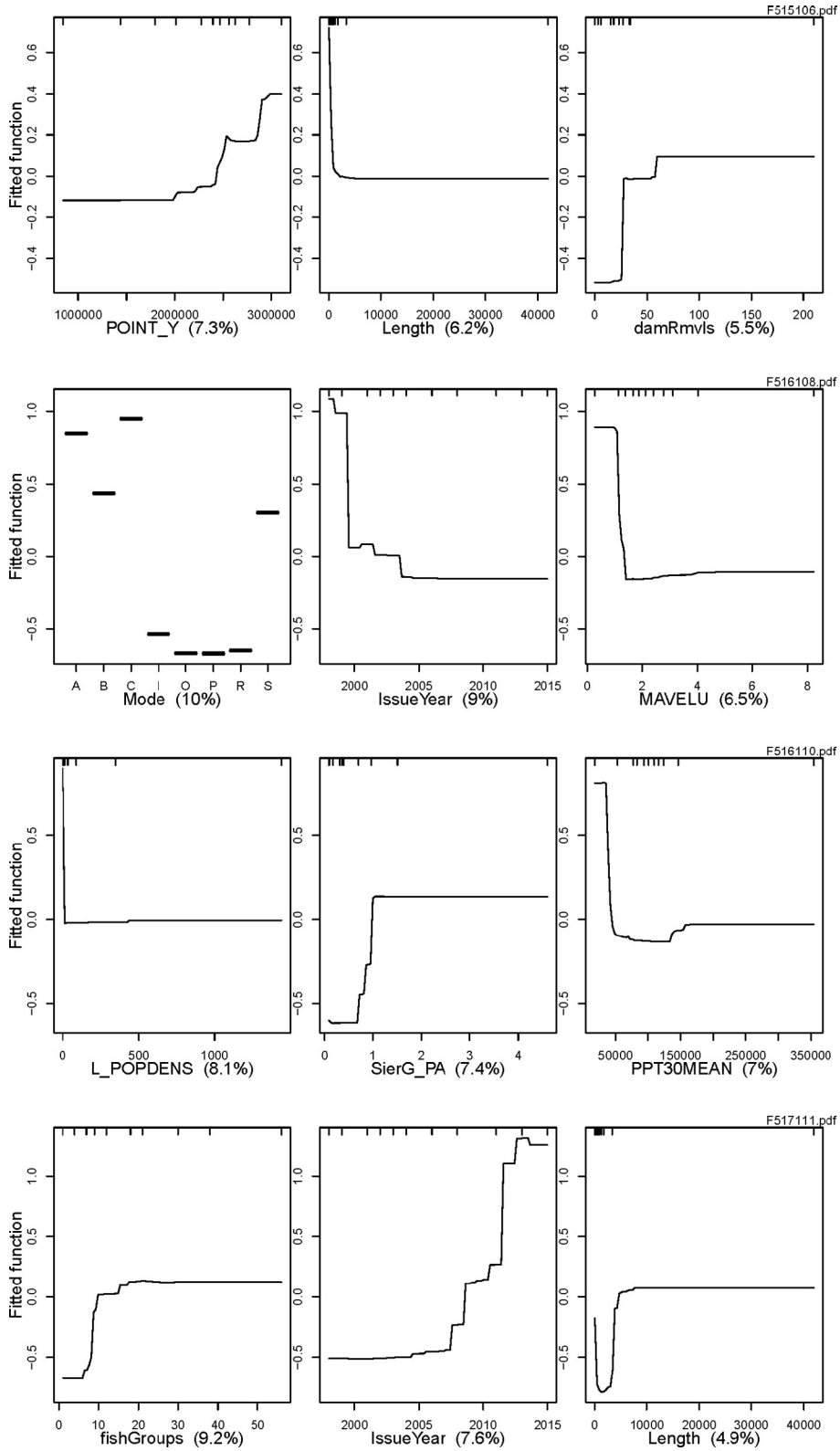

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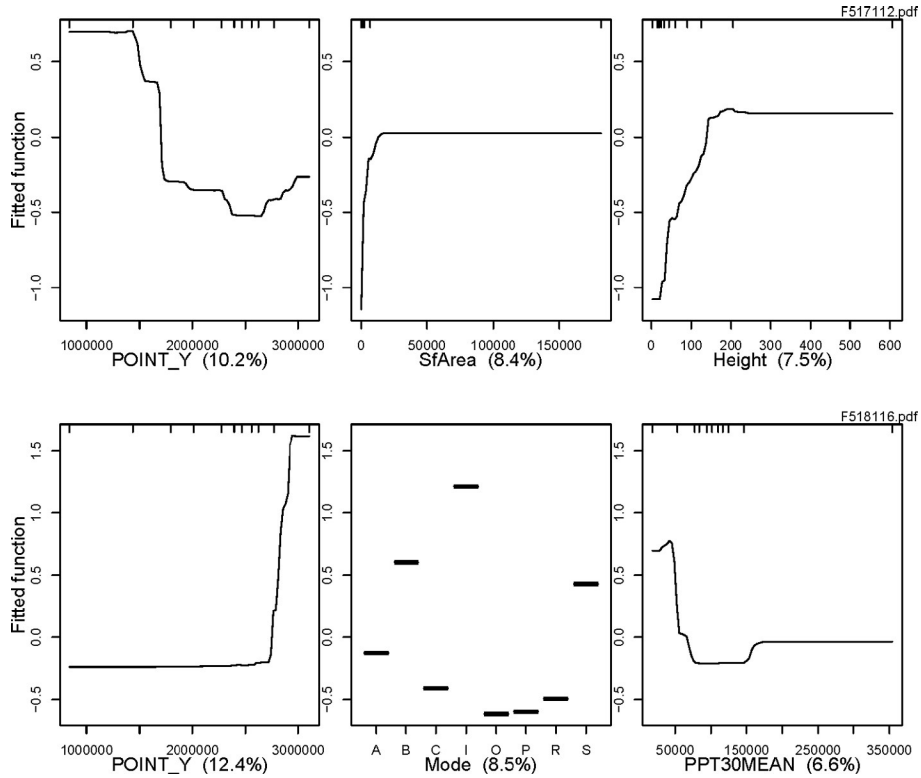

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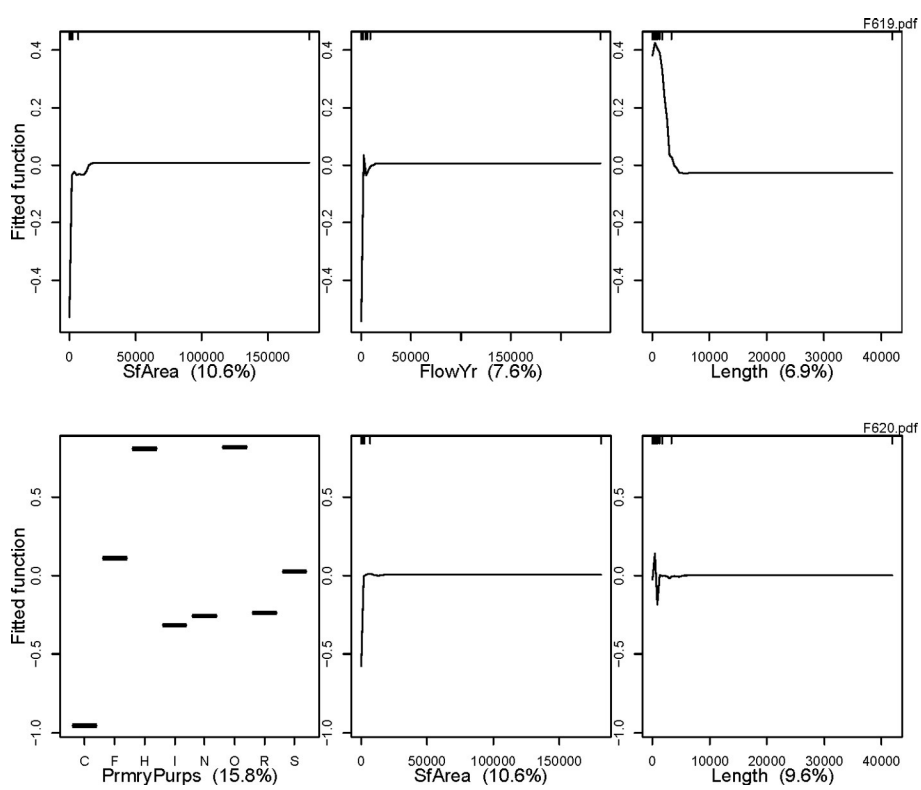

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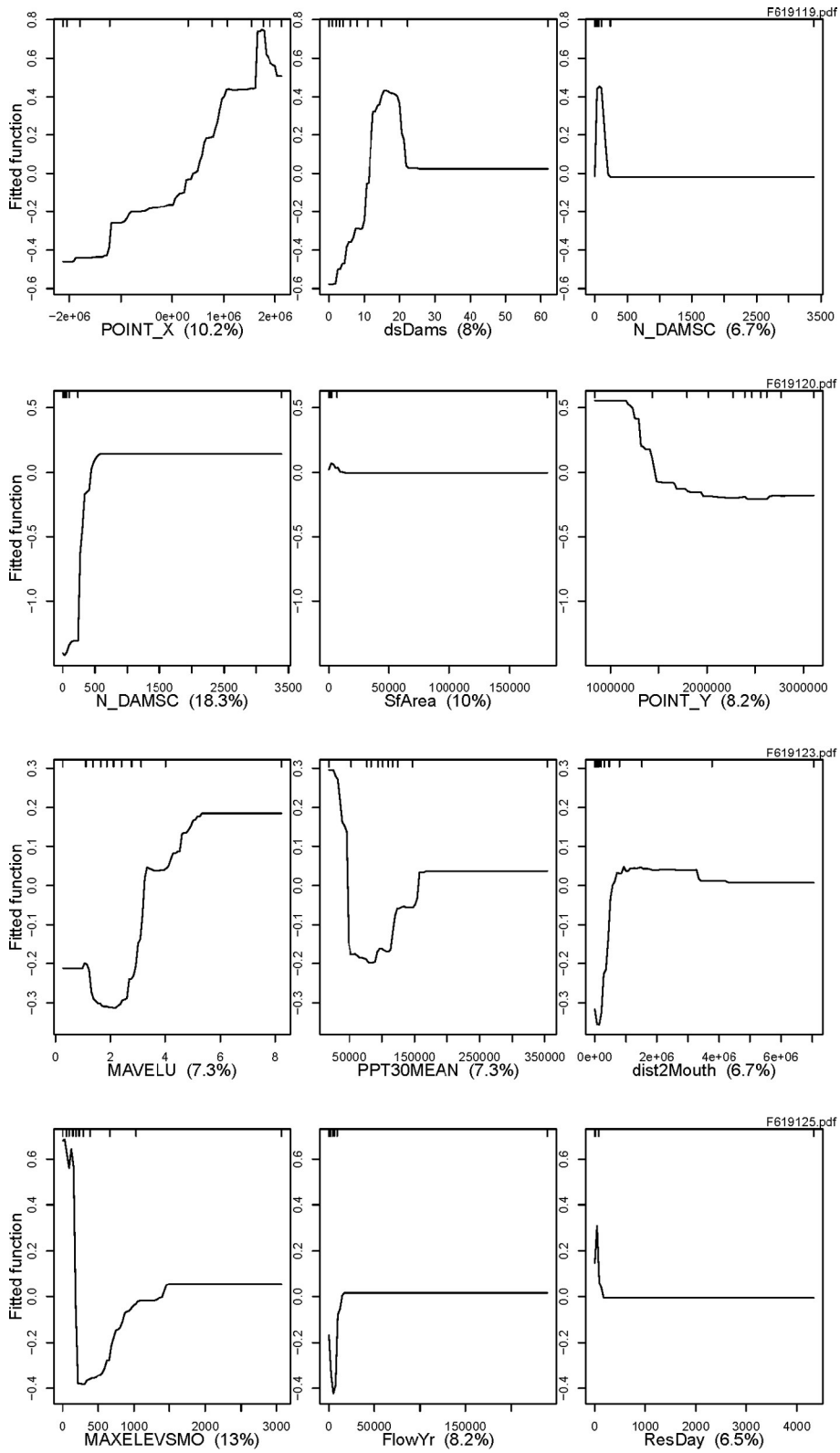

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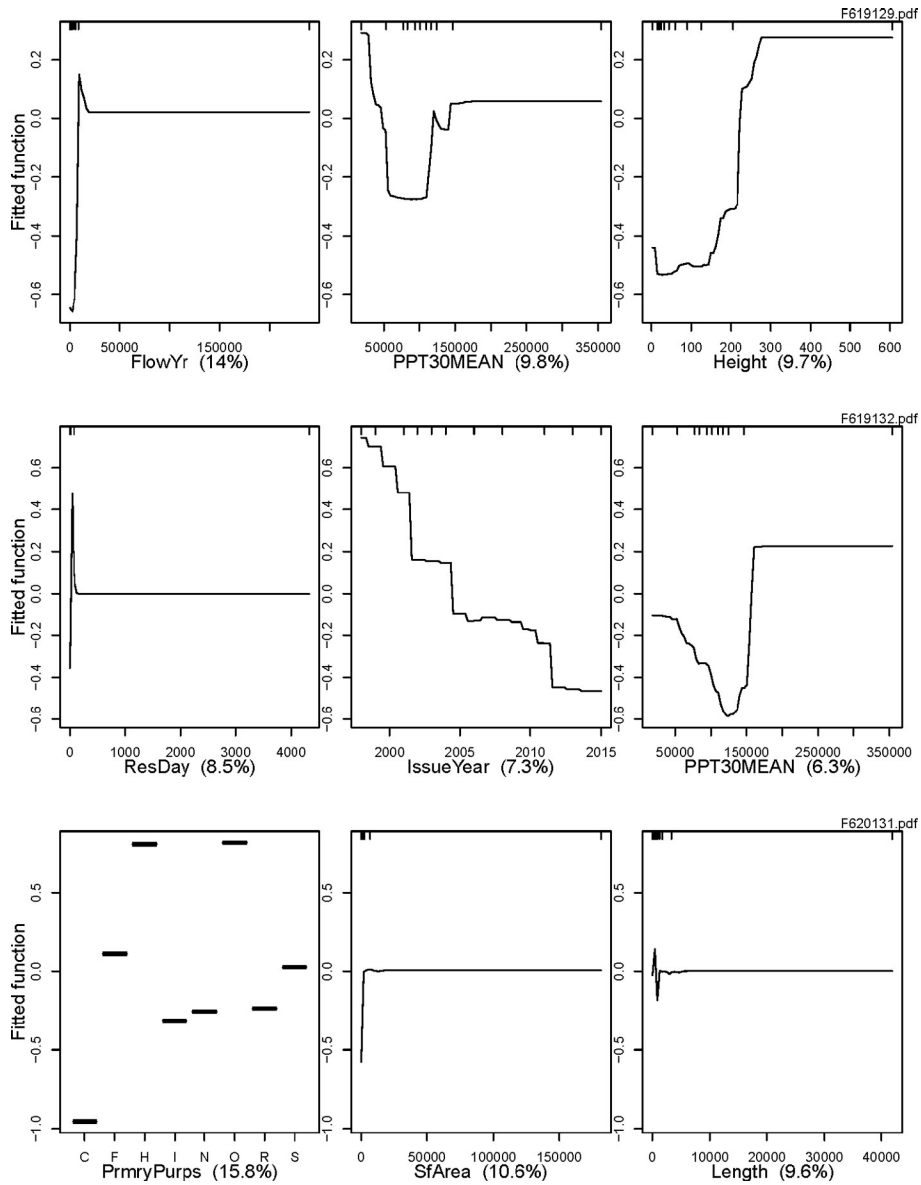

Tier 3 (*continued*).

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