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Application of spatially explicit drift foraging model to characterize enhanced foraging habitat for juvenile Chinook salmon in a restored side channel complex

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The Buttonbush Project

- Big picture goal: apply a bioenergetic modeling approach to determine side channel enhancement benefits for juvenile salmonids.

- Project goal: generate a spatially explicit drift foraging model for juvenile Chinook at the restored Buttonbush Park site using:

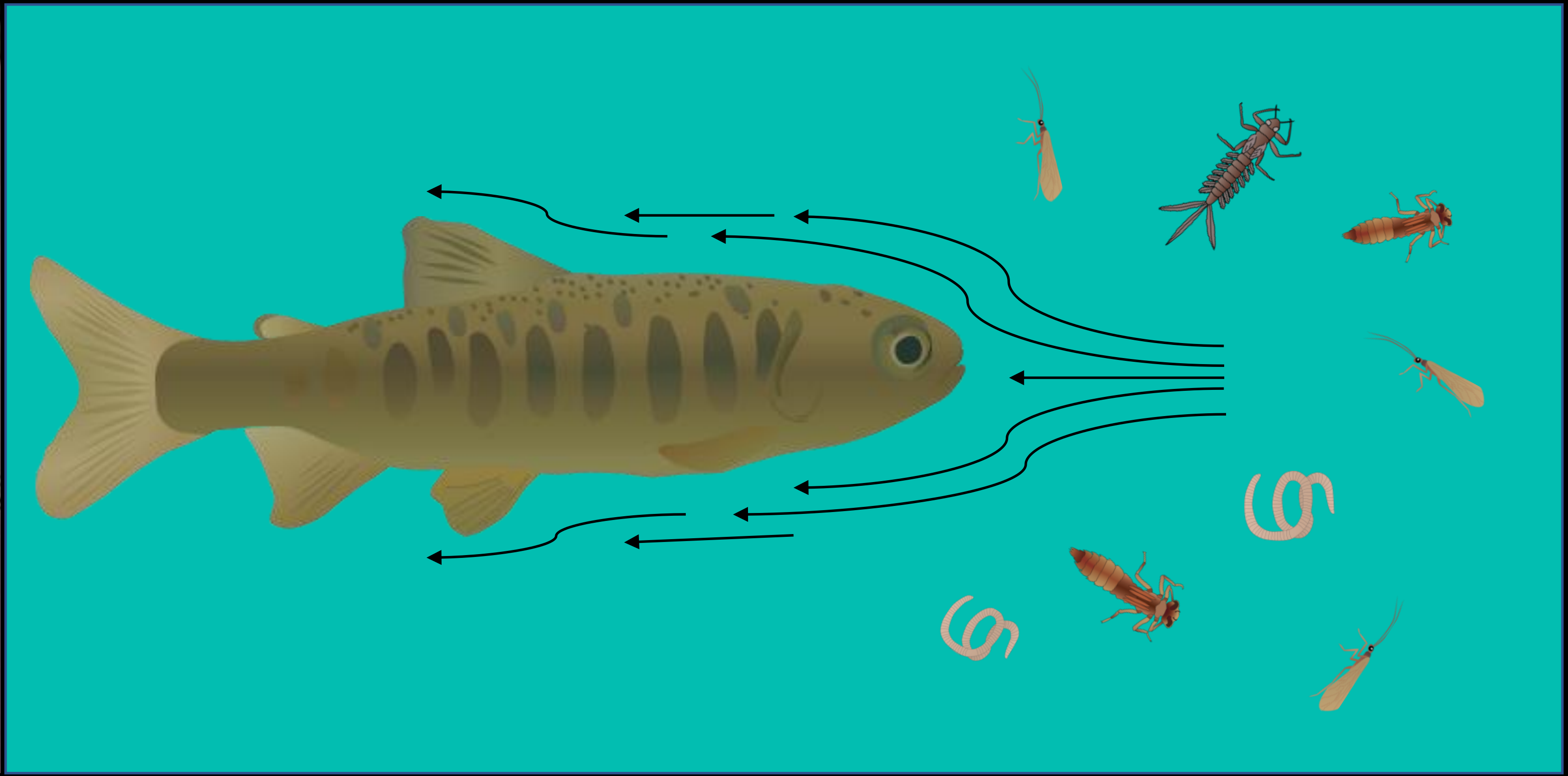
  - Macroinvertebrate drift sampling data from 2018

  - Hydrodynamic model outputs (SRH-2D) representing pre- and post-project conditions

  - A blend of existing drift foraging submodels from the literature

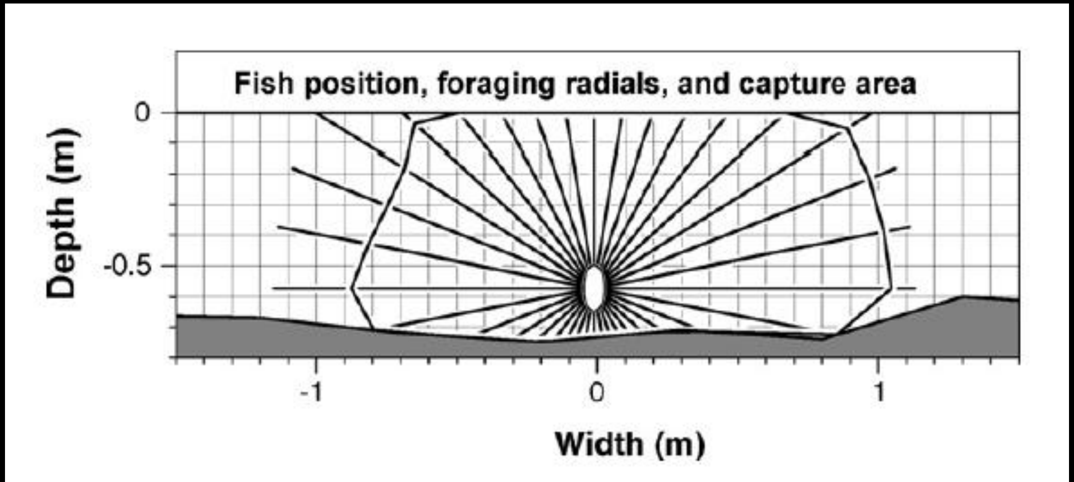
What is a drift foraging model?

It describes the net energy **gained** or **lost** for an individual juvenile salmonid holding station in flow and feeding on suspended food items.



Many approaches have attempted to describe Eulerian flow volumes as longitudinal “stream tubes”

These models require *lots* of assumptions about the minutiae of predatory movement and energy costs



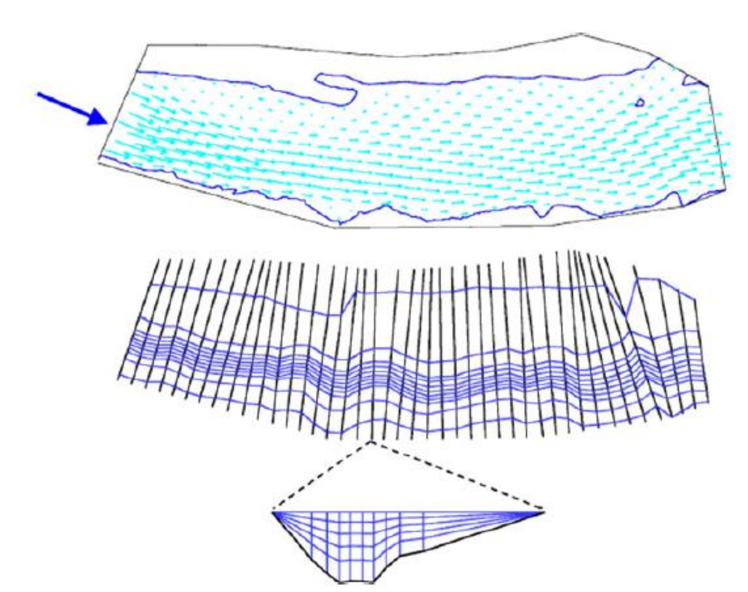
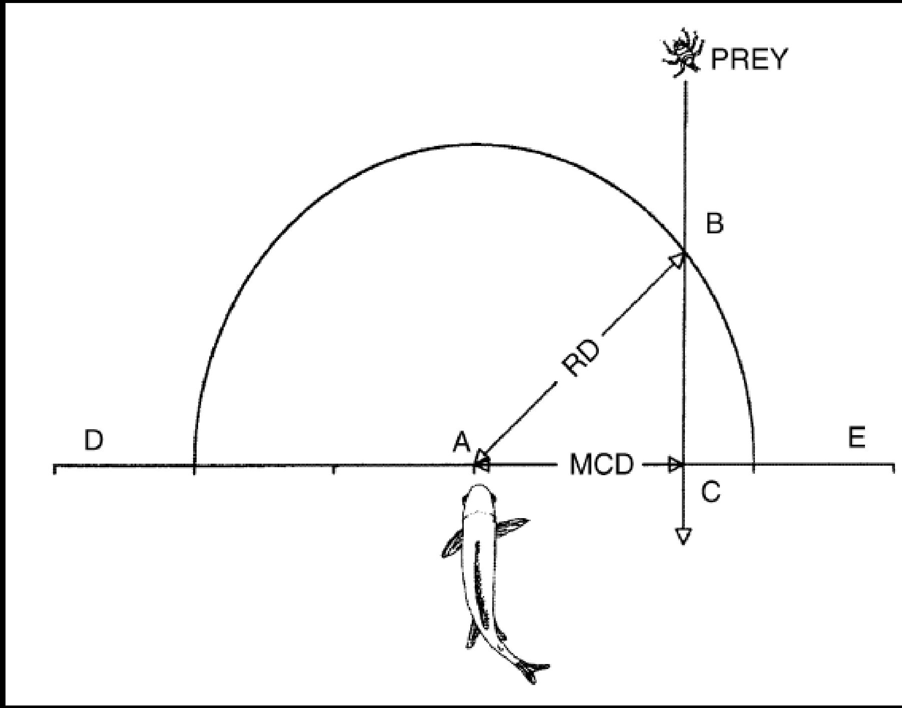
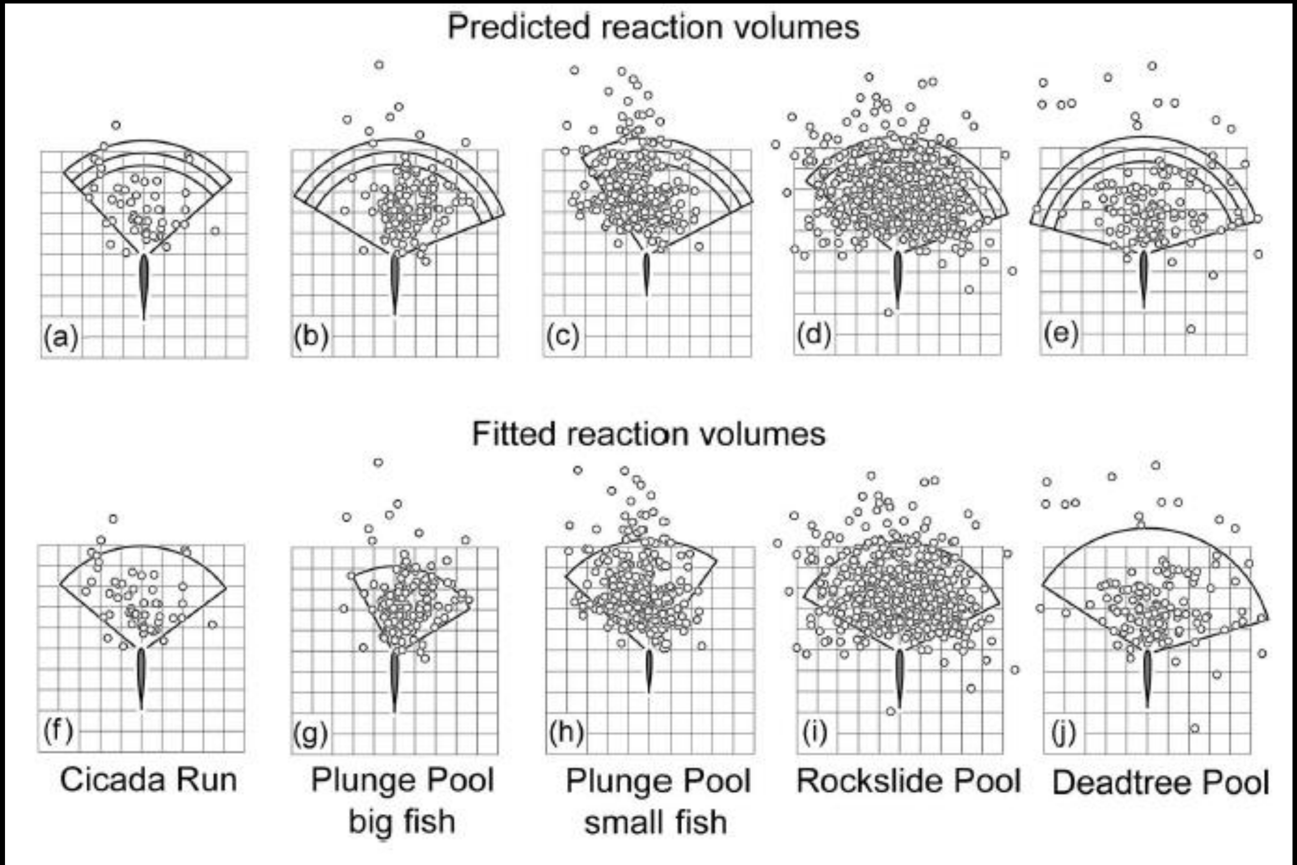
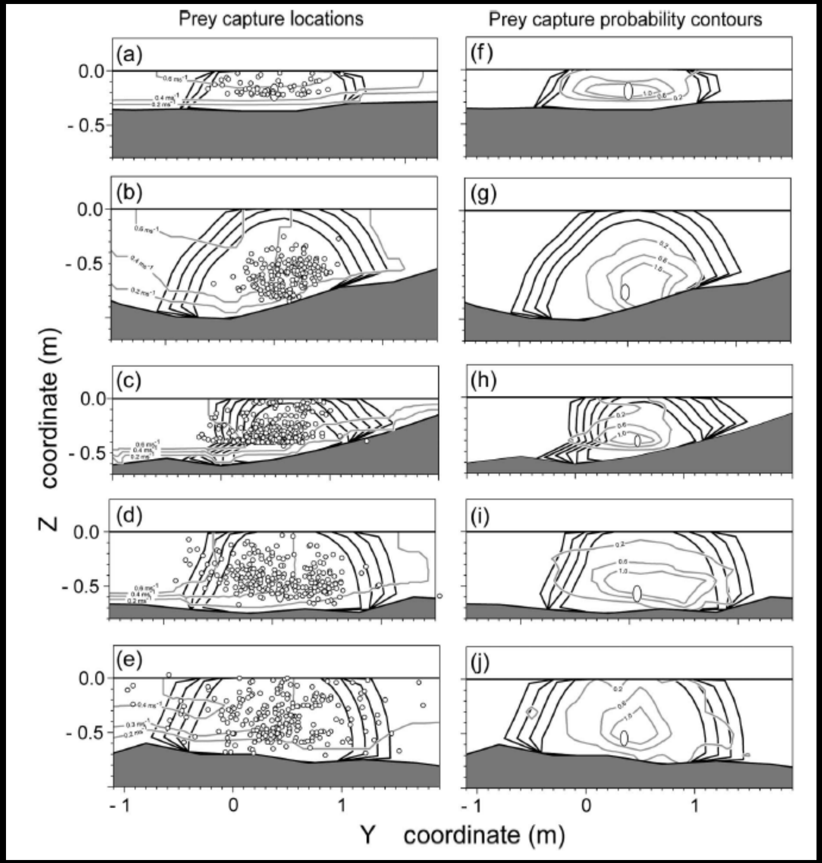


Fig. 2 – Graphical outputs for the Travers pool from River2D (velocity vector plot—arrows indicate direction of flow and relative velocity) and the stream-tube model (plan and cross-section views with user-defined cross-sections and stream tubes). Large arrow indicates direction of flow.

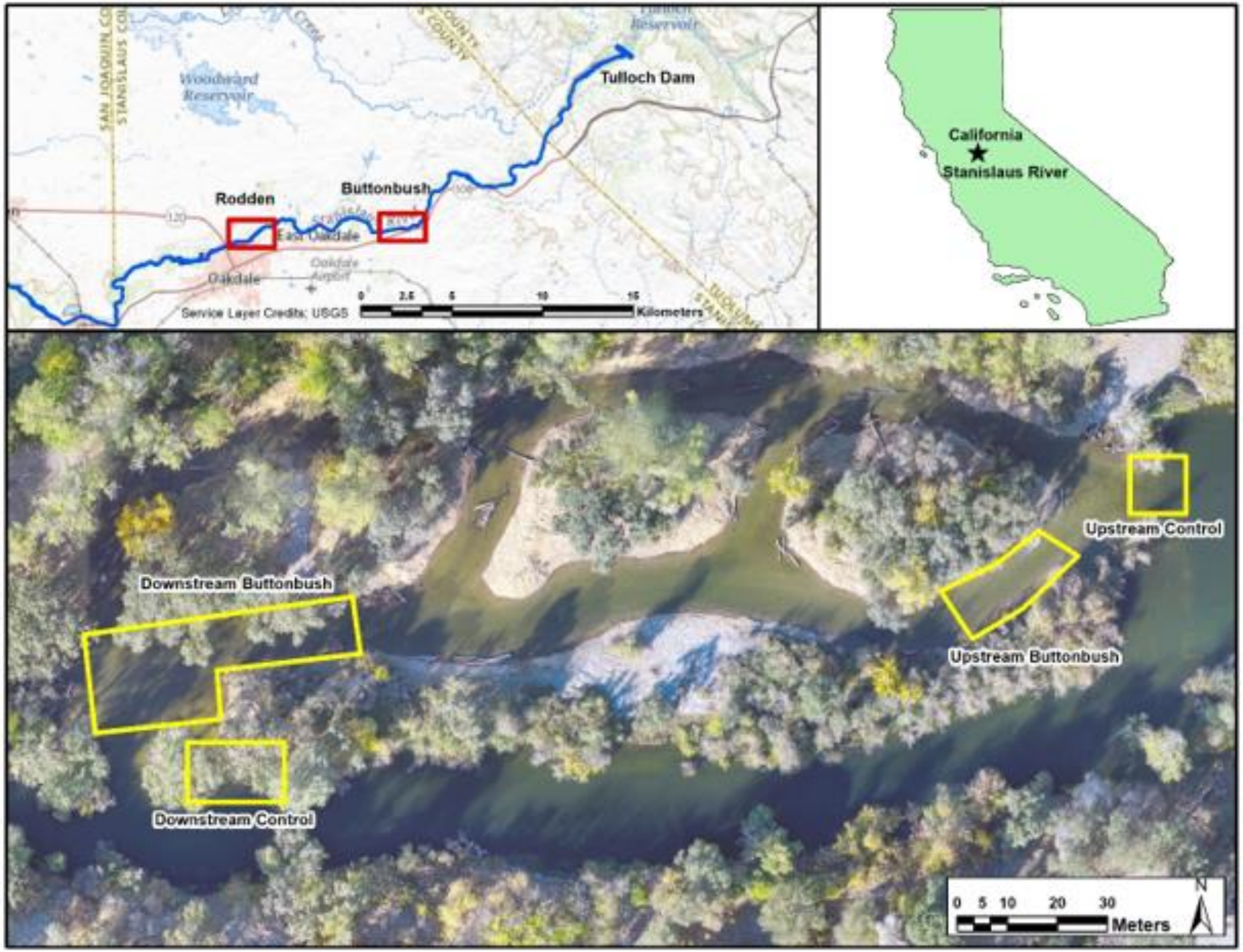


Hughes et al. (2003) is the only example of an attempt to validate an existing drift foraging model (using videography)





Instead of generating a drift foraging model from a single fish’s perspective, why not model a “foraging domain”


Tulloch Dam
Woodward Reservoir
Rodden
Buttonbush
East Oakdale
Oakdale
Service Layer Credits: USGS
0 2.5 5 10 15
Kilometers
California
Stanislaus River
Downstream Buttonbush
Upstream Control
Upstream Buttonbush
Downstream Control
0 5 10 20 30
Meters
N

2018 Macroinvertebrate Drift Sampling

<u>On each sampling date:</u>

- Up and downstream samples
- Samples in the main channel and side channel complex
- Morning and midday samples
- 3 replicates at each location and time, resulting in <u>69 usable sample reps in 2018</u>

Key drift sampling data attributes

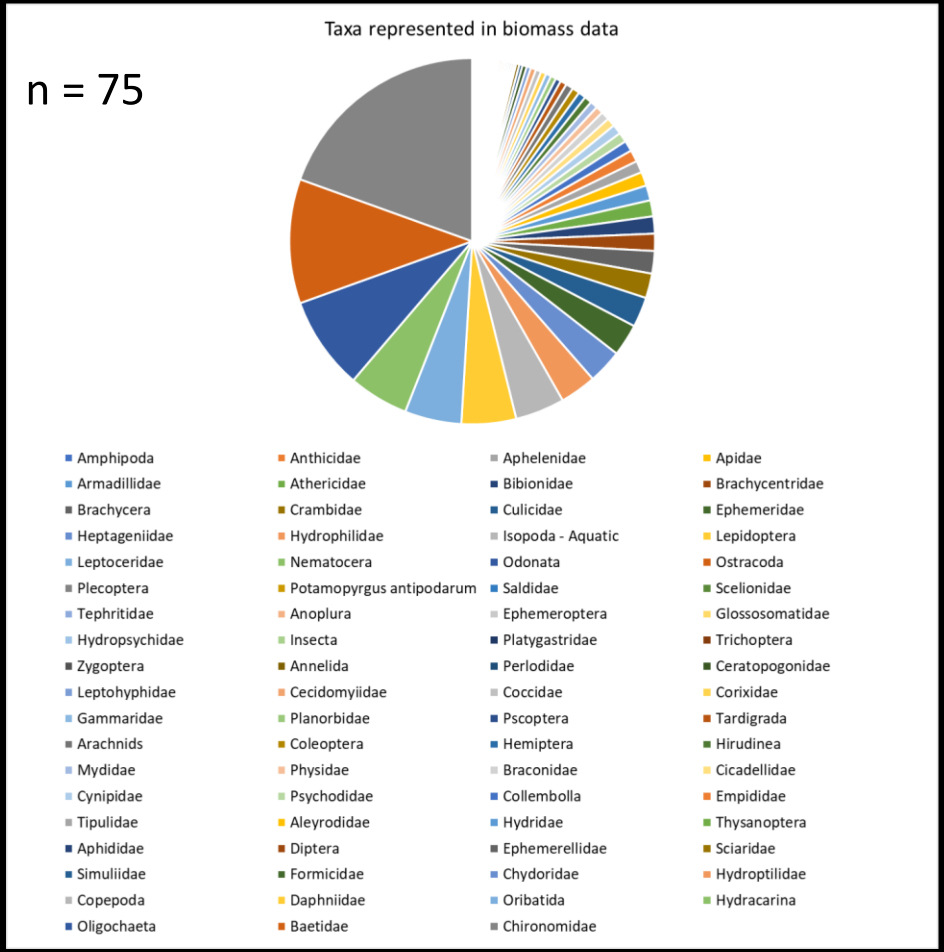
Key predictors:

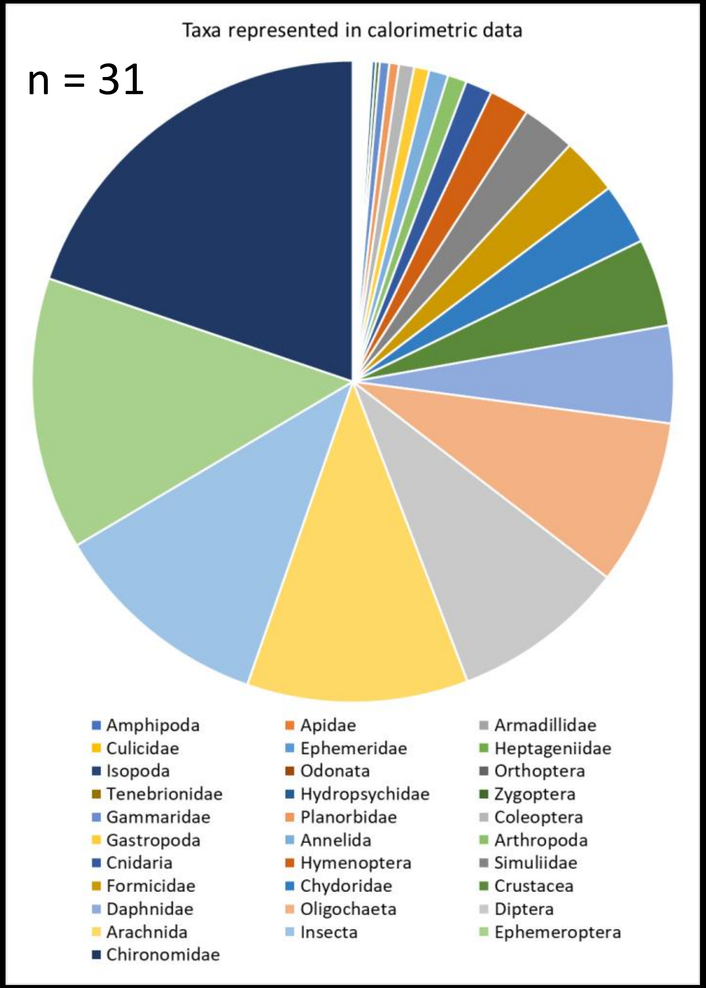
- Velocity magnitude
- Depth
- Water temperature
- Month of sample
- Discharge

Predicting:

- Calorie rate per sample (Cal/s) <- biomass rate <- invert density rate

Macroinvertebrate taxonomic community composition retained after converting biomass data to calorimetric data:



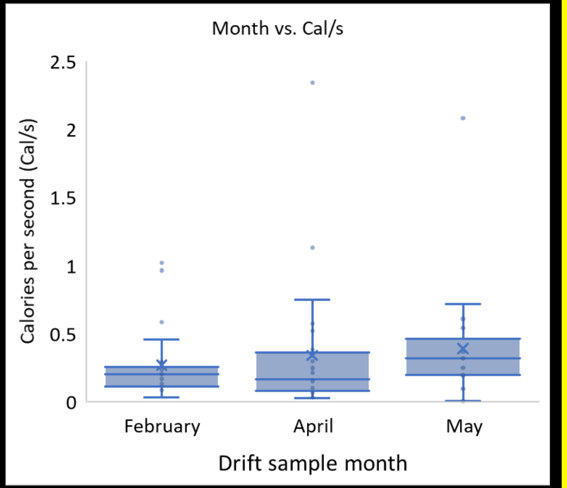


Calorie data sources:

- **All but Cnidaria**: Cumminns and Wuycheck (1971)
- **For Cnidaria**: Norrbin and Båmstedt (1984)

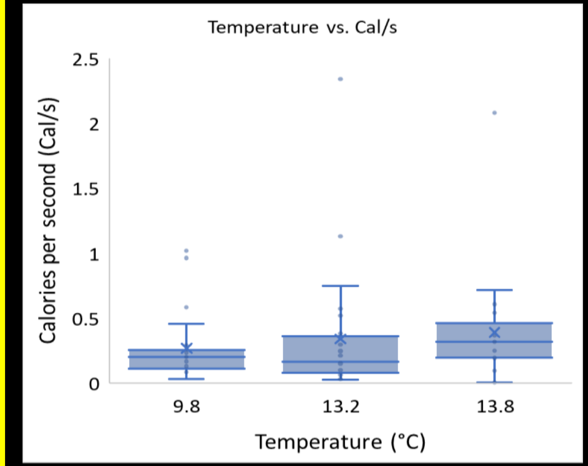
Quick summary of drift sample training data (calorie rate predictors)

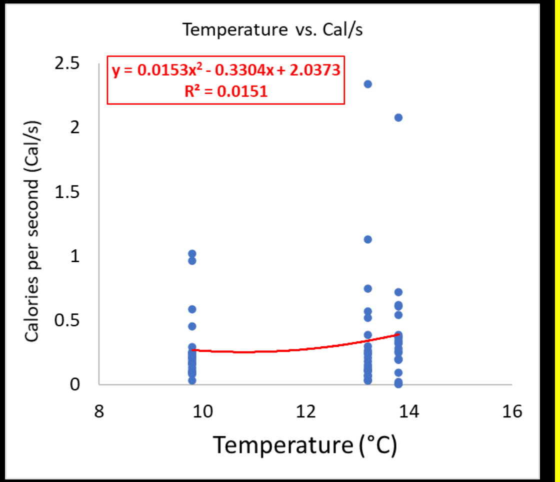
Categorical data:



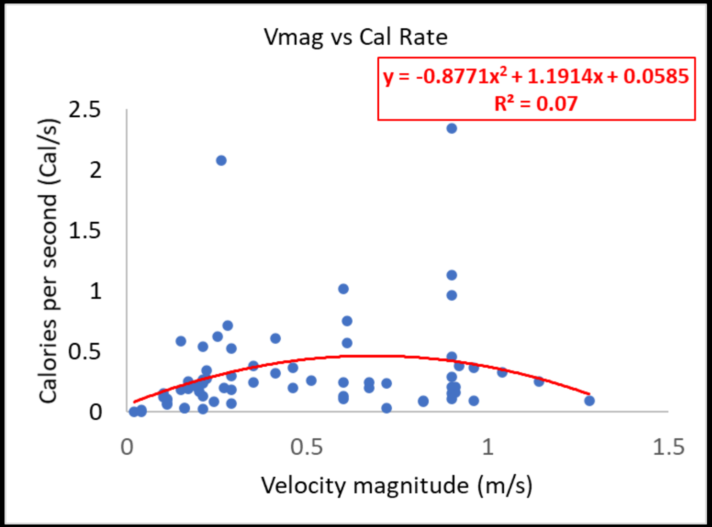
Also 6 different discharge scenarios!

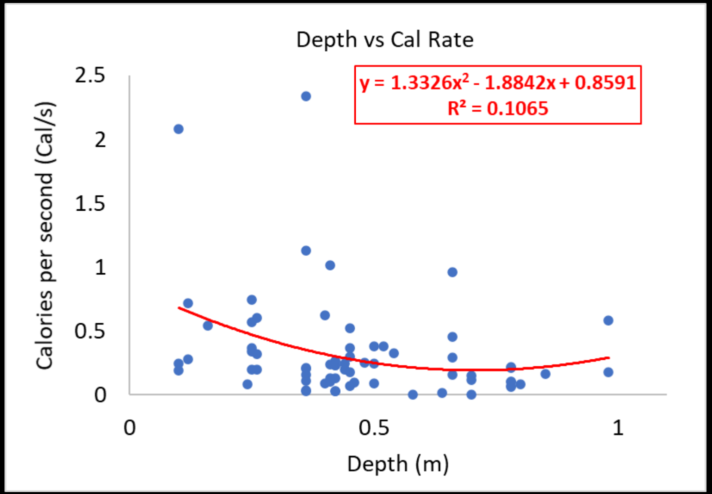
Categorical data fit as numeric:



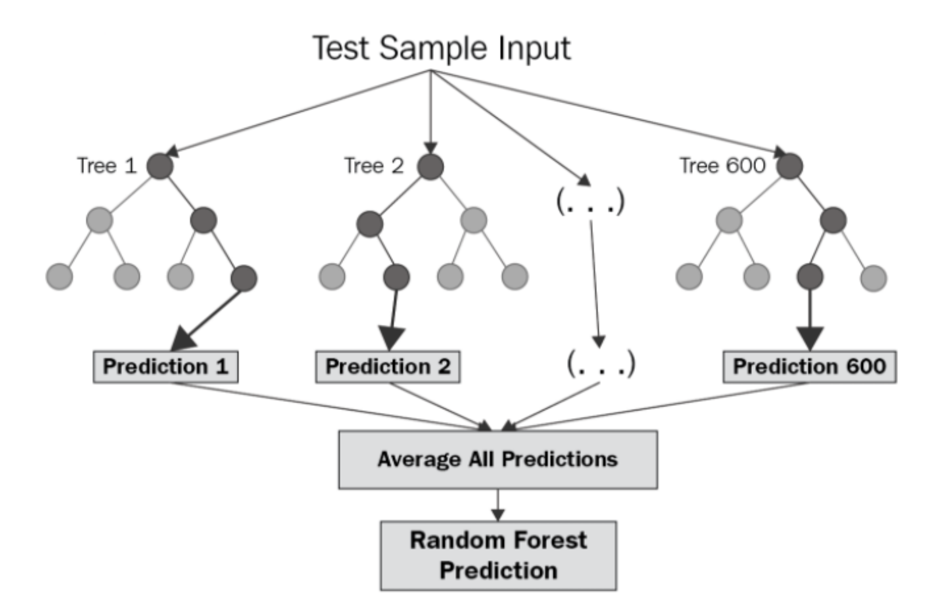


Continuous numeric data:





Using a Random Forest model to predict calorie rates



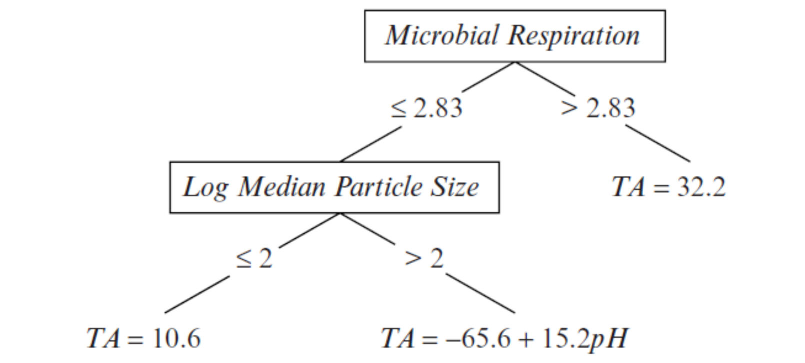
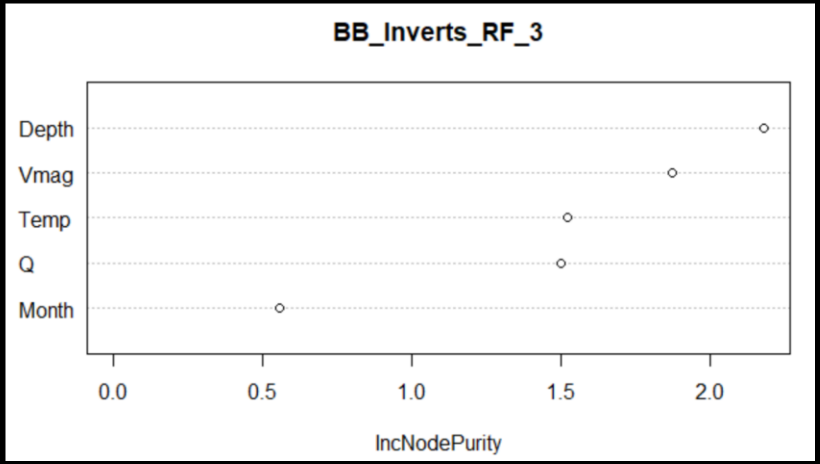


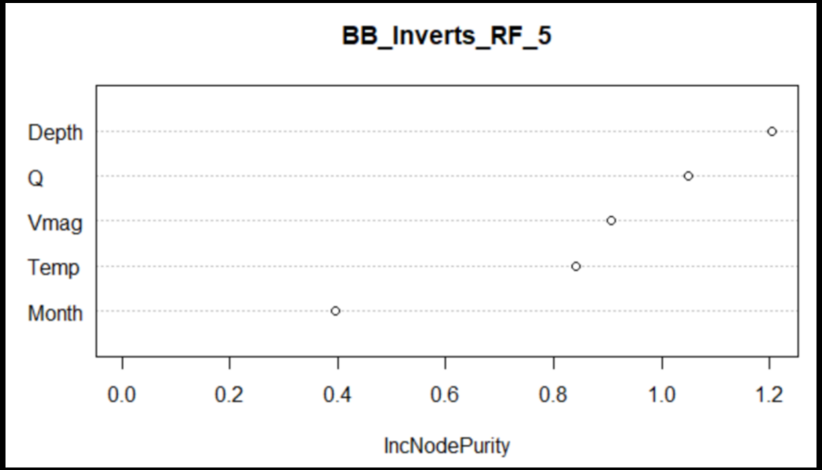
Fig. 19.2 A model tree that predicts the total abundance (TA) of hemi- and eu-edaphic Collembola on the FAM experimental farm at Scheyern (near Munich), Germany

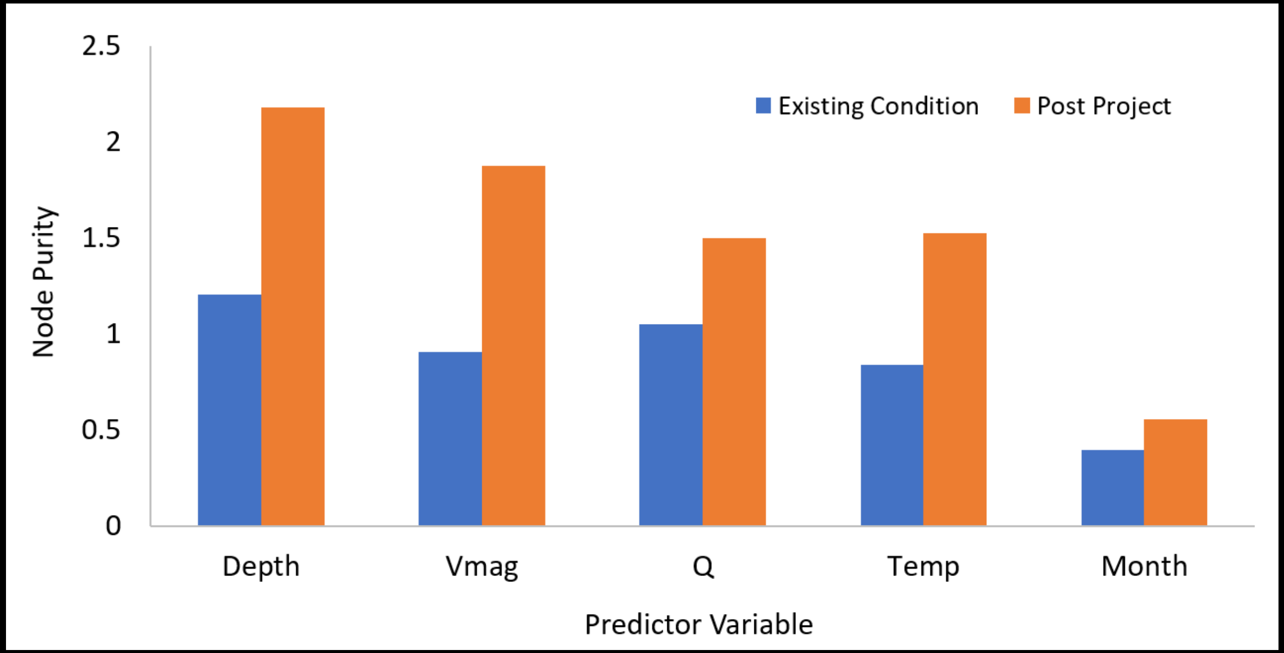
← Habitat suitability example from Džeroski (2009)

- User selects a fixed number of trees to be generated by the model (typically > 500)
- At each node in a given tree, a bifurcation of a predictor variable is encountered. Values are randomly selected each time.
- Predictions in each tree are based on training data. Predictions are then averaged across all trees.
- In our case:
  - Training data comes from the 69 drift sample reps
  - Test data is discretized on a cell-by-cell bases from the SRH-2D model outputs (# of wetted cells)

Random Forest variable importance plots for predicting Cal/s.







Post-project model = more training data = greater node purity

Computational Fluid Dynamics in River Channels

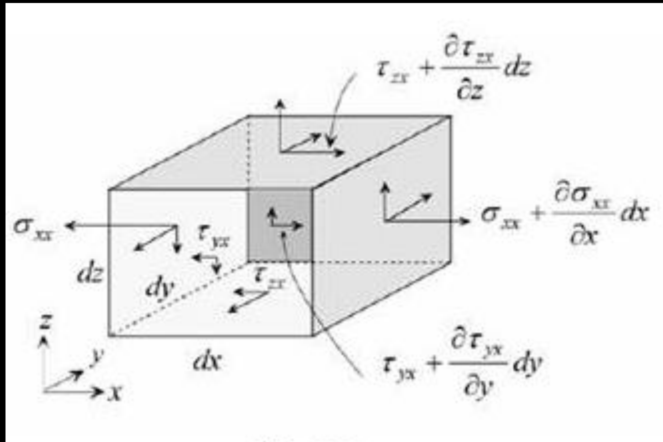
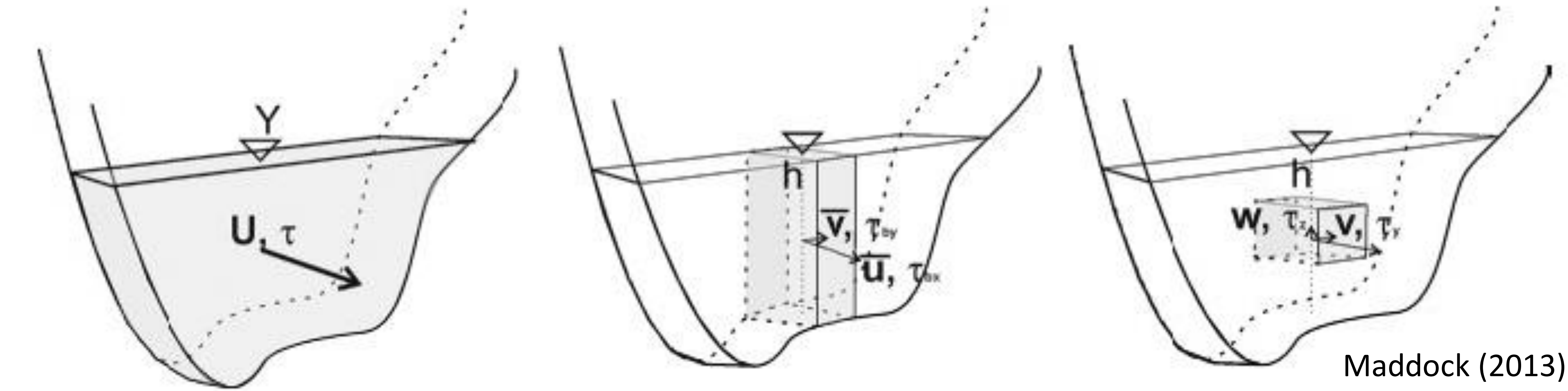


Fig. 2.6

SRH-2D uses this approach



Maddock (2013)

Macroinvertebrate calorie rates for 2018 seining dates

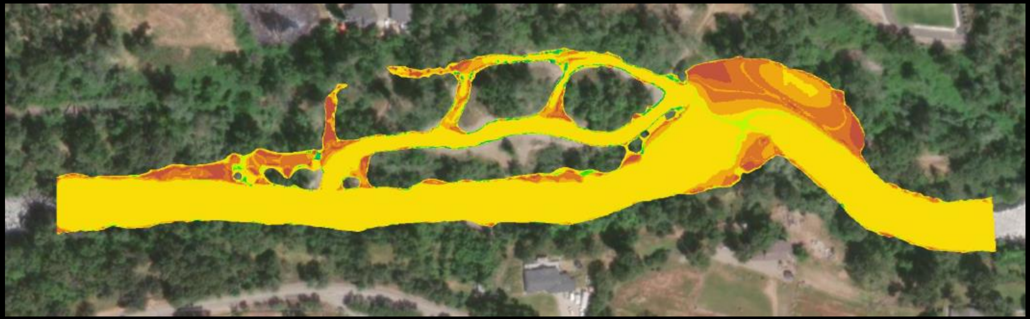
2/21/18 Q: 1501cfs, 11.0°C

2/27/18 Q: 2303cfs, 9.9°C

Cal/s

≤0.27
≤0.37
≤0.47
≤0.57
≤0.66
≤0.76
≤0.86
≤0.96
≤1.06
≤1.16

4/2/18 Q: 1511cfs, 11.7°C



4/19/18 Q: 1392cfs, 11.4°C

5/1/18 Q: 1389cfs, 13.1°C

5/16/18 Q: 2871cfs, 11.8°C

NREI and the pedigree of drift foraging models:

NREI = net rate of energy intake (expressed in Cal/s or J/s)

Positive terms = net energy gained via foraging

Negative terms = energy costs due to:

- Swimming cost
- Egestion
- Excretion
- Other cost estimates (predation strike, searching, etc.)

We borrowed submodels and parameter values from these papers:

Environ Biol Fish

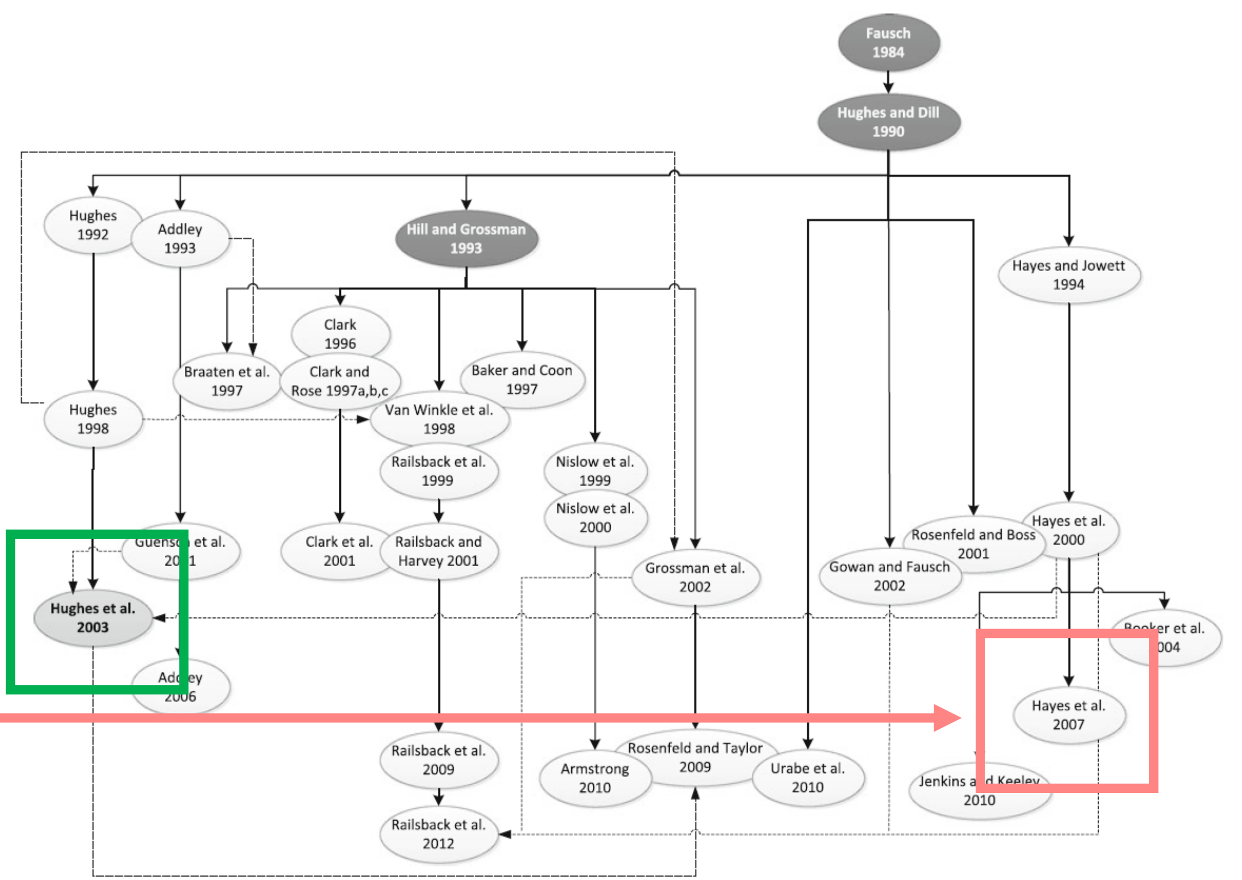


Fig. 1 Drift-feeding and NEI-based habitat selection and habitat quality models derived from Fausch (1984), Hughes and Dill (1990), and Hill and Grossman (1993). See text for full explanation of bibliometric methods

From Piccolo et al. 2014

Structure for NREI model:

NREI = C - S

Energy gained in units of Cal/s:

$$C = 0.7([Cal\ rate]) \times 0.48$$

0.7 = assimilable proportion of macroinvertebrate tissue consumed

0.48 = prey capture success proportion

These parameters come from Hughes et al (2003) via experimental observation.

Energy lost in units of Cal/s:

S = R + F + U

R is the "swimming cost" as referenced by Hayes et al. (2000, 2016) but originally from Elliot (1976):

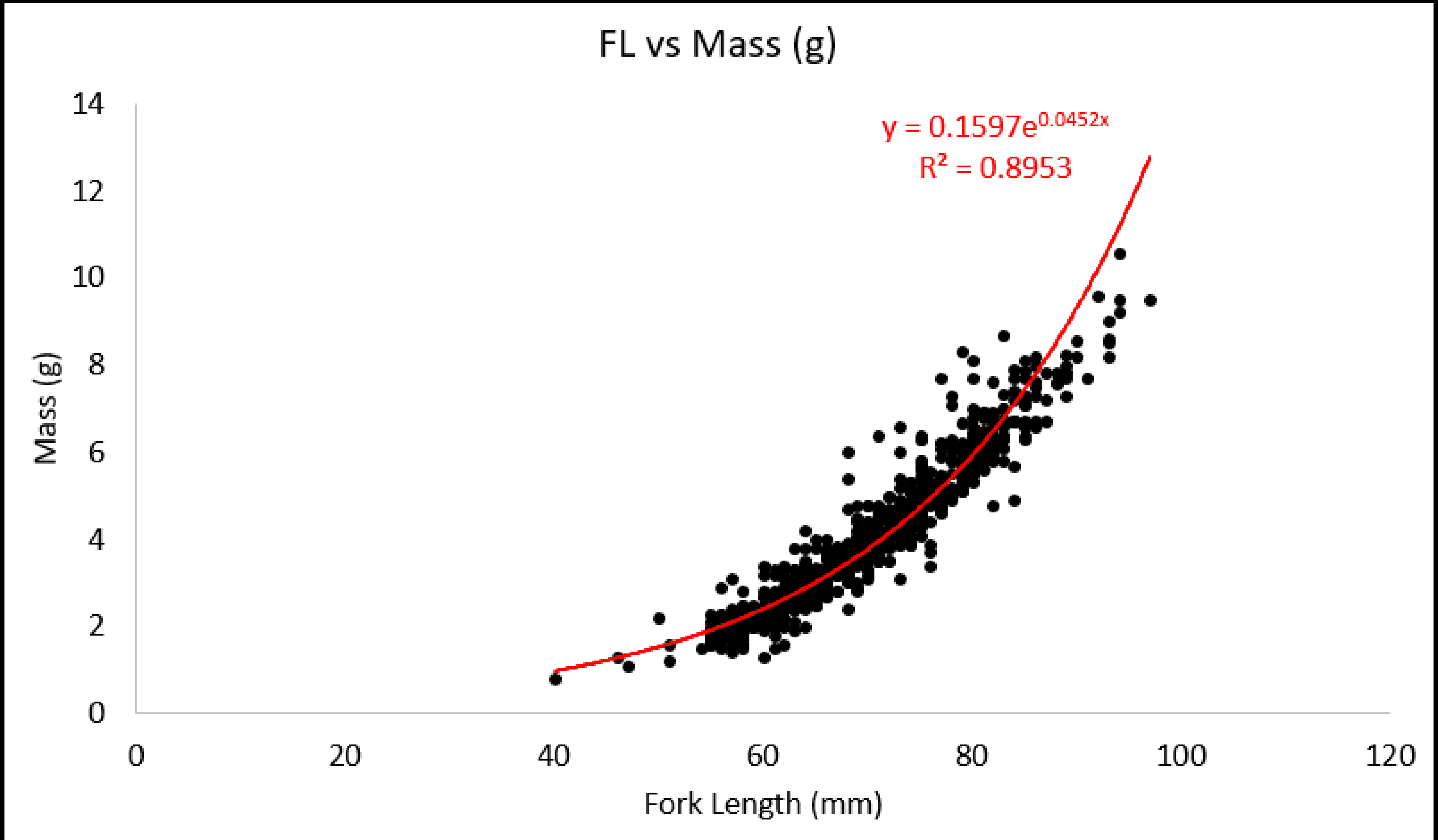
$$R = \frac{a([mass])^{b1} e^{b2*[Temp]} e^{b3*[Vmag]} \times 4.1868}{86{,}400}$$

F and **U** are terms for egestion and excretion, respectively. Sourced from Kitchell et al. (1977) and Elliot (1976).

$$F, U = C \times a \times T^{\beta} \times e^{\gamma P}$$

Where C, T, and P are consumption rate, temperature, and a proportionality constant.

FL vs. body mass relationship from seining data used to interpolate mean mass for each scenario:



NREI Results

Table 2. Modeled NREI scenarios with corresponding discharge, temperature, mean fish mass, changes in wetted area and total net Calories available per second within the model domain, and percent coverage of deleterious habitat (NREI <0) within the model domain.

2018 Scenario	Discharge (m^3/s)	Temp (°C)	Mean Fish Mass (g)	Total Wetted Area (km^2)			Total Net Nutrients Available (Cal/s)			% Deleterious Habitat	
				Pre-Existing	Post-Project	% Increase	Pre-Existing	Post-Project	% Increase	Pre-Existing	Post-Project
Feb. 21	45.03	11.0	0.79	0.018	0.024	33.3	19787.18	22303.27	12.7	0	0
Feb. 27	69.09	9.9	0.82	0.022	0.028	27.3	24488.09	25757.66	5.2	0	0
Apr. 2	45.33	11.7	1.52	0.018	0.024	33.3	32716.33	39687.21	21.3	0	0
Apr. 19	41.76	11.4	1.71	0.017	0.023	35.3	26438.55	32355.47	22.4	0	0
May 1	41.67	13.1	3.28	0.017	0.023	35.3	26100.22	35715.73	36.8	0.60	0
May 16	86.13	11.8	4.93	0.026	0.030	15.4	35728.28	45093.29	26.2	2.96	0

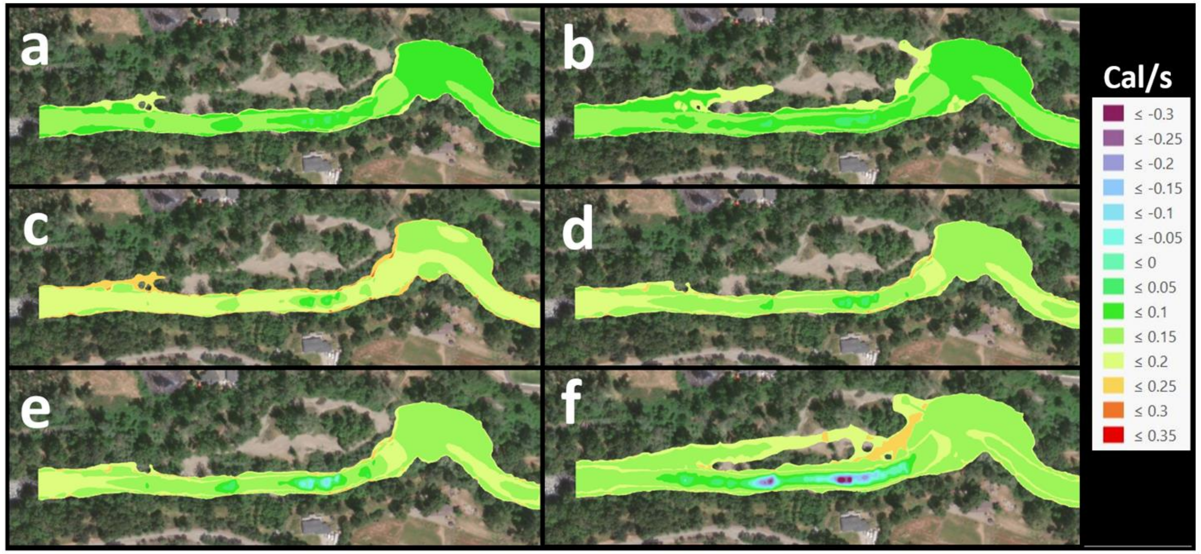


Figure 3. Net rate of energy intake (NREI) output maps representing the <u>pre-existing condition</u> at the Buttonbush Park site. Panels a-f correspond to the six modeled scenarios in 2018 shown in Table 2 (February 21st, February 27th, April 2nd, April 19th, May 1st, and May 16th, respectively). NREI raster layers are displayed here at 0.09m² cell resolution and the NREI color scale corresponds to fixed interval bins of NREI values. Units are in calories per second (Cal/s).

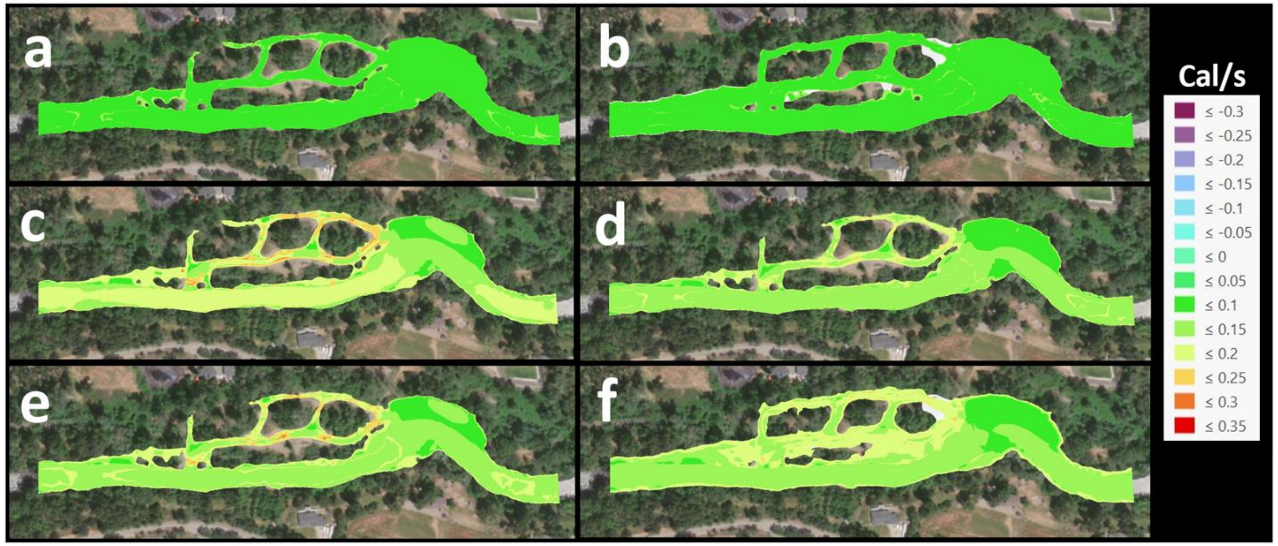


Figure 4. Net rate of energy intake (NREI) output maps representing the <u>post-project condition</u> at the Buttonbush Park site. Panels a-f correspond to the six modeled scenarios in 2018 shown in Table 2 (February 21st, February 27th, April 2nd, April 19th, May 1st, and May 16th, respectively). NREI raster layers are displayed here at 0.09m² cell resolution and the NREI color scale corresponds to fixed interval bins of NREI values. Units are in calories per second (Cal/s).

Testing hypotheses with NREI

Paired t tests comparing the six scenarios in pre- and post-project condition.

Table 2. Modeled NREI scenarios with corresponding discharge, temperature, mean fish mass, changes in wetted area and total net Calories available per second within the model domain, and percent coverage of deleterious habitat (NREI <0) within the model domain.

2018 Scenario	Discharge (m^3/s)	Temp (°C)	Mean Fish Mass (g)	Total Wetted Area (km^2)			Total Net Nutrients Available (Cal/s)			% Deleterious Habitat	
				Pre-Existing	Post-Project	% Increase	Pre-Existing	Post-Project	% Increase	Pre-Existing	Post-Project
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Apr. 2	45.33	11.7	1.52	0.018	0.024	33.3	32716.33	39687.21	21.3	0	0
Apr. 19	41.76	11.4	1.71	0.017	0.023	35.3	26438.55	32355.47	22.4	0	0
May 1	41.67	13.1	3.28	0.017	0.023	35.3	26100.22	35715.73	36.8	0.60	0
May 16	86.13	11.8	4.93	0.026	0.030	15.4	35728.28	45093.29	26.2	2.96	0

Table 3. Results of paired t tests for hypotheses that address our stated scientific questions.

Hypothesis		N	df	t	t Crit (one tail)	p
H_1	Net available nutrient rates at the site are increased in the restored condition					
$H_{1\text{-}0}$	Net available nutrient rates do not change as a result of restoration	6	5	-4.21	2.02	**<0.01**
H_2	Deleterious habitat is reduced in the restored condition					
$H_{2\text{-}0}$	Percent coverage of deleterious habitat remains the same in both pre-existing and post-project conditions	6	5	1.23	2.02	0.14

Proposed next steps:

- Compute growth potential in terms of caloric content (weekly)
- Make assumptions about rearing density by morphological unit type
- Estimate density effects on growth rate
- Sum the calories available per week per habitat unit per scenario
- Based on assumed fish densities, compute how much weekly growth occurs per fish

…Compare modeled weekly individual growth rates to observed growth rates?

Linking growth to caloric content of added tissue

- Edsall et al (1999) computed energy content per unit dry weight tissue put on during growth
- They used juvenile coho
- Growth is sensitive to temperature
- We can use values that correspond to the highest feeding ration:

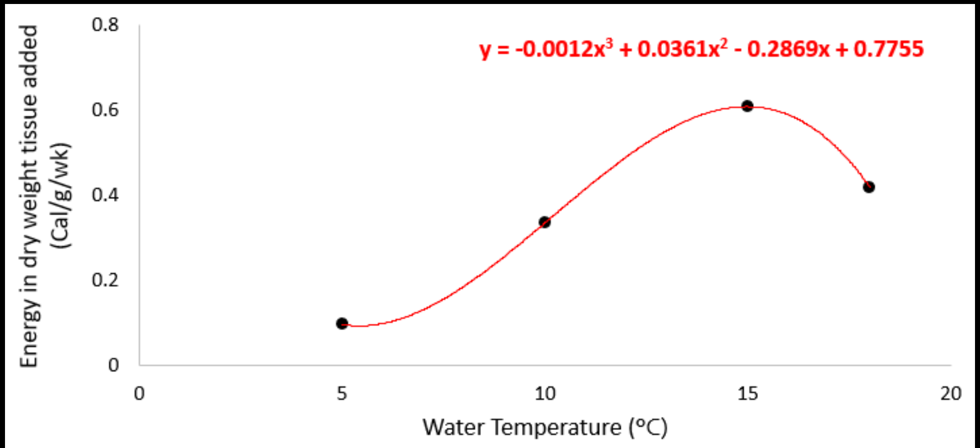


TABLE 2. Body constituents and energy content of yearling coho salmon and of alewives used as food in this study.

Nominal temperature (°C)	Ration[1]	Measurement at start or end of study	Body constituent[2] Water	Lipid	Ash	Carbohydrate	Protein	Total	Energy content[3] As protein	As lipid	Total
Coho salmon											
5	0.90	Start	75.7	3.5	2.2	0.8	17.7	100.0			26.28
		End	76.4	3.5	2.2	0.1	17.8	100.0	19.91	6.53	26.53
	1.72	Start	75.8	3.6	2.3	0.1	18.2	100.0			26.53
		End	74.2	5.0	2.2	0.4	17.3	100.0	17.55	8.45	26.93
10	0.90	Start	74.2	4.8	2.2	1.9	16.9	100.0			26.61
		End	74.5	4.8	2.3	—	18.4	100.0	18.99	8.26	27.24
	1.74	Start	74.7	4.9	2.3	0.9	17.2	100.0			27.06
		End	71.9	6.8	2.4	0.4	18.5	100.0	17.23	10.56	28.05
	3.12	Start	74.9	4.8	2.3	1.0	17.0	100.0			26.99
		End	71.0	8.2	2.3	1.4	18.1	101.0	16.23	12.25	28.39
15	0.94	Start	73.3	6.3	2.2	0.9	17.3	100.0			
		End	73.8	5.9	3.1	—	18.1	100.9	18.76	10.19	27.78
	1.76	Start	74.0	6.7	2.0	—	18.0	100.7			27.86
		End	72.7	7.4	2.1	—	18.0	100.2	17.10	11.72	28.27
	3.53	Start	73.2	5.4	2.6	1.2	17.6	100.0			28.59
		End	70.1	10.2	2.0	—	18.1	100.4	15.53	14.59	27.16
											29.70
18	0.90	Start	72.2	6.2	2.4	1.2	18.0	100.0			27.50
		End	73.2	4.8	2.3	1.0	18.7	100.0	18.27	7.82	26.78
	1.77	Start	73.3	6.1	2.4	0.5	17.7	100.0			27.80
		End	71.1	7.7	2.2	1.0	18.0	100.0	16.14	11.51	28.27
	3.48	Start	73.3	5.6	2.2	—	19.4	100.5			27.51
		End	68.6	10.4	1.8	1.2	18.0	100.0	14.56	14.03	29.26
Alewives		4	75.7	6.7	2.4	0.3	14.9	100.0			28.73

[1] As % wet body weight at start of week.
[2] As % wet weight.
[3] As kJ/g ash-free dry weight.
[4] Sample composited weekly during the study.

Edsall et al.

Tissue baking protocols for deriving dry weight energy content come from:

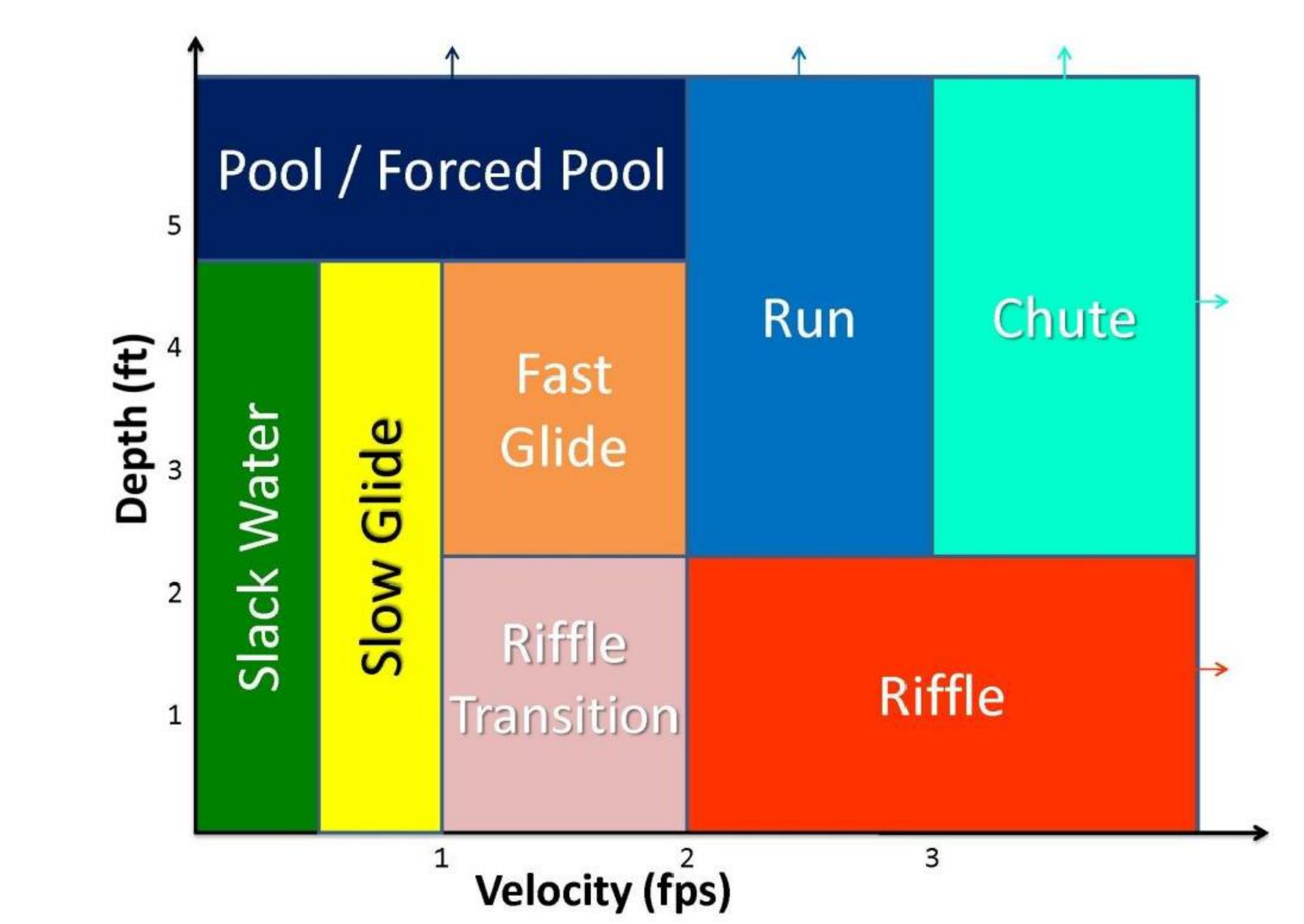
AOAC (Association of Official Agricultural Chemists). 1965. *Official methods of analysis*, volume 10, Washington, D.C.

Rearing densities by habitat type

Using unpublished seine survey data on the Mokolumne from 1997-2004, we can convert CPUE's to mean rearing densities by morphological unit type.

We can conduct a morphological unit analysis for each scenario and sum available calories per MU patch.

Then we will have density polygons for each NREI scenario and an estimate of rearing density across the model domain.



Morphological unit delineations from Wyrick and Pasternack (2012)

Estimating density effects to growth rate

- Corzier et al (2010) modeled length at date for juvenile Chinook as a function of density and temperature. We can create a 1-week ΔFL to correspond to the Edsall et al. numbers for energy content of weekly tissue growth.
- We can apply this model to MU polygons in each NREI scenario to compute % growth rate polygons as a function of density.

Best performing model is also most relevant for us!

Table 3. Model comparisons of the effects of March (T_m), July (T_j), and March–August (T_s) mean temperature, the natural log of fish density (D), population (P), and sample date (J) on fish length (L)

Rank	Model	d.f.	AICc	dAIC	r^2	w	Intercept	T_s^2	$T_s \times D$	$T_m \times D$	$T_j \times D$	T_s	T_m	T_j	D	J
1	$L \sim T_s \times D + P + J$	18	835·56	0	0·752	0·362	69·45*		−1·01*			2·52*			−2·36*	0·3*
2	$L \sim T_s^2 + T_s \times D + P + J$	19	837·7	2·1	0·753	0·127	69·34*	0·45	−1·01*			2·59*			−2·31*	0·3*
3	$L \sim T_s \times D + T_j \times D + P + J$	20	837·77	2·2	0·757	0·121	69·54*		−0·83*		−0·17	2·49*		−0·05	−2·3*	0·29
4	$L \sim T_s \times D + T_j + P + J$	19	838·08	2·5	0·752	0·104	69·48*		−0·99*			2·48*		0·04	−2·39*	0·3*
5	$L \sim T_s \times D + T_m + P + J$	19	838·14	2·6	0·752	0·099	69·45*		−1*			2·57*	−0·03		−2·37*	0·3*
6	$L \sim T_s^2 + T_s \times D + T_j + P + J$	20	839·72	4·2	0·754	0·044	69·32*	0·78	−0·97*			2·51*		−0·13	−2·36*	0·31*
7	$L \sim T_s^2 + T_s \times D + T_m + P + J$	20	840·05	4·5	0·753	0·038	69·28*	0·64	−0·97*			2·83*	−0·13		−2·34*	0·3*
8	$L \sim T_s \times D + T_m \times D + P + J$	20	840·51	5	0·753	0·03	69·47*		−1·1*	0·07		2·53*	−0·02		−0·29*	0·29*
9	$L \sim T_j \times D + T_s + P + J$	19	841·2	5·6	0·747	0·022	69·42*				−0·24*	2·7*		−0·04	−2·32*	0·28*
10	$L \sim T_s^2 + T_s \times D + T_m \times D + T_j + P + J$	21	842·25	6·7	0·754	0·013	69·27*	0·73	−1·11*	0·09		2·81*	−0·13		−2·31*	0·3*

The symbol × indicates an interaction between terms, d.f. = degrees of freedom, ΔAICc = AICc–minAICc (0 = best model), w = AIC weights. The coefficients of all the parameters other than population are also shown; the * indicates the coefficient is significant ($P < 0·05$). All models are significant ($P < 0·001$). This table shows the models with 91% of AICc weights; see text for a description of all models tested.

Applying the final growth model:

$$F_i = \rho_i A_i$$

Where:
ρ_i = density of fish in patch i (#/m^2, from unpublished Mokelumne data)
A_i = area of patch i

$$B = \sum_i G_i F_i$$

Where:
B = total added biomass per week in the site (g/wk)
G_i = individual fish growth in patch i per week (g/wk)
F_i = # of fish in patch i (#)

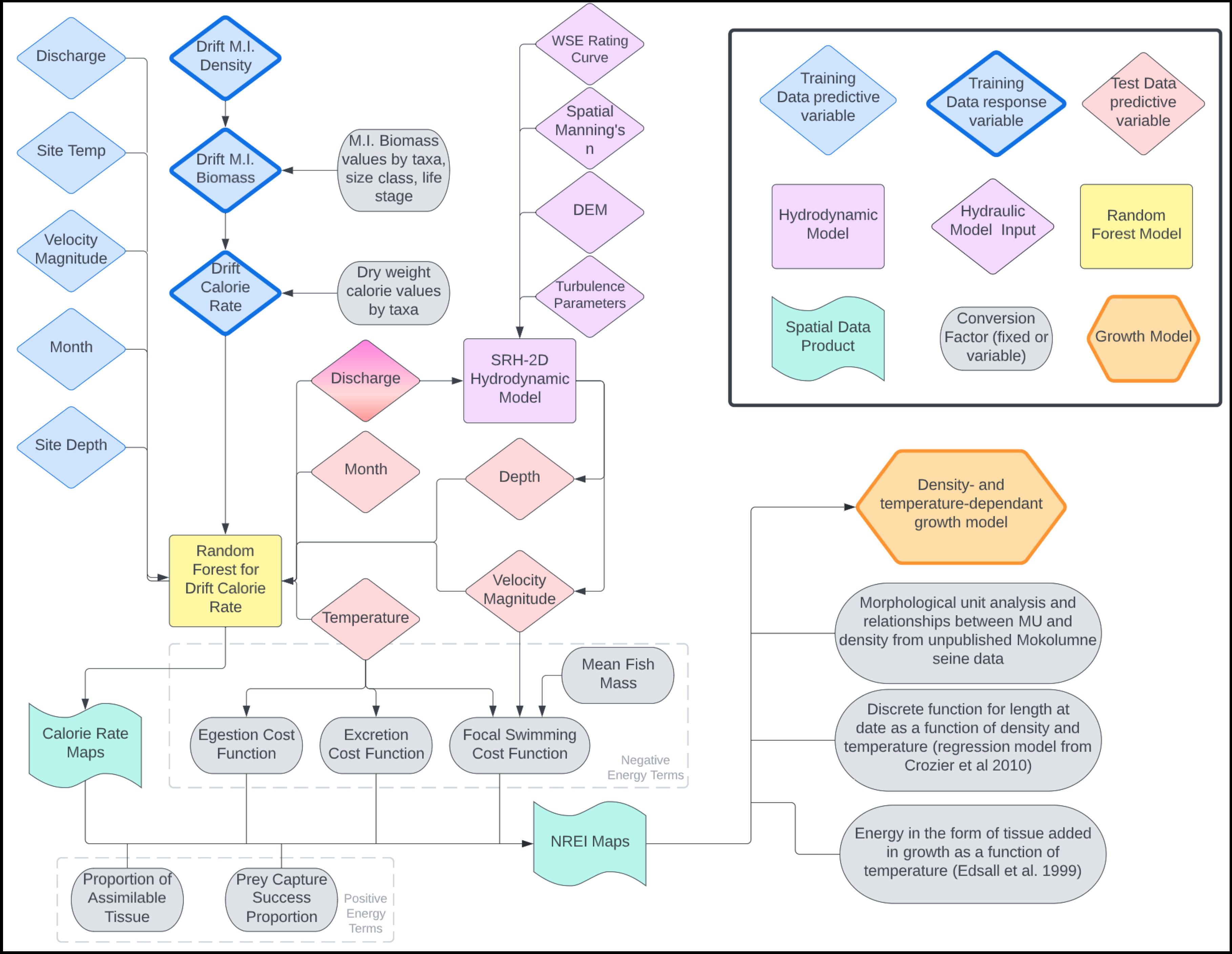
$$G_i = g_i \frac{E_i}{F_i}$$

Where:
E = weekly tissue growth potential in patch I (g/wk)
g = weekly growth rate at temperature i and density i (proportionality constant, from Crozier et al (2010))

$$E_i = \frac{\tau_i}{e_i}$$

Where:
τ = energy content per g of tissue at temperature i (Cal/g, from Edsall et al 1999)
e =energy available per patch per week (Cal/wk)

First paper develops and analyzes NREI



Second paper links NREI to growth potential

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