Appendix 4. Environmental indicators

A multidisciplinary group consisting of ecologists, hydrologists, engineers, economists and decision scientists developed a set of potential indicators that encompass a set of climate, terrestrial, and aquatic ecosystem services of importance in the study region.

4.1 Atmosphere domain

Three indicators were chosen for the atmosphere/climate domain to represent primarily recreational and regulation ecosystem services. The three indicators were derived from two sources of downscaled atmospheric forcing data: 1) spatial averages of metrics derived from input to the coupled PnET-FrAMES model based on Hayhoe et al. (2007), and 2) station based estimates of down-scaled climate data (Wake et al. 2014) using the asynchronous down-scaling method of Stoner et al. (2013).

Extreme hot days (A_{Hot}). The extreme hot days indicator was chosen as an indicator of the atmosphere's regularization service of maintaining temperatures conducive to extended labor outdoors. The indicator was calculated by summing the number of days with maximum daily temperature ($T_{Max}^{i,k}$) exceeding 32°C across the watershed, then averaging this value across the watershed.

Snow days (A_{Snow}). The snow days indicator was chosen as an indicator of the potential recreational opportunities from ample snow-cover provided by the atmosphere. The indicator was calculated by summing the number of days with a minimum of $30\ mm$

snowpack ($S_{Pack}^{i,k}$ [mm (water equivalents)]) across the watershed, then averaging this value across the watershed.

Recreation days. The recreation days indicator was chosen as an indicator of the potential recreational opportunities afforded by pleasant temperatures. The indicator was calculated by summing the number of days with daily max temperatures ($T_{max}^{i,k}$) between $21°\mathrm{C}$ and $32°\mathrm{C}$, then averaging this value across the watershed.

4.2 Land domain

Three indicators were chosen for the land domain that all represent non-use and aesthetic value and provisioning services.

Farm land (L_{Farm}). The farm land indicator was calculated directly from build-out scenario data including modeled agricultural land cover and total population within the UMRW. Farm land was expressed as the number of acres of watershed agricultural-land (A_{Ag}) per resident of the UMRW (P).

Forest cover (L_{Forest}). In addition to non-use, aesthetic, and timber provisioning, total forest cover represents potential recreational services, is considered indicative of important services of [carbon sequestration] and maintenance of biodiversity. The forest cover indicator is calculated directly from build-out scenario data and is expressed as the total forest cover in acres for the UMRW.

Forest type ($L_{ForType}$). In addition to services provided by forest cover, the type of forest, particularly the proportional presence of maple/beech/birch (MBB) is considered important for [tourism] services. The forest type indicator represents the fraction of forest cover considered suitable for MBB. These were taken from New Hampshire average suitability index modeling for present and 2100 for low (B1) and high (A1FI) carbon emission scenarios (Iverson et al. 2008[1]).

4.3 Water domain

Four indicators were chosen for the water domain that represent a diversity of ecosystem services. The four indicators were derived from coupled PnET-FrAMES model output forced using the same land cover and climate datasets used to derive indicators for atmosphere and land domains. The four water domain indicators were expressed in terms of potential stressors to relevant ecosystem services. Associated supply and demand of ecosystem services related to water also evolve with urbanization (Wollheim et al. 2015).

Water supply (W_{Supply} $[p\ d]$). Water supply was chosen as an indicator of potential stress to human provisioning needs. Water supply represents the spatial and annual sums of population potentially affected (P_{Supply}) by limited water availability, times the number of days per year persons were potentially affected. To calculate potentially affected population, we first use to calculate the daily flow accumulation (FA) (Tarboton et al. 2009) at each grid cell to estimate water availability for the population in the grid cell (V). We then accumulate the downstream difference between water supply ($Q -$

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[1] http://www.nrs.fs.fed.us/atlas/

Q_{env}) (stream flow minus environmental flow) and total human consumptive demand ($U\ [L\ d^{-1}] = P\ [p] * u[L\ p^{-1} d^{-1}]$) where u is a per capita water demand of residents in New Hampshire, which 284 L/p/d (Horn et al. 2008).

$$V = FA(\max(Q - Q_{env}, 0) - U) \tag{4.3}$$

Affected population ($P^{i,k}_{Supply}$) is then calculated as the maximum of local population or the population that is expected to have insufficient supply, except in densely populated cities ($\rho_{pop} > 350\ P\ km^{-2}$) where supply is assumed available elsewhere in the watershed. This density is consistent with areas of known public water supply systems in the UMRW. The demand of these areas is transmitted downstream, so the high demand can trigger water shortfalls in downstream cells.

As formulated, W_{Supply} considers both rural and urban water consumers in a simple consistent framework that is flexible across development patterns. The indicator assumes that streamflow is an appropriate indicator of water supply even where actual abstractions may come from groundwater resources.

Flood attenuation ($W_{Flood}\ [p\ d]$). Flood attenuation was selected as an indicator of potential impact to human and infrastructure safety. Flood attenuation represents the spatial and annual sums of population potentially affected (P_{Flood}) by local flooding, times the number of days per year persons were potentially affected. To calculate affected population, we assume that the entire population of a grid-cell (at ~1.5 km2) is potentially affected when daily mean discharge in the grid cell from PnET-FrAMES exceeds an estimate of the 100-year flood discharge. The threshold defining flood runoff was spatially distributed dependent on mean April precipitation, channel slope, upstream wetland fraction, and catchment area following Olson et al. (2009).

Fish habitat (W_{Fish} $[km]$). Fish habitat was selected as an indicator of potential non-use or aesthetic value, as well as recreational value of sport fishing. Fish habitat is calculated as the fraction of the total length of all streams and rivers in the watershed that exceed at least one threshold associated with either water temperature, salinity (as chloride), or in-stream flow at least one time in each year. We use a 7-day rolling mean water temperature and determine when this value exceeds the median of freshwater fish tolerances (29.2°C) from Eaton and Scheller (1996). We use 4-day rolling mean of chloride to determine when it exceeds the USEPA chronic water quality criteria for chloride ($230\ mg$ Cl L^{-1}) (USEPA 1988). We use the 7-day rolling mean of discharge to determine when it is below an estimate of in-stream flow requirement equal to present day 7Q10, or the 10th-percentile of annual minimum 7-day rolling mean discharges. We estimate present-day 7Q10 in runoff as $0.122\ [mm\ d^{-1}]$ using USGS daily discharge data for 12 stations in the Merrimack River Watershed with at least 17 years of data.

Nitrogen export ($W_{Nitrogen}$ $[kg$ N $y^{-1}]$). Nitrogen export was selected as an indicator of the watershed regulation service of processing excess anthropogenic dissolved inorganic nitrogen (DIN) prior to export to sensitive estuarine habitats. $W_{Nitrogen}$ was calculated by subtracting an estimate of the annual estuary nitrogen loading that was determined to be protective of estuarine ecosystem function ($\dot{m}_{DIN}^{*} = 350\ [kg$ N $km^{-2}y^{-1}]$, Trowbridge and NHDES 2010) from the total annual export of DIN predicted by PnET-FrAMES.

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Figs. A4.1 – A4.4.

Fig. A4.1. Comparison of mean daily (annual only) modeled values with observations for a) streamflow (mm/d), b) water temperature (degC), c) DIN (mg/L) and d) specific conductivity (uS/cm)

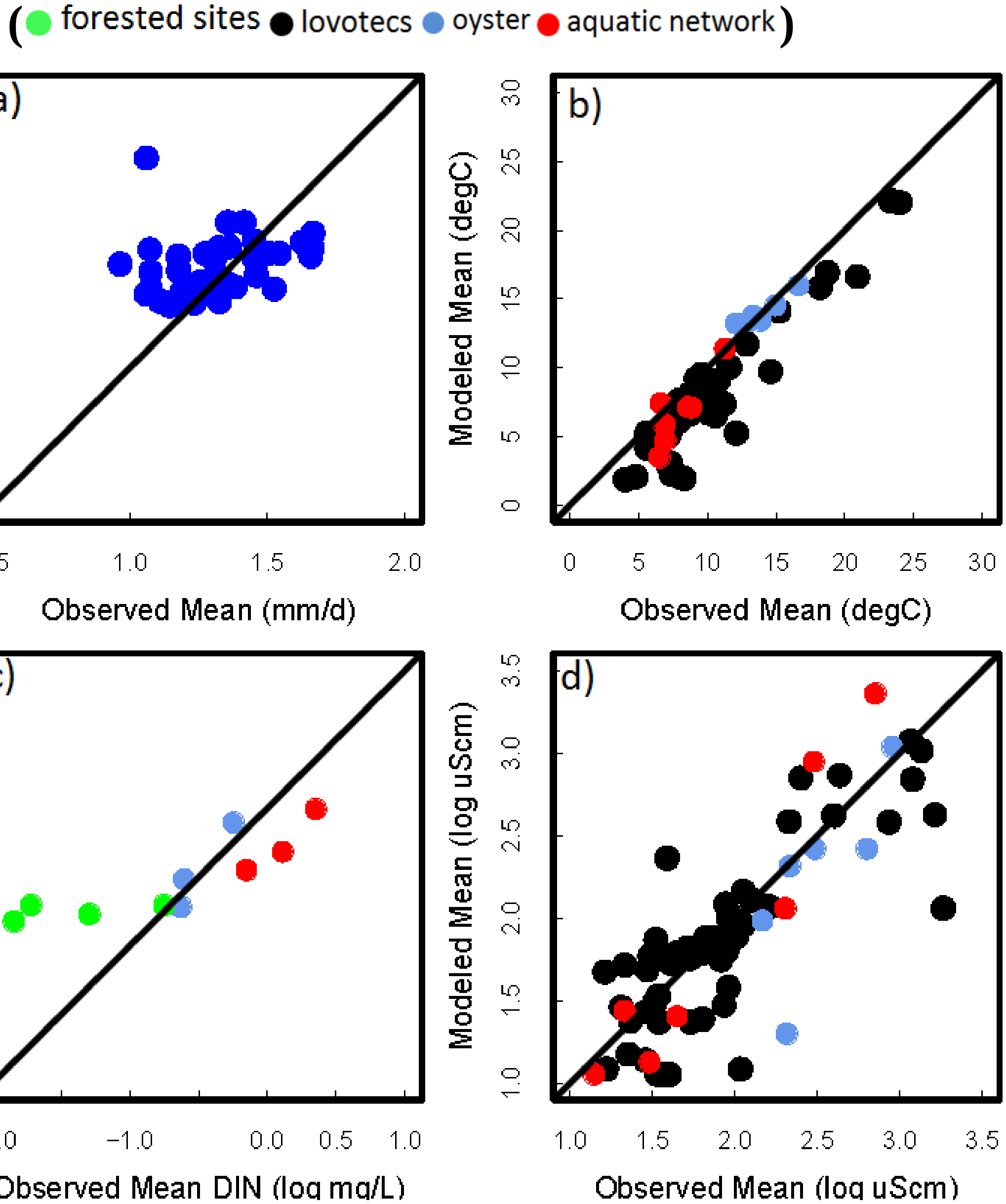


Fig. A4.2. Comparison of mean daily (summer only) modeled values with observations for a) streamflow (mm/d), b) water temperature (degC), c) DIN (mg/L) and d) specific conductivity (uS/cm)

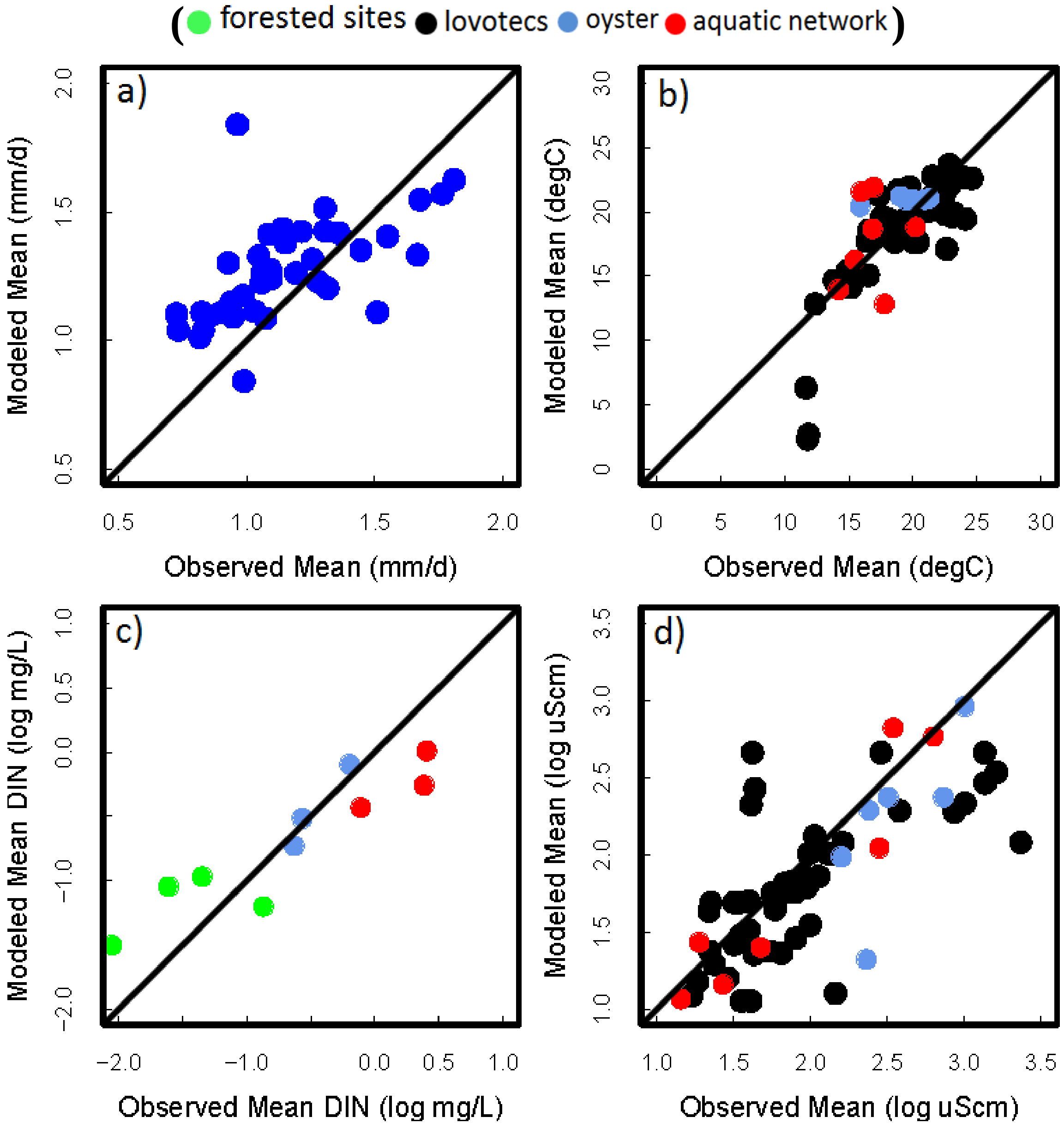
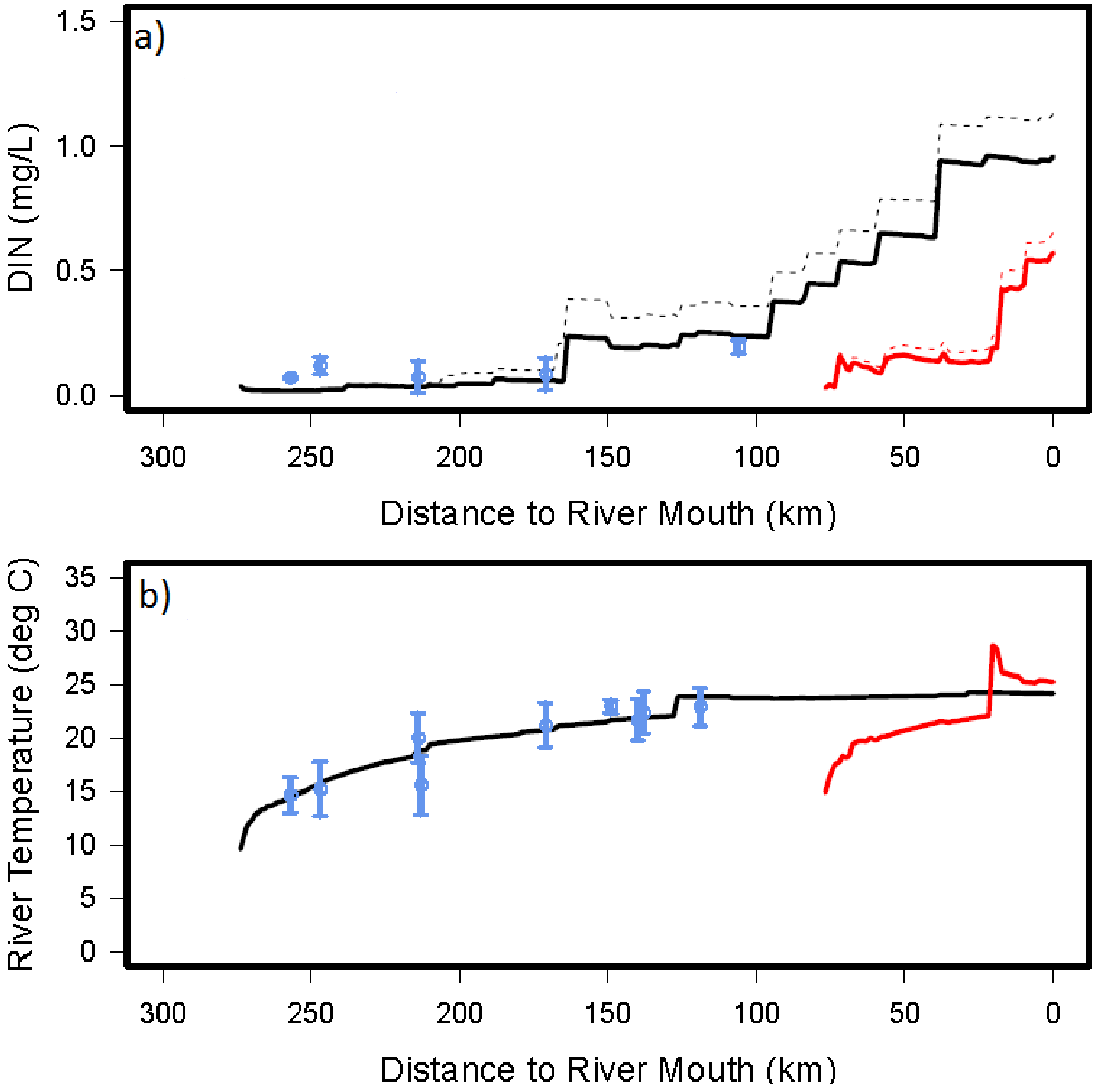


Fig. A4.3. Basin profiles (i.e. the longest flow path distance from the basin mouth to headwaters) for (a) DIN (mg/L), (b) river water temperature (deg C) and (c) specific conductivity (uS/cm) during mean summer conditions. The black and red lines represent coupled model results for the Merrimack and Piscataqua Rivers, respectively. Blue points show the mean and standard deviations for observations at LoVoTECS sites. The dotted line represents conservative mixing of DIN in a simulation without instream denitrification (Fig. A4.3a)



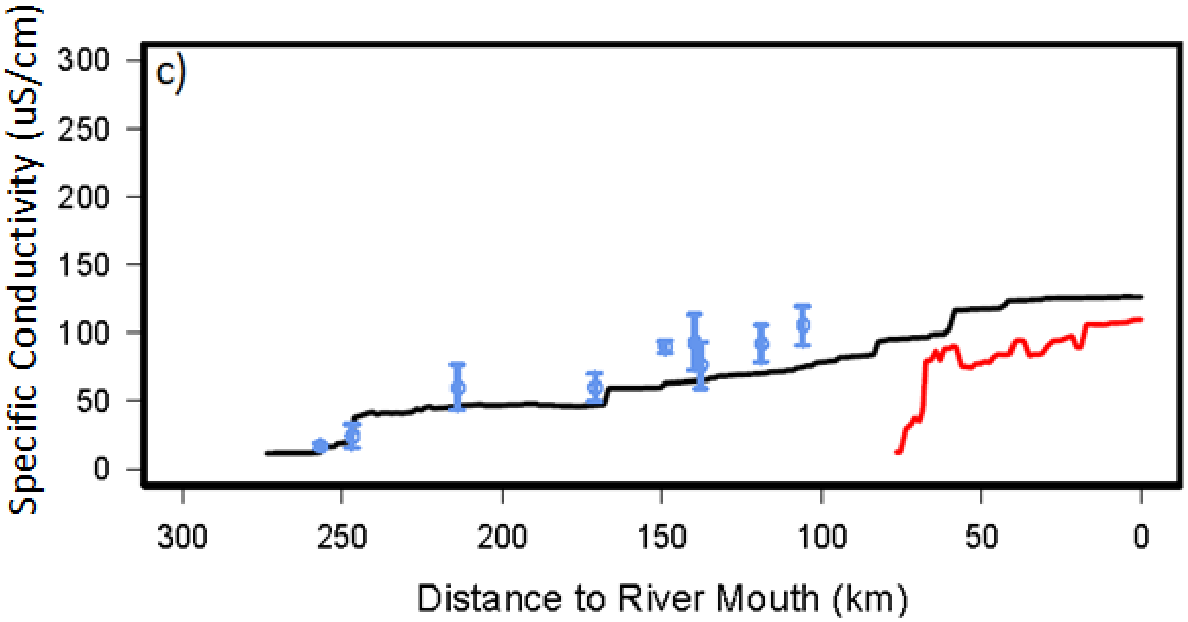

c)
Specific Conductivity (uS/cm)
300
250
200
150
100
50
0
300
250
200
150
100
50
0
Distance to River Mouth (km)

Fig. A4.4. Distribution of forest nitrogen load, summer water temperature and precipitation: a) Forest Nitrogen Load (kg/yr), b) Headwater Temperature Impaired (km d), c) Annual Precipitation (mm/yr), d) Summer Precipitation (mm/yr), and e) Carbon Sequestration (kg C yr^{-1} km^{-2}) between 2075-2100 for four scenarios compared to contemporary range (1980-2005). (a-e) Boxes represent first to third quartiles of data with line defining median, whiskers extend to 1.5 × IQR, outliers as circles beyond.