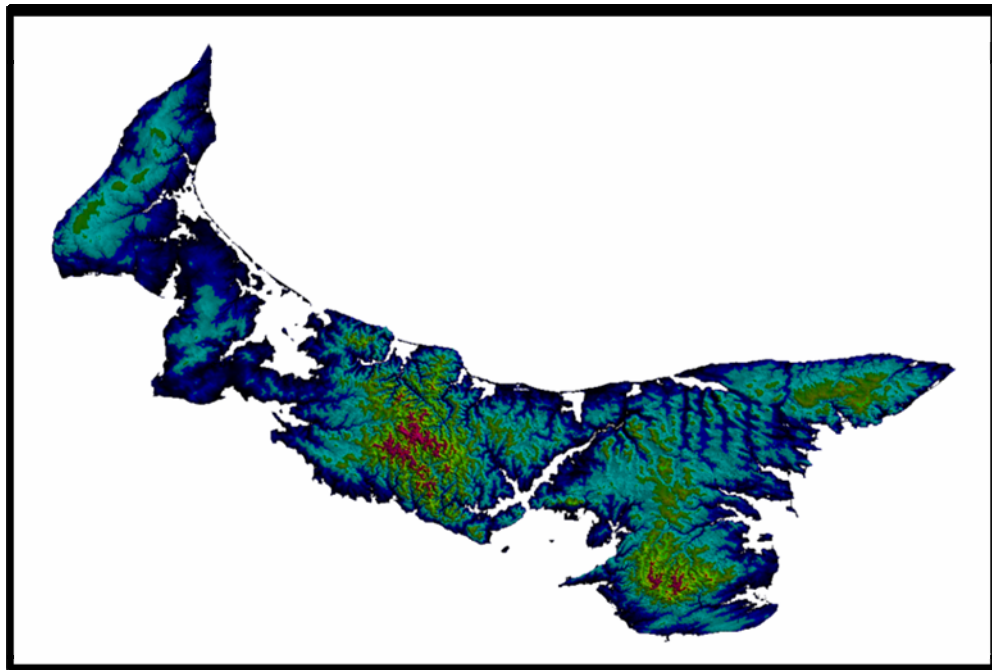


# MODELLED POTENTIAL TREE SPECIES DISTRIBUTION FOR CURRENT AND PROJECTED FUTURE CLIMATES FOR PRINCE EDWARD ISLAND, CANADA

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## Abstract

To promote the sustainability of forests, one of the key issues for forest practitioners is to understand how site quality, species distribution, and ultimately plant growth are affected by environmental site conditions and how these factors may vary with changes in climate. In this report, we provide a description of a spatially explicit modelling framework that relates modelled climatic factors and potential tree species response to potential species distribution. As a demonstration of the method, we apply it to thirteen tree species native to Prince Edward Island (PEI), Canada, for both current (1971-2000) and projected mean climate conditions for 2011-2040, 2041-2070, and 2071-2100.

**Potential species distribution (PSD)** is modelled in this report as a function of (i) incident photosynthetically active radiation (PAR; portion of visible light used in photosynthesis), (ii) growing degree days (GDD; an index of heat accumulation), and (iii) soil water content (SWC). Spatial estimates of PAR and SWC are obtained with an existing process-based model, the **Landscape Distribution of Soil moisture, Energy, and Temperature model (LandSET)**. GDD and average air temperature are estimated from remote sensing data derived primarily from Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat Enhanced Thematic Mapper Plus (Landsat-7 ETM+) optical and thermal (infrared) image data. Average air temperature and annual precipitation (presented as an interpolation of climate station precipitation measurements) serve as input to **LandSET** in the calculation of SWC. In this assessment, the influence of hydraulic conductivity in the re-distribution of water in the landscape is assumed to vary with soil drainage category, SWC, slope position, and flow accumulation. Due to inadequate soil fertility information for PEI, soil fertility is not included in the report's definition of PSD. Also, no attempt is made to account for forest-forming dynamics associated with inter- and intra-specific competition, forest succession, species invasion and extirpation, and disturbance in the calculation of PSD.

Climate change scenarios for future environmental conditions and species distribution for PEI are based on statistical downscaling of coarse-grid climate projections from the first generation Canadian Coupled Global Climate Model (CCGCM1) using a “business as usual” greenhouse gas emission scenario (IS92a) for fourteen climate stations across Atlantic Canada. Species vital attributes defining potential species response to modelled long-term climatic conditions and SWC are based on values reported in the scientific literature.

PSD for current and future climates indicate that habitat of cold-hardy species on the Island, such as white spruce, balsam fir, and white birch, will deteriorate with climate warming. Isolated pockets of suitable habitat for these species is expected to persist longer in cooler areas of the landscape, i.e., adjacent to cold water bodies (e.g., Gulf of St. Lawrence and Northumberland Strait) and, to a minor extent, higher elevations. Under similar climatic conditions, hardwood species like yellow birch and sugar maple are expected to benefit from elevated GDD in the second tri-decade (2011-2040) and potentially face decline in the third and fourth tri-decade (i.e., 2041-2070 and 2071-2100). Suitable habitat for white ash, red maple, and red oak on the Island is projected to ameliorate/expand over the next 100 years with climate warming. The report does not examine PSD of tree species currently not found growing on the Island.

## 1. Introduction

Forests are an important resource worldwide due to their roles in (i) regulating local-to-global carbon budgets, (ii) supporting socio-economic activities in many rural and urban communities, (iii) conserving biodiversity, and (iv) regulating climate and atmospheric composition. As Canada possesses about 10% of global forests (Anonymous, 2007), developing further understanding of the geo-biophysical and ecological processes of forests and forested landscapes is important to Canadians. The focus of this report is to relate a number of vital attributes of selected tree species and their modelled response to potential distribution on Prince Edward Island (PEI), Canada, for current and future climatic conditions. Knowing where specific tree species may have the potential to grow in the landscape is important for the sustainable management of forests (e.g., Smith *et al.*, 1997).

Biophysical variables known to affect tree species distribution, potential occurrence, abundance, and growth include (i) incident photosynthetically active radiation (PAR; portion of visible light used in photosynthesis), (ii) growing degree days (GDD: a temperature related index), (iii) soil water content (SWC), and (iv) soil fertility (SF; Smith *et al.*, 1997; Aussenac, 2000; Bourque *et al.*, 2000; Ung *et al.*, 2001; Gustafson *et al.*, 2003).

There are many additional factors with potential to influence the presence or absence of tree species in the landscape, including minimum winter temperatures, winter thaw-freeze severity (Bourque *et al.*, 2005), number of frost-free days, snow accumulation, alkaline soils, soil acidification, forest floor thickness, soil composition and compaction, intra- and inter-species competition, disturbance regimes (including harvesting), and time since disturbance. None of these factors are included in our climate- and SWC-centric definition of modelled **potential species distribution (PSD)**.

Methods that relate potential species occurrence to abiotic factors can be quite effective, but are limited in terms of capturing spatial variation. Attempts to up-scale site suitability indices (such as PSD) and related ecological variables from tree plot or transect sources to landscapes are greatly affected by the data and methods used for geospatial interpolation, e.g., kriging and co-kriging, inverse distance weighing, linear triangulation, and application of numerical splines (e.g., Bourque and Gullison, 1998; Gustafson *et al.*, 2003; Monserud *et al.*, 2006). Remote sensing (RS) data and process-based models to estimate values for temperature-mediated variables, such as GDD and SWC, assist with spatial representation due to their ability to generate near-continuous data of the earth's surface.

Another method of forest-site characterisation using RS data is done through vegetation indices, such as normalised difference vegetation index (NDVI; a measure of vegetation greenness) and enhanced vegetation index (EVI; e.g., Ma *et al.*, 2006; Waring *et al.*, 2006). Although proved useful, these RS-based methods lack predictive capability and fail to inform as to (i) the suitability of specific sites to support plant growth beyond what is already there, and (ii) the specific current and future environmental conditions that encourage growth among different plant species.

In earlier work we have developed methods to map (i) PAR and SWC using process-based models, particularly with the **Landscape Distribution of Soil moisture, Energy, and Temperature model (LandSET)**; Bourque and Gullison, 1998; Bourque *et al.*, 2000; Hassan *et al.*, 2006), and (ii) GDD from RS data (Hassan *et al.*, 2007a, and 2007b). As part of this work, we have also developed methodologies to map PSD for a high balsam fir [*Abies balsamea* (L.) Mill.] content region in northwestern New Brunswick (NB), Canada (Hassan and Bourque, 2009). PSD values range

between 0-1, where 0 represents unfavourable site conditions and, thus, potentially *low probability* of species occurrence, and 1, superior site conditions and *high probability* of species occurrence.

In this report, we employ the formulation described in Bourque *et al.* (2000) and Hassan and Bourque (2009) to provide PSD surfaces for thirteen tree species native to PEI, Canada (between 45° 56' 46.7" N to 47° 03' 32.9" N latitudes and 61° 58' 8.2" W to 64° 24' 35.4" W longitudes) for current (1971-2000) and projected climate scenarios for 2011-2040, 2041-2070, and 2071-2100. The species investigated include

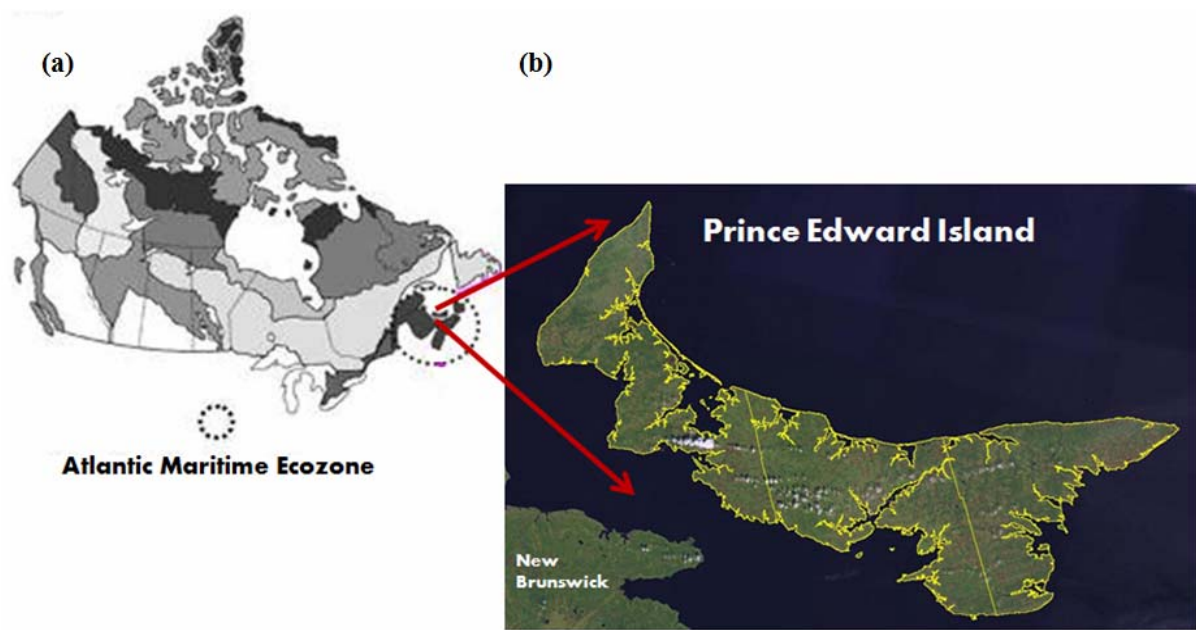
- i. seven **softwood** species, i.e., white spruce (*Picea glauca* (Moench) Voss), white pine (*Pinus strobus* L.), eastern white cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), balsam fir, red pine (*Pinus resinosa* Ait.), and red spruce (*Picea rubens* Sarg.); and
- ii. six **hardwood** species, i.e., white ash (*Fraxinus americana* L.), yellow birch (*Betula alleghaniensis* Britton), white birch (*Betula papyrifera* Marsh.), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), and red oak (*Quercus rubra* L.).

We exclude soil fertility (SF) in our formulation of PSD because currently no suitable map of SF exists for PEI with our particular resolution needs. In this report, we make no attempt to examine the northward migration of tree species non-native to PEI. Interaction between these species and those native to PEI forest (those not eliminated by climate warming) will define the future dynamics of forest development in PEI in an evolving climate regime.

## 2. Methods

### 2.1. Study Area

Canada is divided into fifteen terrestrial ecozone, generalised land-surface groupings based on similar soil formation, climate, and land use cover types described in the Canadian National Ecological Framework (Ecological Stratification Working Group, 1996). The Province of PEI (Figure 1) falls in the Atlantic Maritime Ecozone of eastern Canada (Figure 1a), and is characterised by a highly fragmented landscape (predominantly forest and agriculture) and gently rolling terrain (i.e., elevations ranging from 0-143 m above mean sea level, AMSL). Forests occupy about 43% of the province's land base and agriculture, 38%. Provincial climate is largely influenced by the region's proximity to Northumberland Strait on the south and west of the Island and the Gulf of St. Lawrence on the north and east. With maritime influence, the arrival of the seasons is usually delayed by several weeks. On average, winters are milder than most regions of Canada. Spring is late and cool. Summer is modest and breezy. The province experiences an annual mean temperature and total precipitation range of 5-6°C and 1000-1360 mm (Environment Canada; [http://climate.weatheroffice.ec.gc.ca/climate\\_normals/index\\_e.html](http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html), last accessed on October, 2009).



**Figure 1.** Atlantic Maritime ecozone of eastern Canada (a) and a mosaic of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) images depicting the Canadian Province of Prince Edward Island (PEI; outlined in yellow; b). White patches are clouds.

## 2.2. Species Attributes and Habitat

1. **White spruce** is found to grow from Newfoundland to British Columbia, and as far north as the Northwest Territories (NWT) and Yukon. The northern limit of white spruce is correlated to the 10°C mean July isotherm, cumulative summer GDD, growing-season mean net radiation, and low light conditions. Other biotic and abiotic variables affecting the northern distribution of white spruce include lack of soil, low soil fertility, low soil temperature, fire, insects, and diseases (Burns and Honkala, 1990a). Mean annual precipitation across the species' range varies from 1270 mm in Nova Scotia (NS) and Newfoundland to 250 mm throughout the Northwest Territories, Yukon, and portions of Alaska. Conditions are most severe along the species' southern limit where mean annual precipitation varies from 380-510 mm and mean July daily temperatures can reach 24°C. White spruce grows best in regions where the growing season > 60 days. White spruce can grow on a range of soil types. In general, good growth occurs where soil water-to-air ratios are balanced. The species will tolerate a wide range of moisture conditions, but will not tolerate standing water as a result of reduced rooting space (Burns and Honkala, 1990a).
2. **White pine** grows in a cool-moist climate. Distribution of white pine coincides with the mean July temperature range of 18-23°C. Annual precipitation varies from 510-2030 mm across its range. Throughout its range, precipitation is about 1-1.5 times the evaporation rate. White pine is found on nearly all soil types in its range, but performs the best on well drained sandy soils of low to medium quality. On sandy sites, white pine regenerates naturally and competes well. White pine will also grow on fine sandy loams and silt-loam soils with inferior drainage when there is no competition from hardwoods, especially during the establishment phase (Burns and Honkala, 1990a).

3. **Eastern white cedar** extends westward from Anticosti Island in the Gulf of Saint Lawrence to the southern part of James Bay and through central Ontario and southeast Manitoba. Eastern white cedar grows in a relatively cool-moist climate. Annual precipitation across its range varies from 710-1170 mm and temperatures are generally cool. The southern limit of the species has an annual mean temperature > 10°C in the northern Lakes States (USA) and up to 16°C in the southern Appalachians. Eastern white cedar grows on a variety of organic and mineral soils. It does not fare well on excessively wet or dry sites. The species normally grows best on slightly acidic to neutral soils (pH, 5.5-7.2). Eastern white cedar is usually dominant in nutrient-rich swamps, where it can compete well and is protected from fire. On upland sites, eastern white cedar is commonly found growing next to seepage zones. Eastern white cedar mostly grows in mixed stands, but on occasion can be found to grow in pure stands (Burns and Honkala, 1990a).
4. **Eastern hemlock** is a slow growing, long-lived species (> 800 years) which grows well in diffuse light. The northern limit of eastern hemlock extends from northeastern Minnesota and western 1/3 of Wisconsin eastward through northern Michigan, south-central Ontario, through southern Quebec, NB, and NS. Eastern Hemlock is limited to regions with cool-humid climates. In the northern areas of its range, January temperatures average -12°C and July temperatures, ~16°C. Annual precipitation varies from < 740 mm in the heavy snowfall regions in the north to > 1270 mm, elsewhere. In the more productive areas of the range (along the Atlantic Coast and southern Appalachian Mountains), January temperatures can reach as high as 6°C and annual precipitation can be > 1520 mm. Eastern hemlock grows best on moist to very moist soils with good drainage. In Canada and northeastern States, hemlock is found to grow on shallow loams and silt loams (Burns and Honkala, 1990a).
5. **Balsam fir** develops best in the eastern part of its natural range, including in NB, NS, and PEI. The provinces are distinguished by their cool temperatures and abundance of moisture. Growth of balsam fir is most favourable in areas with a mean temperature of 2-4°C and annual precipitation of 760-1100 mm. The species grows on a broad range of inorganic and organic soils characterised by a thick mor humus and well-defined A horizon resulting from leaching. Soil moisture is the most important determinant of growth potential, with soil nutrients being less important (Burns and Honkala, 1990a). Species commonly associated with balsam fir in the Acadian-forest portion of its natural range include black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce, white birch, trembling aspen (*Populus tremuloides* Michx.), yellow birch, American beech (*Fagus grandifolia* Ehrh.), red maple, sugar maple, eastern hemlock, eastern white pine, tamarack (*Larix laricina*), black ash (*Fraxinus nigra*; Farrar, 1995), and eastern white cedar. Red spruce is frequently associated with balsam fir in NB, NS, and the state of Maine (Burns and Honkala, 1990a).
6. **Red pine** is confined to the northern forest region and southern edge of the boreal forest. Its range stretches from Cape Breton Island to southeastern Manitoba in a westward direction to Massachusetts, in the south. It also grows locally in several states and in Newfoundland. Red pine grows in areas with cool-to-warm summers, cold winters, and low to moderate precipitation. Average annual precipitation varies from about 510-1010 mm throughout the species' range. The northern limit of red pine coincides with the 2°C mean annual isotherm (Burns and Honkala, 1990a). Red pine is commonly found on dry, sandy soils low in fertility. Red pine is rarely found growing in swamps, but can be found to grow along their borders. Productivity in red pine, in general, increases from ridges to plains to uplands.

7. **Red spruce** grows from the Maritime Provinces to southeastern Ontario, and south to the state of Massachusetts. Red spruce is also found to grow along the Appalachian Mountains. It grows best in a cool, moist climate with an annual precipitation of about 910-1320 mm. Red spruce reaches maximum growth in the Appalachian Mountains, where the air is humid and rainfall is heaviest during the growing season. Soils where red spruce grows are mostly acidic, with pH's from 4-5.5. Lack of proper aeration in poorly drained sites limits the growth of red spruce. Red spruce can grow both in pure and mixed stands (Burns and Honkala, 1990a).
8. **White ash** is never a dominant species in the forest. White ash is found to grow from Cape Breton Island to northern Florida in the east, to eastern Minnesota, south to eastern Texas. The climate in the species' range varies considerably: mean January temperatures vary from -14°C to 12°C and the mean annual minimum temperatures vary from -34°C to -5°C. Mean July temperatures fluctuate between 18 °C to 27°C. Mean annual precipitation ranges from 760-1520 mm. The length of the frost-free period across the species' range varies from 90-270 days. It grows best on nutrient-rich, moist, well-drained soils (Burns and Honkala, 1990b). Although seldom found in swamps, white ash is tolerant of occasional flooding. White ash forms a minor component of the Sugar Maple-Beech-Yellow Birch, Hemlock-Yellow Birch, and Red Spruce-Balsam Fir forest associations.
9. **Yellow birch** grows from Newfoundland to southeastern Manitoba in the west, to New Jersey in the south and along the Appalachian Mountains, as far south as eastern Tennessee. Greatest concentration of yellow birch occurs in NB, Quebec, Ontario, and the northern states of Maine, Michigan, and New York. Yellow birch grows in cool areas with plenty of precipitation. Its northern limit coincides with the 2°C average annual temperature isotherm and the southern and western limits with the 30°C maximum temperature isotherm. Annual precipitation across its range varies from about 1270-640 mm (Burns and Honkala, 1990b). Yellow birch grows in diverse geology, topography, and soil and moisture conditions. It grows best on well-drained, fertile loams and moderately well-drained sandy loams. Although its growth maybe poor, yellow birch can also grow on soils with inferior drainage because of reduced competition from other species. Yellow birch appears in all stages of succession.
10. **White birch** is a short-lived species found to grow from Newfoundland west to northwest Alaska. White birch is a northern species adapted to cold temperatures. Its range is constrained to the north by the 13°C July isotherm and to the south, by the 21°C isotherm. White birch tolerates wide fluctuations in pattern and amount of precipitation. In general, the climate where white birch grows has short cool summers and long cold winters. White birch is found to grow on almost any soil type and topography, from steep rocky outcrops of mountains to wetlands in the boreal forest. Best development of the species occurs on the deeper well-drained soils, mostly of glacial origin. Poorest development of the species occurs on excessively dry and wet sites (Burns and Honkala, 1990b). White birch grows either in pure stands or in mixtures of varying proportions.
11. **Sugar maple** is one of the largest and more important hardwoods. The species range extends eastward from southwest corner of Manitoba, through central Ontario, southern Quebec, and the Maritime Provinces. Its southern limit coincides with central New Jersey and southern border of Tennessee. Sugar maple is constrained to regions with cool-moist climates. Across the species' range, January temperatures range from -18°C to 10°C and July temperatures from 16°C to 27°C. Annual precipitation ranges from 510 near the species' western limit to 2030 mm in the southern Appalachian Mountains. Most of the range receives about 1270 mm

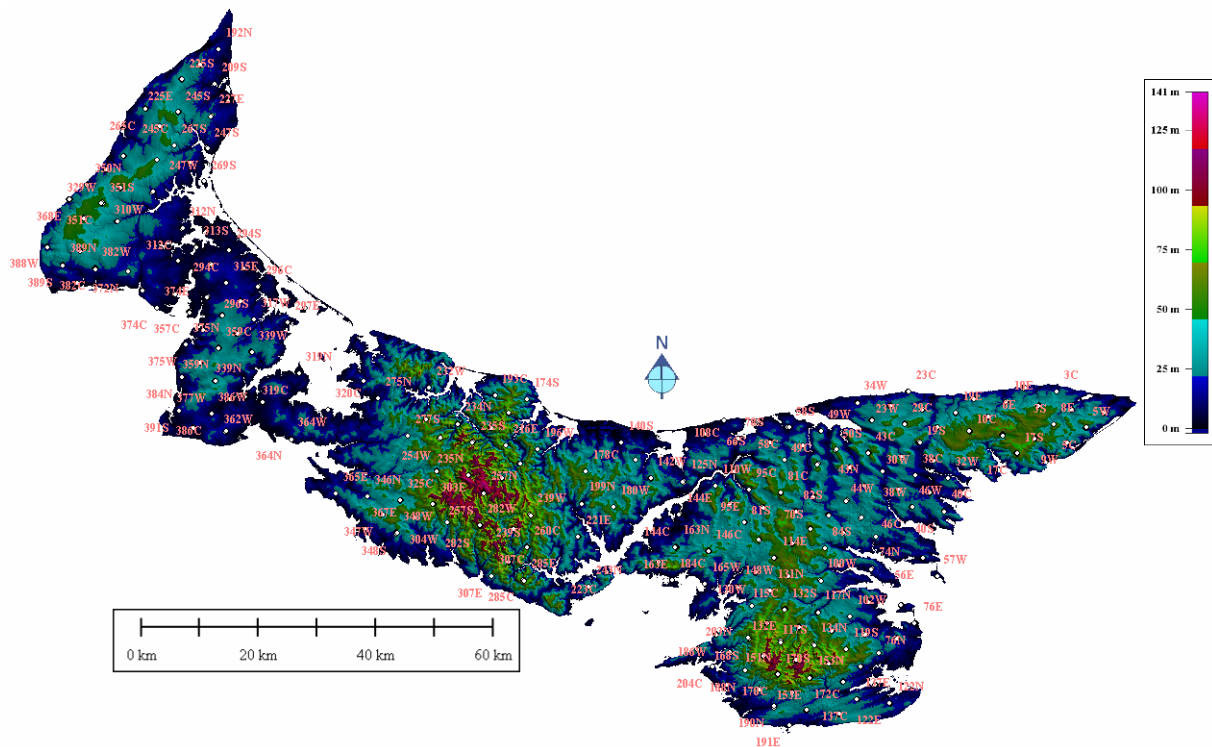


per year. Sugar maple grows on sands, loamy sands, sandy loams, loams, and silt loams, but it performs best on well-drained loams (Burns and Honkala, 1990b). Sugar maple most frequently grows on soils with pH 5.5-7.3. Sugar maple forms a significant component in six major forest associations.

12. **Red maple** is one of the most abundant hardwood in eastern North America. It grows from the Atlantic Provinces to Florida and Texas, in the south. The northern limit of the species' range corresponds with the -40°C mean minimum isotherm. The western limit is defined by the drop in precipitation and dry conditions in the interior of the continent. Of all the maples, red maple has the greatest tolerance of climatic conditions. Red maple grows on a diversity of sites, from dry ridges and southwest slopes to peat bogs and swamps. It can tolerate very wet to very dry sites. It develops best on moderately well-drained, moist sites (Burns and Honkala, 1990b).
13. **Red oak** grows from Cape Breton Island to Ontario, in Canada. Mean annual temperature across its range is ~4°C in the north to 16°C in the extreme south. Mean annual precipitation varies from about 760-2030 mm throughout the species' range. Red oak grows on cool-moist soils. Red oak can be found in all topographic positions, but it grows best on lower and middle slopes with a north-facing or east-facing orientation, in deep ravines, and well-drained valley bottoms. Factors which promote red oak growth include depth and texture of the A horizon, slope orientation, slope position, surface configuration, and depth of the water table (Burns and Honkala, 1990b).

### 2.3. Data Requirement and Processing

Data required to generate maps of PSD, included (i) a Digital Elevation Model (DEM; Figure 2) of PEI, (ii) precipitation surface, (iii) **LandSET**-modelled estimates of PAR and SWC (Bourque and Gullison, 1998; Bourque *et al.*, 2000), (iv) RS-based estimates of GDD (Hassan *et al.*, 2007a and 2007b), and (v) statistically-downscaled temperatures and growing season lengths. A 10-m DEM of PEI was generated from 1.5-m resolution **Light Detection And Ranging** (LiDAR) point-data acquired from the province. Supplementary datasets used in confirming current species distributions included inventory plots (Figure 2) and GIS forest inventory maps from which species presence were recorded, courtesy of the PEI Department of Environment, Energy, and Forestry (PEI DEEF).

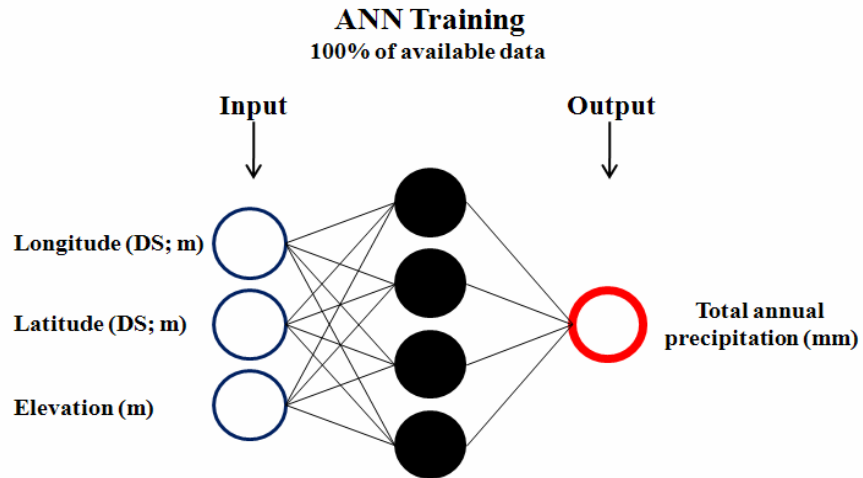


**Figure 2.** Geographic distribution of 720 inventory plots for PEI (labeled white symbols); Digital Elevation Model (DEM) of PEI is in the background.

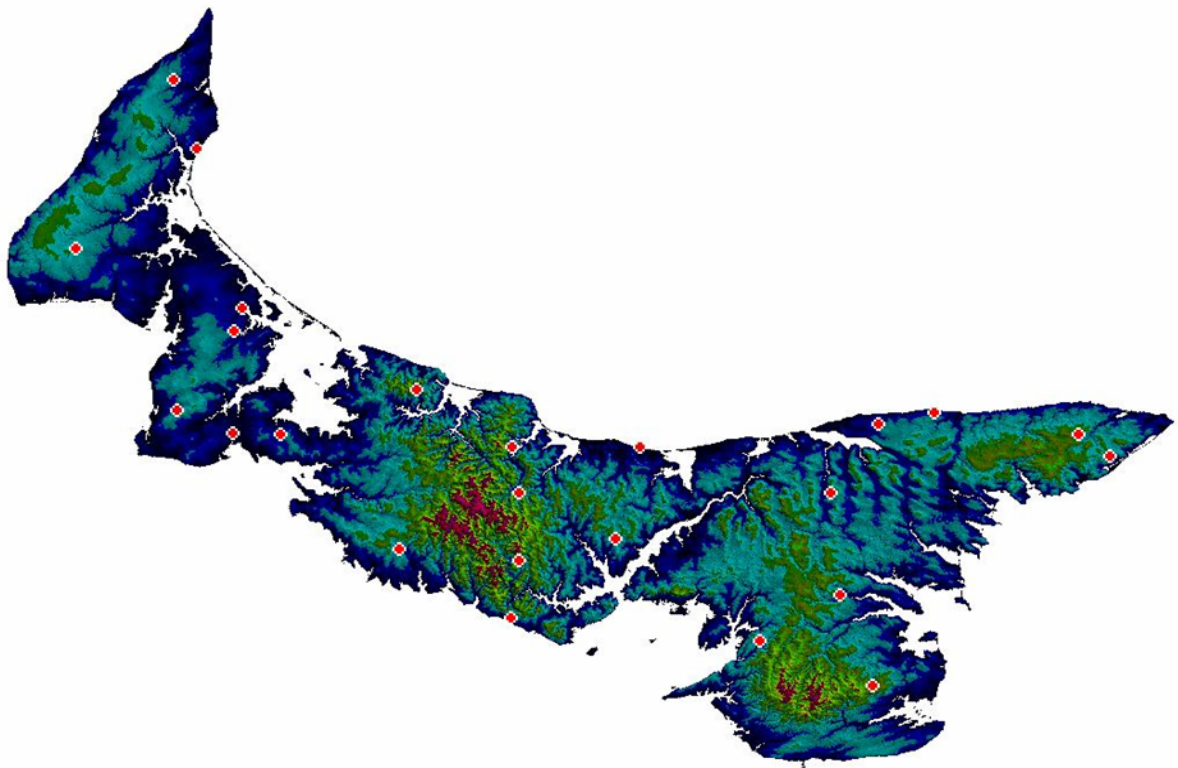
### 2.3.1. Precipitation

In order to construct a mean annual total precipitation surface for PEI (in mm), a generalised (trained) artificial neural network (ANN) was employed. Training of the ANN was based on the generalised Delta rule or backward error propagation method in NNModel32. It consisted of an input, a hidden, and an output layer. The input layer consisted of the independent variables of longitude, latitude [converted to Double Stereographic (NAD 1983-CSRS) PEI coordinates, in m], and elevation (m; Figure 3). The target output consisted of annual total precipitation at all Environment Canada climate stations on PEI (24, altogether; Appendix A).

Normally a fraction of the dataset is used to train the ANN. The other fraction is used to check the reliability of model calculations. However, because of the limited number of samples, the entire dataset was utilised in training the ANN. Training datasets provided the ANN with required information for computational learning (Bourque and Gullison, 1998). The ANN was trained by reducing discrepancies between output and target precipitation values (Appendix A) through the adjustments of internal weights (represented as lines in Figure 3). The trained ANN was then applied to the individual cells of the DEM to obtain the required precipitation surface. Figure 4 shows the relative location and elevation (in m AMSL) of the climate stations that provided precipitation data.



**Figure 3.** Representation of artificial neural network (ANN) constructed to model average annual precipitation (in mm). Inputs are based on elevation (m AMSL) and Double Stereographic (DS; NAD 1983-CSRS) coordinate transformation of Digital Elevation Model (DEM) longitude and latitude (in m).



**Figure 4.** Geographic distribution of 24 Environment Canada climate stations (red symbols) on PEI providing precipitation data (refer to Appendix A for station name and coordinates).

### 2.3.2. Photosynthetically Active Radiation (PAR)

In calculating incoming solar radiation and PAR, terrain attributes of (i) slope, (ii) aspect, (iii) horizon angle, (iv) view factor, and (v) terrain configuration factor were obtained by processing height data from the DEM (after Bourque and Gullison, 1998). Incoming solar radiation at the top of the atmosphere was partitioned into its direct and diffused components and each were treated differently as they passed through the atmosphere and interacted with the underlying terrain before being summed at the surface (Bourque and Gullison, 1998). Atmospheric transmissivity, although made variable during the day a mean mid-afternoon value of 0.70 was used as a basis for the calculations (Bourque and Gullison, 1998). Hourly solar-radiation values generated with the solar-radiation module of **LandSET** were integrated to provide a growing season total. Amount of available PAR was set as 45% of calculated incident solar radiation (Hassan *et al.*, 2006). Incident PAR was assumed unaffected by changes in atmospheric composition and climate.

### 2.3.3. Growing Degree Days (GDD)

A GDD map at 28.5 m resolution was developed by Hassan *et al.* (2007b) by employing (i) Landsat-7 ETM+ surface reflectance data to provide a one-time estimate of EVI at 28.5 m resolution, (ii) a chronological series of 16-day composites of MODIS EVI at 250 m resolution for the 2003-2005 growing periods, and (iii) a 1-km resolution base map of GDD (see Hassan *et al.*, 2007a, for additional detail) based on the standard definition of GDD, i.e.,

$$\text{GDD} = \sum_{i=1}^{i=n} (\bar{T} - T_{\text{base}}), \text{ when } \bar{T} - T_{\text{base}} > 0, \quad (1)$$

where  $\bar{T}$  is the average temperature,  $T_{\text{base}}$  the base temperature of 5°C (Hassan *et al.*, 2007a), and  $i=1$  represents the start-day and  $i=n$ , the end-day of the growing season. Data fusion and data augmentation at fine spatial resolution (at 28.5 m) was possible because of the strong correlation between GDD and EVI (Hassan *et al.*, 2007a). GDD, by virtue of its calculation as an integration of temperature differences  $> 0.0$  from early April (start of the melt period) to late October (start of the freeze period; Hassan *et al.*, 2007a), inherently incorporates variable growing season lengths in its calculation.

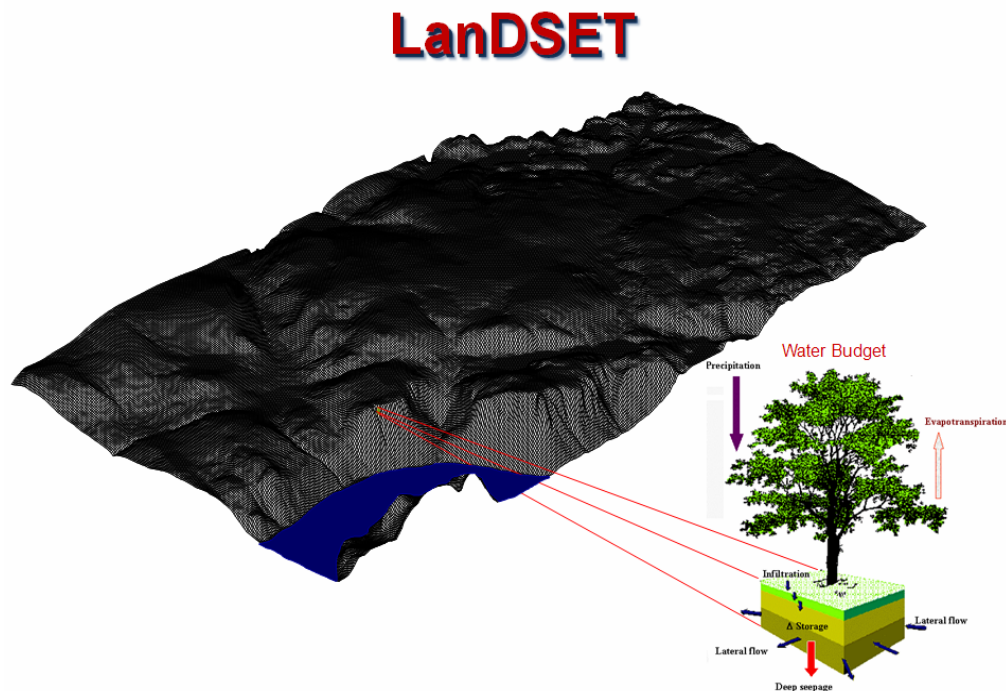
### 2.3.4. Soil Water Content (SWC)

Long-term average soil water content for PEI was estimated with the SWC-module of **LandSET** (after Moore *et al.*, 1993; Gallant, 1996). The SWC-module addressed soil water distribution according to a point-by-point assessment of hydrological fluxes (including precipitation, evapotranspiration, percolation, and surface runoff; all expressed in mm d<sup>-1</sup>; Figure 5). Input to the model included topography, by way of DEM height values and cell size specification (10 m), net radiative fluxes (in MJ m<sup>-2</sup>), and long-term annual average precipitation amounts described spatially by interpolation of climate station precipitation data. Prior to the calculation of SWC, the

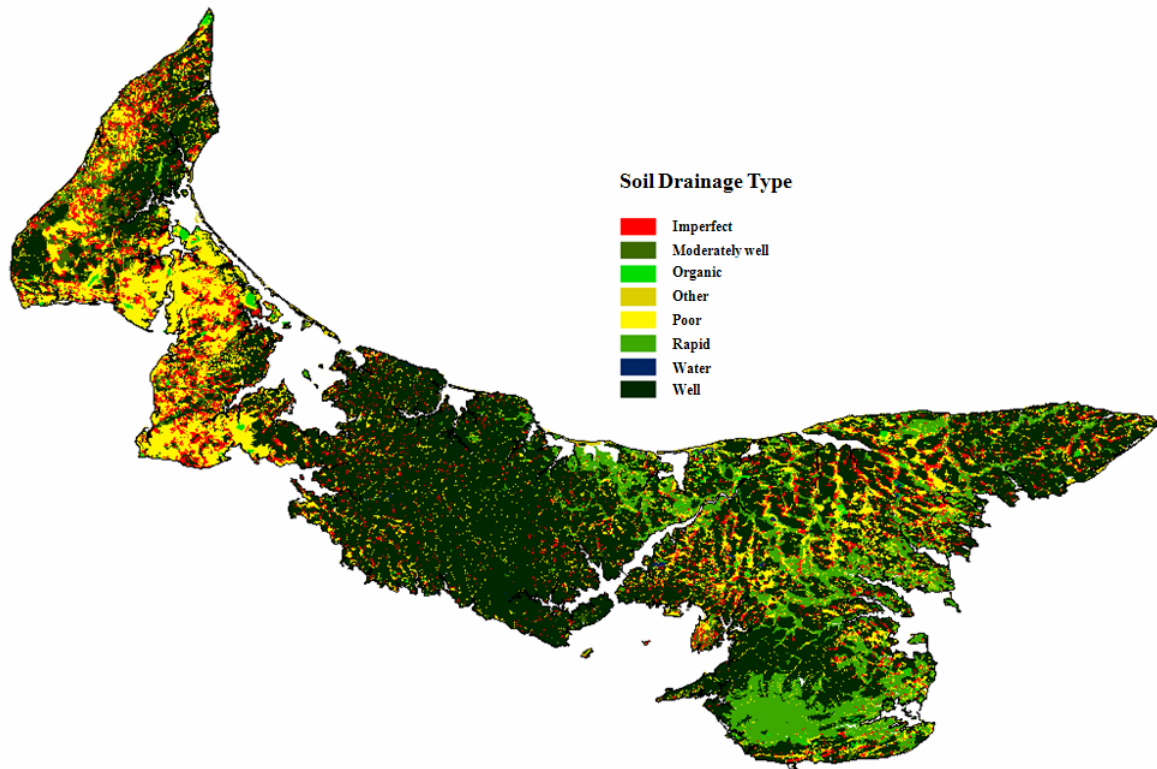
raw DEM was treated by removing false depressions with the pit-filling algorithm of Planchon and Darboux (2001).

Hydrological inputs to individual grid-points were precipitation and lateral flow from upslope regions, and outputs were percolation (deep seepage), evapotranspiration, and surface runoff flows to regions downslope. Surface water on valley slopes was channeled downslope according to zones of confluence (and divergence) in the local topography. Calculation of grid-point evapotranspiration was based on an application of the Priestley-Taylor equation (Priestley and Taylor, 1972), grid-point SWC, and a **LanDSET**-evaluation of net all-wave radiation. The SWC values were in the range of 0-1, with 0 being associated with the driest sites at or below the permanent wilting point, and 1 with the wettest sites at field capacity. Percolation was based entirely on SWC and occurred whenever soils were at field capacity (Bourque *et al.*, 2000). At field capacity, percolation rates were defined as a function of soil property and the saturated conductivity of the soil. Values for the equation parameters are listed in Bourque and Gullison (1998) and Bourque *et al.* (2000).

In assessing SWC, the influence of soil properties (i.e., infiltration capacity, hydraulic conductivity) on soil water was assumed to vary with soil drainage (Figure 6). Soil drainage, from rapid to poor (Figure 6), were assigned hydraulic conductivities based on values reported in the literature, e.g., Clapp and Hornberger (1978). These values (Table 1) controlled the rate water is transmitted through the soil during the unsaturated and saturated phases.



**Figure 5.** The **LanDSET** model simulates soil water content in the landscape according to cell-by-cell assessments of hydrological fluxes and storage. Input to the calculation of SWC includes available solar radiation and hydrological inputs of annual mean precipitation and lateral flow from upslope regions (inset). Hydrological outputs are infiltration, deep seepage, evapotranspiration, surface runoff, and changes in soil-water storage.



**Figure 6.** Soil drainage map of PEI (courtesy of PEI DEEF). The dark blue polygons represent areas with surface water.

**Table 1:** Hydraulic conductivity of soils as a function of drainage class.

Soil Drainage	Maximum Conductivity <sup>1</sup>
	(mm d <sup>-1</sup> )
Rapid	5.0
Well	4.5
Moderately well	3.5
Imperfect	1.5
Organic (Poorly drained)	0.5
Poor	0.5

<sup>1</sup> Maximum conductivity is the hydraulic conductivity during saturation. During the unsaturated phase, maximum conductivity is reduced in **LanDSET** as a power function of soil water content (SWC).

### 2.3.5. Evaluating Modelled PSD for Current Climate

Species occurrence in PEI inventory plots (PEI DEEF, 2009) and GIS forest cover was used as an indication of current species distribution across the province. The assessment included 720

inventory plots and the provincial Corporate Resource Inventory 2000 data. In an attempt to investigate the degree to which current PSD reflected actual species distribution, inventory plots and GIS forest inventory polygons containing the target species were compared with the species' PSD. For purpose of assessment, several assumptions were made:

- Tree species were considered to have occurred in an inventory plot and GIS forest cover polygon, if the species represented at least 10% of the observed composition in that plot or polygon.
- Raster cells representing the landscape were considered to have the biophysical attributes needed for species occurrence, where the predicted PSD > 0.

Locations of plots were linked to the corresponding raster-based prediction of PSD for current climate conditions (1971-2000) to summarise the correlation between observed and predicted occurrences for each species. The analysis summarised the relative frequency of each of the four possible outcomes, namely

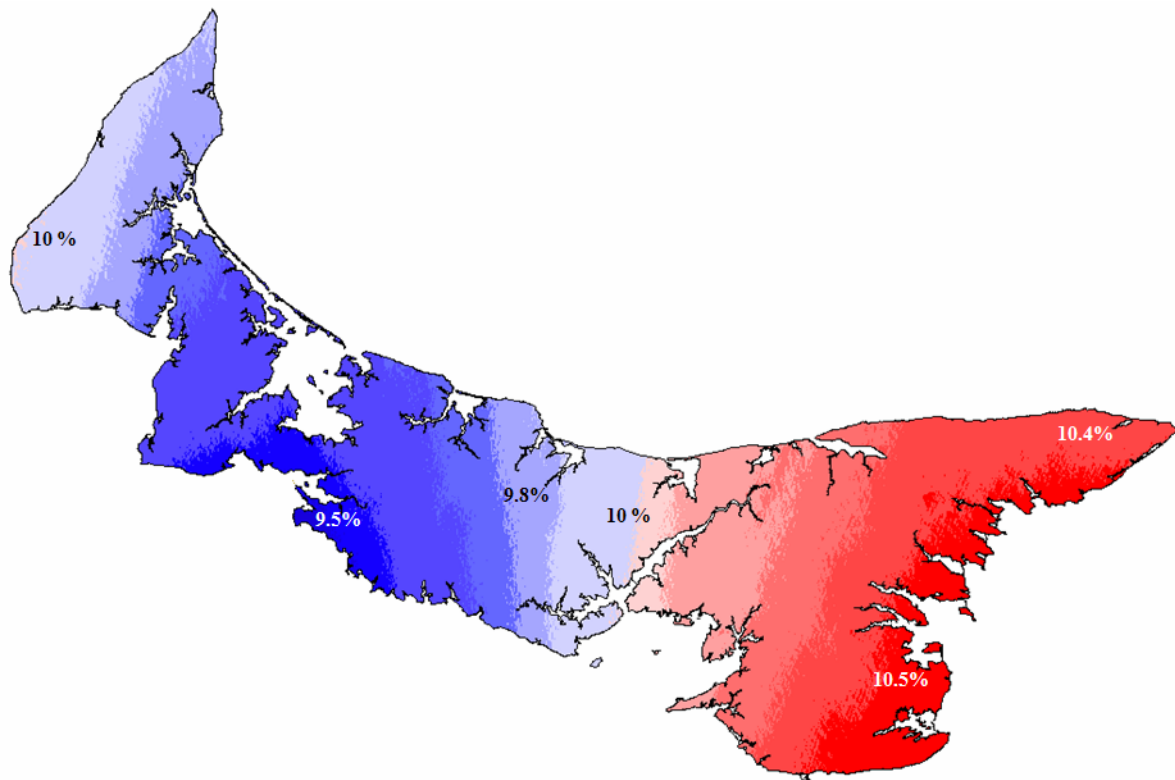
1. **Predicted vs. Observed Species Occurrence:** This outcome demonstrates positive agreement between predicted species occurrence and inventory-plot ground observations.
2. **Predicted vs. Observed Species Absence:** This outcome demonstrates positive agreement between predicted species absence and inventory-plot ground observations.
3. **Predicted Occurrence vs. Observed Species Absence:** This outcome is indeterminate with respect to model predictions, as species absence from the inventory plots maybe the result of other forest-forming factors not addressed in the current definition of PSD (e.g., species succession, disturbance, land conversion).
4. **Predicted Absence vs. Observed Species Occurrence:** The outcome demonstrates potential inaccuracies in the modelled biophysical factors and/or associated species environmental response functions (eq.'s 2-4 and model parameter values in Table 2). Source of modelled inaccuracy is associated with uncertainty in (i) species response threshold definition, (ii) DEM, and (iii) resolution (plot vs. DEM-cell resolution).

### 2.3.6. Projected Future Climates

Climate change scenarios for PEI were based on Environment Canada's statistical downscaling of coarse-grid climate projections generated with the first generation Canadian Coupled Global Climate Model (CCGCM1) using a "business as usual" (conservative) greenhouse gas emission scenario (i.e., IS92a scenario). IS92a is similar to the B2 emission scenario used by the Intergovernmental Panel on Climate Change (Nakicenovic *et al.*, 2000). Statistical downscaling facilitated the spatial downscaling of daily independent-dependent variable associations using multiple regression. The independent variables provided daily information concerning the mean synoptic state of the atmosphere by means of CCGCM1 projections; meanwhile, the dependent variable described conditions at the individual climate stations. Daily values for each month were averaged to reduce the amount of data requiring processing at a later time (Lines, pers. comm., 2008; Environment Canada). Monthly point-estimates were subsequently interpolated to yield province-wide contours of monthly maximum and minimum temperatures and growing season lengths.



Future climate change scenarios for PEI were based on fine-scale projections at 14 representative climate stations distributed across Atlantic Canada, including (1) Goose Bay, Cartwright, Gander, and Saint John's in Newfoundland; (2) Charlo, Chatham, Fredericton, Saint John, and Moncton in NB; (3) Nappan, Kentville, Greenwood, and Shearwater in NS; and (4) Charlottetown in PEI. The stations were selected according to the quality of their long-term historical daily records of temperature and precipitation. Interpolated maps of statistically-downscaled monthly maximum and minimum temperatures were then used to generate coarse-grain maps of growing season mean temperature (mean of 6-7 monthly mean temperatures) and GDD (based on a monthly application of eq. 1 and a base temperature of 5°C) for current and future 30-year time slices for PEI (i.e., 1971-2000, 2011-2040, 2041-2070, and 2071-2100). Based on the current conditions (1971-2000), maps of proportional change were generated for each tri-decade. Proportional increases from current conditions were then applied to the MODIS-based GDD (at 28.5 m resolution) to update their values for future conditions at 10-m resolution. Figure 7 provides an example of projected proportional changes in growing season mean temperature from current conditions (1971-2000) to 2011-2040.



**Figure 7.** Percentage increases in growing-season mean air temperature from current climate conditions (1971-2000) to 2011-2040 based on averaging 6-7 monthly mean temperature surfaces derived from statistically downscaled monthly maximum and minimum air temperatures. Similar surfaces were developed for each tri-decade (2041-2070 and 2071-2100), with current conditions as reference.

Precipitation projections, because of the sporadic nature of precipitation events, were based on a single constant proportional change applied to all current precipitation values (at point locations and across the interpolated field). Most regional climate models indicate that the Atlantic Provinces of Canada are likely to experience a 5% increase in precipitation in 2011-2040, a 10% increase in 2040-2070, and a 15% increase in 2071-2100 from current levels, as a result of



climate change (e.g., <http://atlas.nrcan.gc.ca/site/english/maps/climatechange>, site last accessed October, 2009). Although specific precipitation events may have a localised impact on tree-growing conditions, no Global Climate Model (GCM) can model these events (and their associated intensities) with much precision and, as a result, only the long term influence of precipitation and SWC on tree species habitat is addressed here.

## 2.4. Species Response Functions and Potential Species Distribution

In order to model PSD, we generated a series of generic response functions for PAR, GDD, and SWC (below). Index values of relative PSD for individual DEM grid-points were obtained by multiplying individual grid-point evaluations of species environmental response (Figure 8). Description of species response functions and associated parameter values (Table 2) appear below.

- a. PAR affects tree growth and tree distribution differently for different species. Shade-tolerant species such as sugar maple utilise low light levels more efficiently than shade-intolerant species, like trembling aspen and white birch (Oliver and Larson, 1996). As a result, shade-intolerant species are predicted to have reduced growth potentials in regions inherently low in sunlight. Species response to PAR (Figure 8a) is modelled with

$$R(\text{PAR}) = c_1 \cdot \left\{ 1 - \exp \left[ -c_2 \left( \frac{\text{PAR}}{\text{PAR}_{\max}} - c_p \right) \right] \right\}, \quad (2)$$

where  $c_1$  is a scaling factor,  $c_2$  is the slope of the response curve (Figure 8a),  $c_p$  is the light-compensation point, and  $\text{PAR}_{\max}$  is maximum PAR on south-facing slopes in northern latitudes (Bourque *et al.*, 2000).

- b. Plant metabolic processes and growth increase with temperature (Nilsen and Orcutt, 1996), as a result plant ranges correlate fairly well to annual heat inputs and GDD (Hassan *et al.*, 2007a). Species response to GDD (Figure 8b) assumes a parabolic function, i.e.,

$$R(\text{GDD}) = \frac{4(\text{GDD} - \text{GDD}_{\min}) \cdot (\text{GDD}_{\max} - \text{GDD})}{(\text{GDD}_{\max} - \text{GDD}_{\min}) \cdot (\text{GDD}_{\max} - \text{GDD}_{\min})}, \quad (3)$$

where  $\text{GDD}_{\min}$  and  $\text{GDD}_{\max}$  are the minimum and maximum values of GDD (e.g., Bourque *et al.*, 2000; Hassan and Bourque, 2009). The mid-point between  $\text{GDD}_{\min}$  and  $\text{GDD}_{\max}$

represents the GDD value that promotes optimal growth. In this work,  $GDD_{min}$  and  $GDD_{max}$  coincide with GDD at the northern and southern limits of the species range.

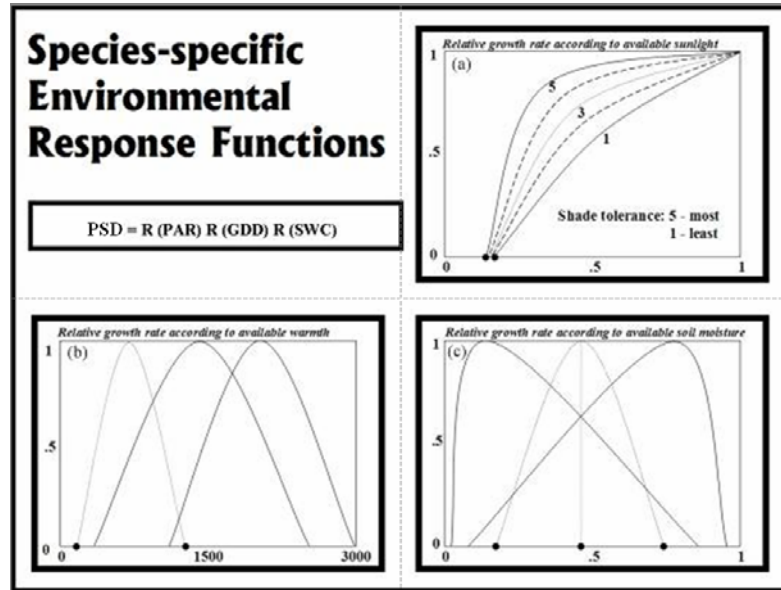
- c. Tree species differ in their soil water requirements (Oliver and Larsen, 1996). Species response to SWC (Figure 8c) is modelled after Bourque *et al.* (2000), i.e.,

$$R(SWC) = \max\left(0, \kappa \xi^\alpha (1 - \xi)^{\frac{1}{\alpha}}\right)$$

where

$$\begin{aligned} \xi &= \frac{SWC - SWC_{min}}{SWC_{max} - SWC_{min}}, \\ \chi &= \frac{\Psi - SWC_{min}}{SWC_{max} - SWC_{min}}, \quad SWC_{min} < \Psi < SWC_{max}, \\ \kappa &= \frac{1}{\chi^\alpha (1 - \chi)^{\frac{1}{\alpha}}}, \text{ and} \\ \alpha &= \sqrt{\frac{\chi}{1 - \chi}}. \end{aligned} \quad (4)$$

Equation parameters  $SWC_{min}$  and  $SWC_{max}$  are the plant's lower and upper SWC-tolerance limits, below or above which plant growth ceases (i.e., when  $SWC < SWC_{min}$  and  $SWC > SWC_{max}$ ), and  $\Psi$  is an intermediate value of SWC that provides the greatest growth response [i.e.,  $R(SWC)=1$ ; Bourque *et al.*, 2000].



**Figure 8.** Generic species-specific environmental response functions for photosynthetically active radiation (PAR, panel a), growing degree days (GDD, panel b), and soil water content (SWC, panel c; after Bourque *et al.*, 2000). PSD is obtained by multiplying the individual response values constrained between 0 and 1. Definition of response curves for PAR, GDD, and SWC for a particular species is based on the species vital attributes in Table 2.

**Table 2:** Parameter values for species response functions for PAR, GDD, and SWC (eq.'s 2-4) for seven softwood and six hardwood species.

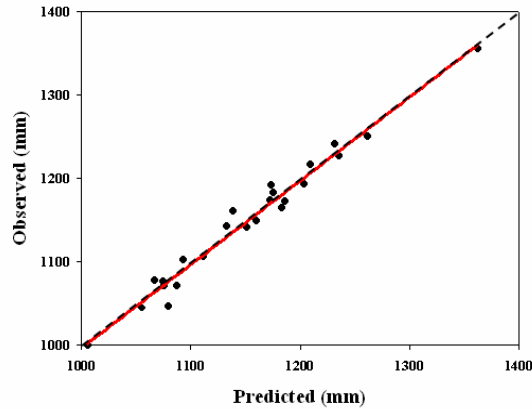
Species	Shade-tolerance class <sup>1</sup>	PAR <sup>2</sup>			GDD <sup>3</sup>		SWC <sup>4</sup>		
		c <sub>1</sub>	c <sub>2</sub>	c <sub>p</sub>	GDD <sub>min</sub>	GDD <sub>max</sub>	SWC <sub>min</sub>	SWC <sub>max</sub>	Ψ
White spruce	2	1.26	1.79	0.12	500	2100	0.2	0.9	0.55
White pine	2	1.26	1.79	0.12	1100	3400	0.18	0.75	0.53
Eastern white cedar	3	1.13	2.44	0.09	500	2500	0.62	0.999	0.8
Eastern hemlock	5	1.02	4.17	0.03	1300	2900	0.2	0.6	0.5
Balsam fir	4	1.05	3.29	0.06	563	2011	0.087	0.999	0.5
Red pine	1	1.58	1.19	0.15	1400	2300	0.2	0.95	0.7
Red spruce	4	1.05	3.29	0.06	800	2900	0.2	0.8	0.6
White ash	2	1.26	1.79	0.12	1275	5600	0.55	0.999	0.66
Yellow birch	3	1.13	2.44	0.09	1100	2900	0.1	0.8	0.52
White birch	1	1.58	1.19	0.15	400	2400	0.085	0.87	0.395
Sugar maple	4	1.05	3.29	0.06	800	2900	0.0	0.67	0.38
Red maple	3	1.13	2.44	0.09	550	7250	0.08	0.95	0.5
Red oak	2	1.26	1.79	0.12	1525	3878	0.58	0.95	0.73

<sup>1</sup>1 represents least shade tolerant, and 5 most shade tolerant; <sup>2</sup>Values are derived from the literature, e.g., from Urban (1990, 1993), Kimmins (1997), Nilson and Orcutt (1996); <sup>3</sup>GDD tolerance limits of species; based on a review of the scientific literature by Smith (1998), Burns and Honkala (1990a, 1990b), and references from the internet; <sup>4</sup>0 and 1 represent the soil's permanent wilting point and field capacity, respectively (Bourque et al., 2000).

### 3. Results and Discussion

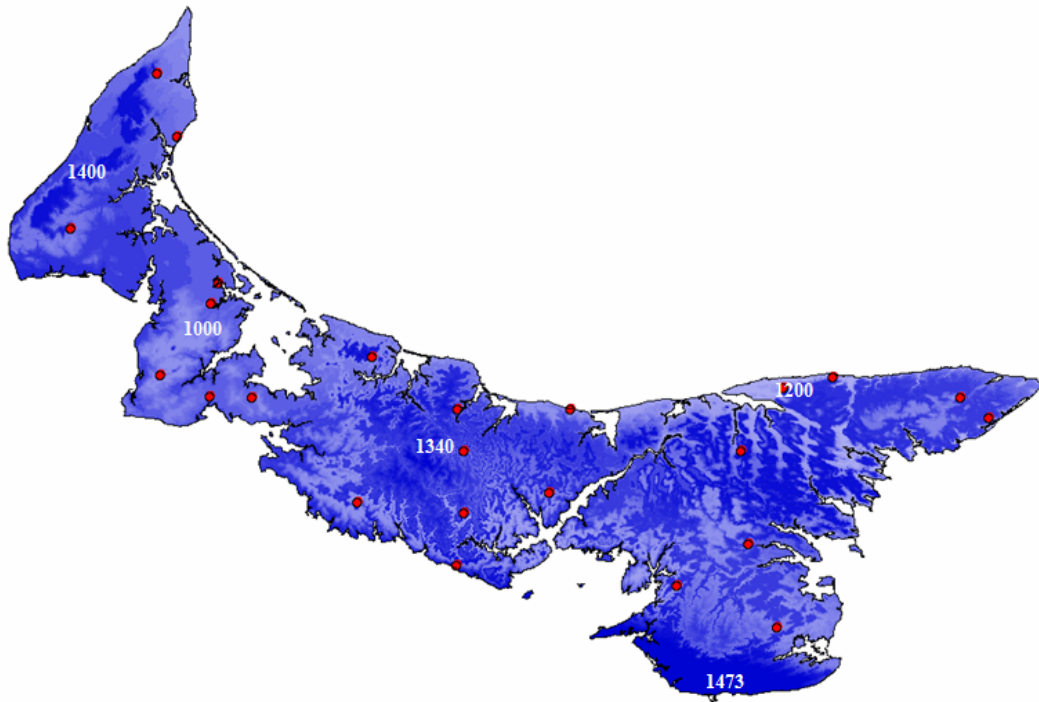
#### 3.1. Biophysical Variables

A comparison of ANN-predicted and observed values of mean annual total precipitation is presented in Figure 9. For perfect agreement, all data points should have aligned perfectly along the 1:1 correspondence line (diagonal line). Although dispersion exists in the prediction-vs.-observation data pairs, both the y-intercept (-5.64) and the slope (1.00) of the regression line fitted to the data were not statistically different from zero and unity at the 5% significance level.



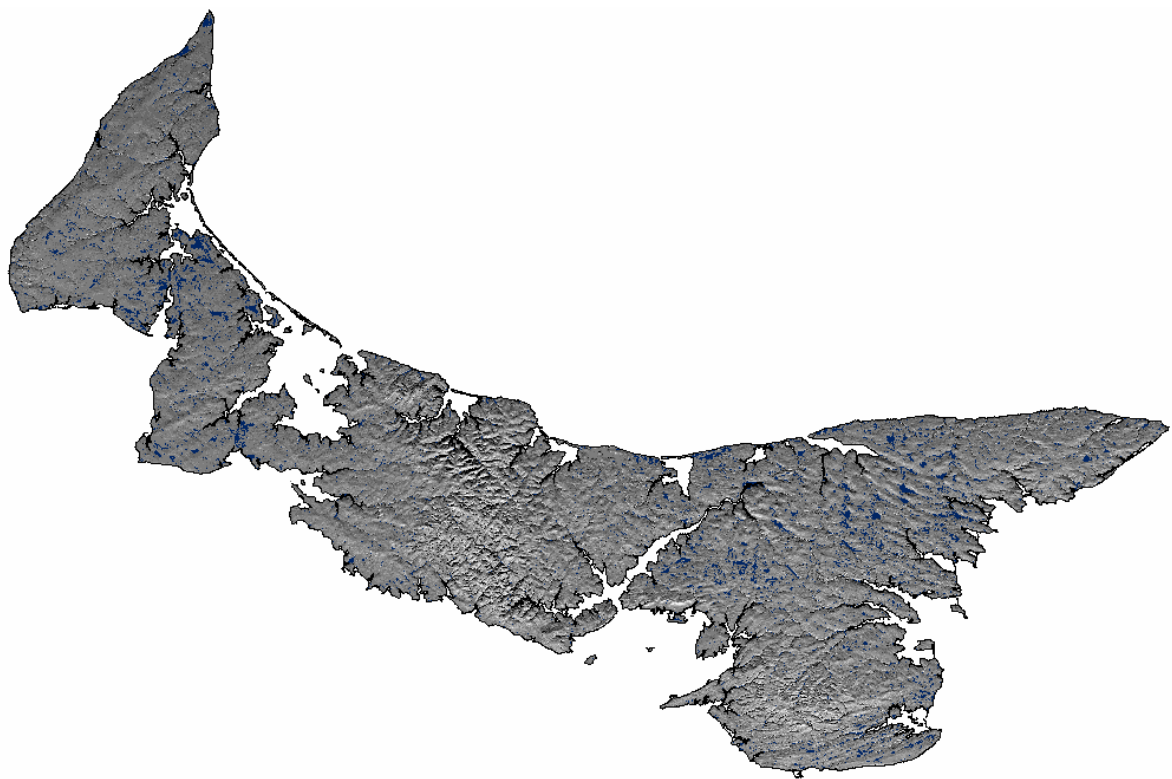
**Figure 9.** Scatter diagram of predicted vs. observed mean annual total precipitation (mm). Level of agreement, as shown by the alignment of prediction-to-observation data points along the 1:1 correspondence line (diagonal dashed line), was 0.97 (adjusted- $r^2$ ). The slope and y-intercept of the regression line fitted to the data, shown in red, were not statistically different from 1.0 and 0.0 at the 5% significance level. Standard error of estimate was  $\pm 13.1$  mm.

The results show that, for the most part, the trained ANN was able to reproduce annual precipitation totals within 13.1 mm (standard error of estimate). The ANN was able to explain about 97% of the variability in the data (adjusted- $r^2=0.97$ ). Analysis of internal weights of the trained ANN revealed that elevation contributed 34.0% towards the calculation of precipitation, followed by latitude (33.8%), and longitude (32.2%). Spatial distribution of current annual total precipitation for PEI is given in Figure 10.

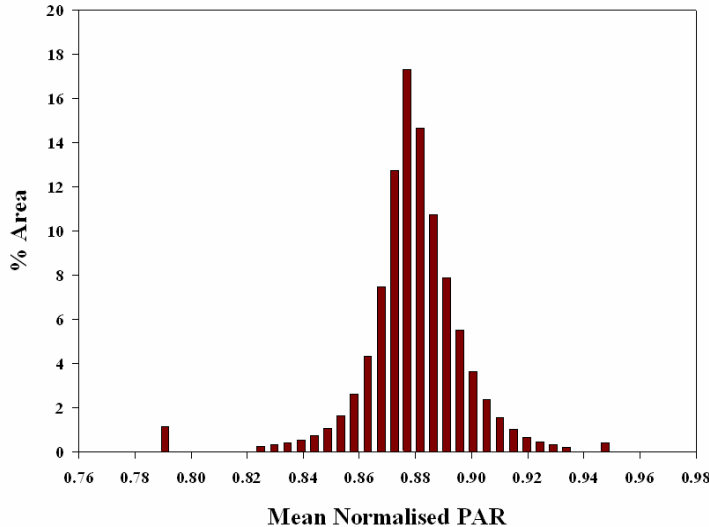


**Figure 10.** Distribution of mean annual total precipitation (mm) for current conditions (1971-2000). The red symbols represent the locations of 24 Environment Canada climate stations used in the study (Appendix A). Blue scale colours correspond to variation in annual total precipitation, with light blue being the lower precipitation and dark blue, higher precipitation levels.

Figures 11 and 12 provide PAR distributions for cloud-free conditions modelled with **LandSET**. A comparison between field-based measurements of PAR and modelled PAR at two forest-sites in NB using **LandSET** revealed a strong correlation, giving an  $r^2$ -value of 0.96 (Hassan *et al.*, 2006).



**Figure 11.** Distribution of **LandSET**-modelled growing season accumulated photosynthetically active radiation (PAR) for cloud-free conditions and an assumed mean mid-afternoon atmospheric transmissivity of 0.7. Light gray colours denote high incident PAR, especially on south-facing slopes, and the darker grays, low incident PAR (mostly on north-facing slopes). Blue on the map represents fresh water fed wetlands.



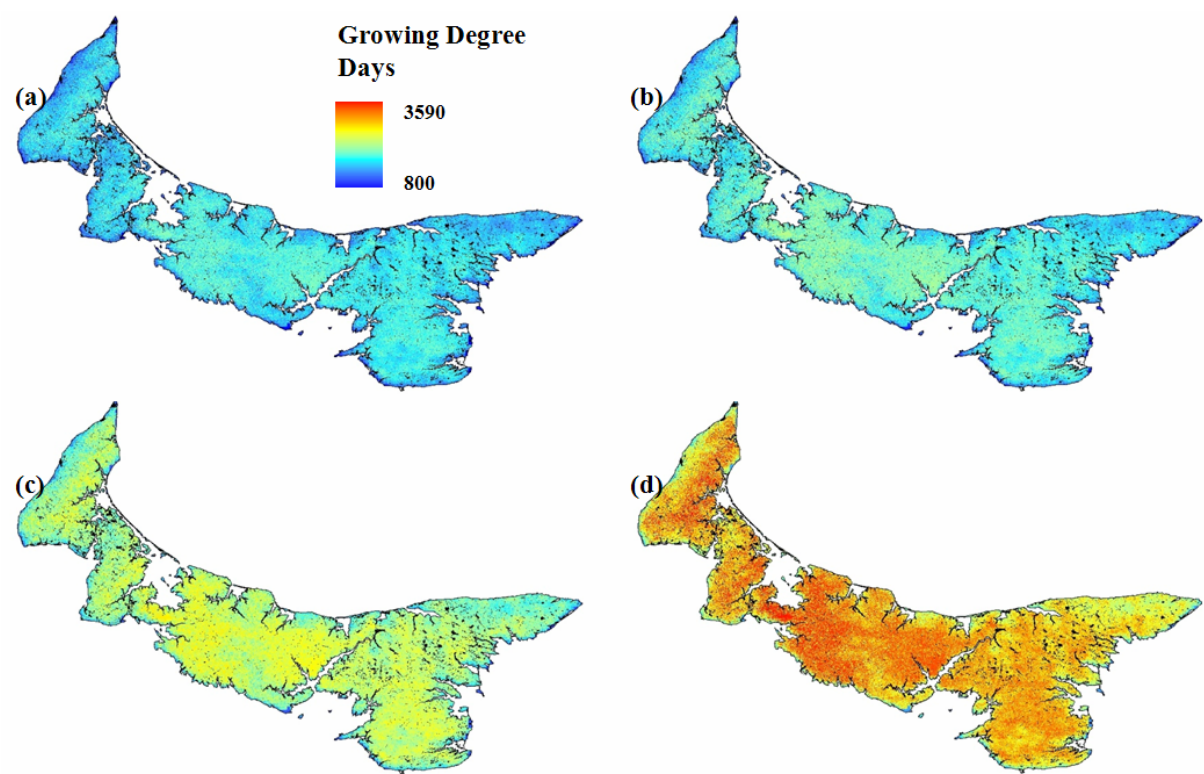
**Figure 12.** Photosynthetically active radiation (PAR) frequency distribution (% of PEI). Values along the x-axis are mean values of normalised PAR (i.e.,  $PAR/PAR_{max}$ ) for individual PAR groupings.

Figure 13 shows the distributions of GDD for both current and future climatic conditions. GDD values for current conditions were in between 800-1989 from the coolest to the warmest locations on the Island, with an average of 1647 province-wide. These values are consistent with values reported by (i) Environment Canada (Canadian Climate Normals for PEI, 1971-2000; <http://climate.weatheroffice.ec.gc.ca/>, site last accessed October, 2009) and (ii) the United States Department of Agriculture (USDA; <http://forest.moscowfsl.wsu.edu/climate/current/>, site last accessed October, 2009) for GDD calculated with a base temperature of 5°C. Figure 14 shows the frequency distribution of GDD as a function of current and future climatic states. As expected, the distribution peaks shift toward higher values as climate warms. Projected increases in GDD from present-day conditions are on average

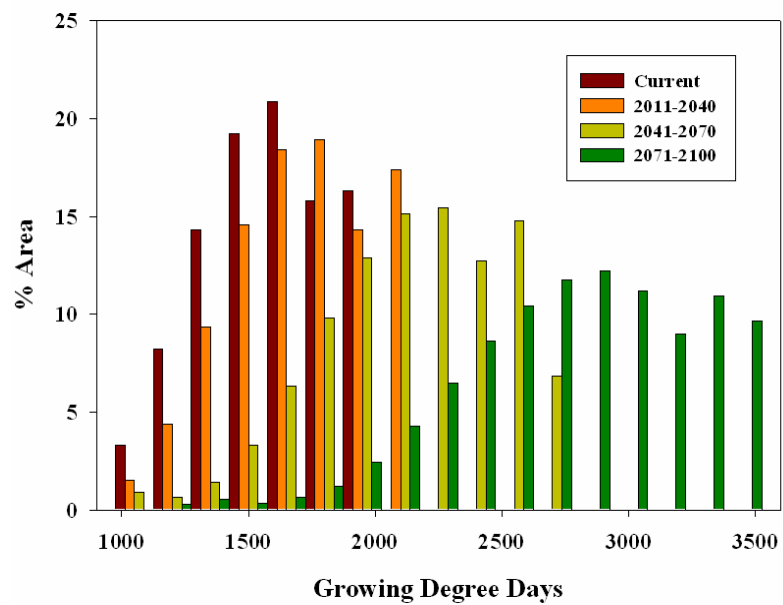
- (i) **137** degree-days higher in 2011-2040 (39-225 Island-wide), representing an Island-wide growing season mean temperature increase of **1.4°C** and GDD average of 1785;
- (ii) **573** higher in 2041-2070 (254-736), representing an Island-wide growing season mean temperature increase of **2.5°C** and GDD average of 2220; and
- (iii) **1211** higher in 2071-2100 (529-1620), representing an Island-wide growing season mean temperature increase of **4.7°C** and GDD average of 2858

as a result of increased average temperatures and longer growing seasons compared to present-day conditions. Also, the range of GDD is shown to increase with climate warming, causing the distributions to flatten out from 1971-2000 to 2071-2100 (Figure 14). GDD projections over the next 100 years indicate that the temperature regime of PEI will gradually converge to a temperature regime comparable to present-day conditions in southern Pennsylvania (PA), central New Jersey (NJ), and southern Ohio (OH) States, USA (Figure 15).

Under an A2 emission scenario (an aggressive emission scenario corresponding to a future with moderate economic and high population growth; Nakicenovic *et al.*, 2000), **annual mean temperatures** in PEI are predicted to increase by 2-3°C over the next 80 years (by 2080; Barrow *et al.*, 2004). Trends in climate warming on PEI, unlike other regions of Canada (particularly in northern and western Canada), are not expected to deviate substantially between the IS92a and B2 (low emission scenarios; Nakicenovic *et al.*, 2000) and A2 emission scenarios, because of the moderating effect of nearby oceans on the area's climate (Barrow *et al.*, 2004).

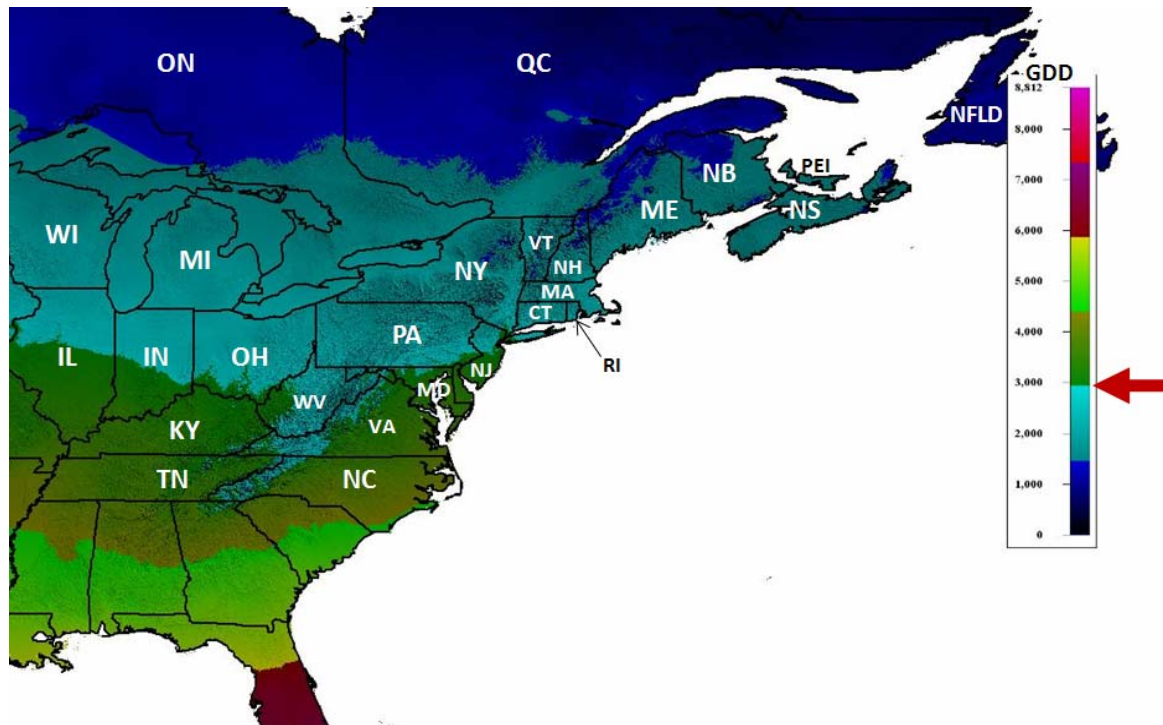


**Figure 13.** Spatial distribution of growing degree days (GDD) for current climatic conditions, 1971-2000 (a) and future conditions for 2011-2040 (b), 2041-2070 (c), and 2071-2100 (d).



**Figure 14.** Growing degree day (GDD) frequency distributions (% of PEI) for current climatic conditions (1971-2000) and future conditions for 2011-2040, 2041-2070, and 2071-2100. GDD are based on values from Figure 13.





**Figure 15.** Accumulated growing degree day (GDD) map base temperature of 5°C for a significant portion of eastern North America for current climatic conditions (after USDA, 2009; <http://forest.moscowfsl.wsu.edu/climate/current/>). Red arrow next to the legend marks the 2071-2100 GDD average for PEI. Province and state nomenclature, from west to east include: ON=Ontario, WI=Wisconsin, IL=Illinois, MI=Michigan, IN=Indiana, KY=Kentucky, TN=Tennessee, OH=Ohio, WV=West Virginia, NC=North Carolina, VA=Virginia, MD=Maryland, PA=Pennsylvania, NJ=New Jersey, NY=New York, CT=Connecticut, RI=Rhode Island, MA=Massachusetts, NH=New Hampshire, VT=Vermont, ME=Maine, QC=Quebec, NB=New Brunswick, NS=Nova Scotia, PEI=Prince Edward Island, and NFLD=Newfoundland.

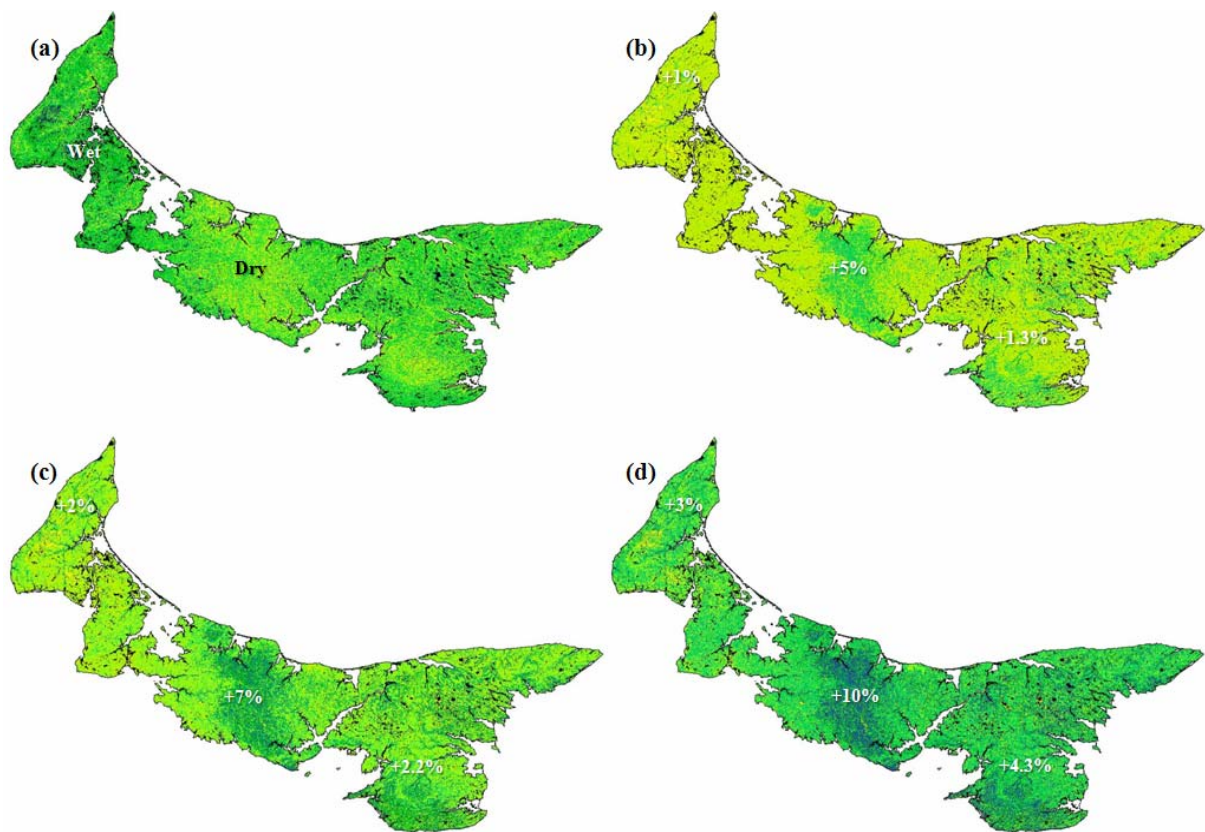
Some features of the current GDD map (Figure 13a) worth highlighting include:

- (i) Elevational differences on PEI had a minor influence in the distribution of GDD.
- (ii) The areas along the coast had lower GDD at around 800-1300 due to their proximity to cold water.
- (iii) Forested areas exhibited relatively cooler conditions compared to agricultural lands (mean GDD of 1631 vs. 1685), due to the cooling effect associated with higher evapotranspiration rates by forests during summer. Mean GDD over wetlands was even lower at 1597, because of exposed surface water and equally elevated rates of evapotranspiration. Pattern in current land use has potential to impact GDD determined by RS techniques. This effect is potentially carried forward with each successive calculation of future climate states.

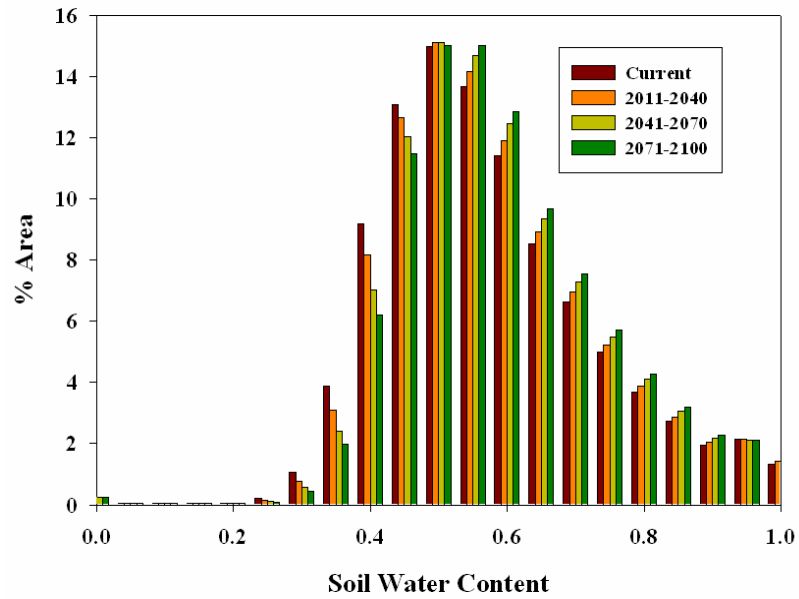
Figure 16a shows the distribution of SWC for current climatic conditions. Figures 16b-16d show % difference of future soil water conditions for 2011-2040, 2041-2070, and 2071-2100 as a function of current soil water conditions with a 5%, 10%, and 15% increase in current annual precipitation and projected increase in mean temperature. SWC across PEI is expected to increase with climate change, albeit at different rates (Figures 16b-16d). Frequency distributions of SWC as a function of % area of PEI are given in Figure 17 for current and future climates.



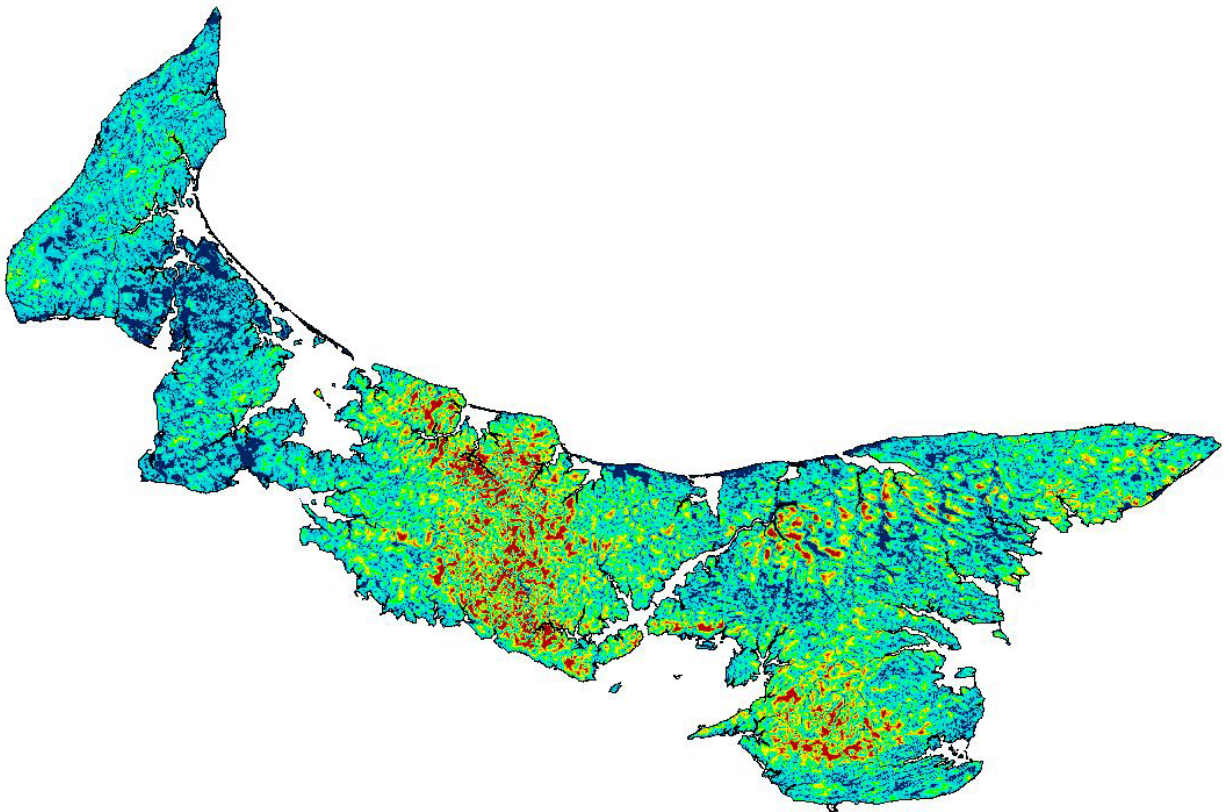
Greatest wetting of the soils (5-10%) is predicted to occur in the central and southeastern parts of the Island over the next 100 years. Figure 18 gives the wetted areas map of PEI for current hydrological conditions. Figures 16a and 18 give near similar information about soil water distribution across PEI; although from different perspectives (soil water storage vs. slope position). In terms of SWC distribution for current conditions in NB, a comparison between **LandSET**-derived SWC and values derived from RS-based methods (involving MODIS surface reflectance data and a calculation of vegetation greenness or NDVI; Hassan *et al.*, 2007c) revealed very similar distributions (i.e.,  $r^2=0.96$ ; Figure 19).



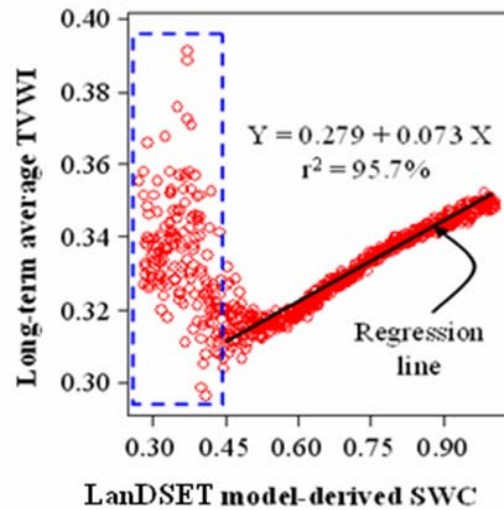
**Figure 16.** *LandSET*-derived soil water content (SWC) for current (a) and future conditions for 2011-2040, 2041-2070, and 2071-2100 as % difference maps from current soil water conditions (Figure a). Dark green to blue colours in Figure (a) represent the wetter areas of the landscape, while the yellow colours represent the dryer areas. Dark green colours in the % difference maps (b-d) represent the greatest increase in soil water content from current conditions. Yellow to light green colours in the % difference maps (b-d) represent the smallest increase in soil water content. Black areas denote fresh-water wetlands on the Island.



**Figure 17.** Soil water content (SWC) frequency distributions for current climatic conditions (1971-2000) and future conditions for 2011-2040, 2041-2070, and 2071-2100. Current SWC are based on values from Figure 16a.



**Figure 18.** Wetted areas map of PEI (at 10-m resolution) based on current hydrological features. Dark blue colours represent potentially wet sites on the Island and reddish-brown colours, dryer sites.



**Figure 19.** Comparison of **LanDSET**-generated SWC with long-term averages of wetness index calculated from MODIS surface reflectance data and greenness index (NDVI) for the Province of New Brunswick (Hassan et al. 2007c). Points that deviate from the regression line (i.e., **LanDSET** model-derived values < 0.45) account for < 0.5% of all points considered.

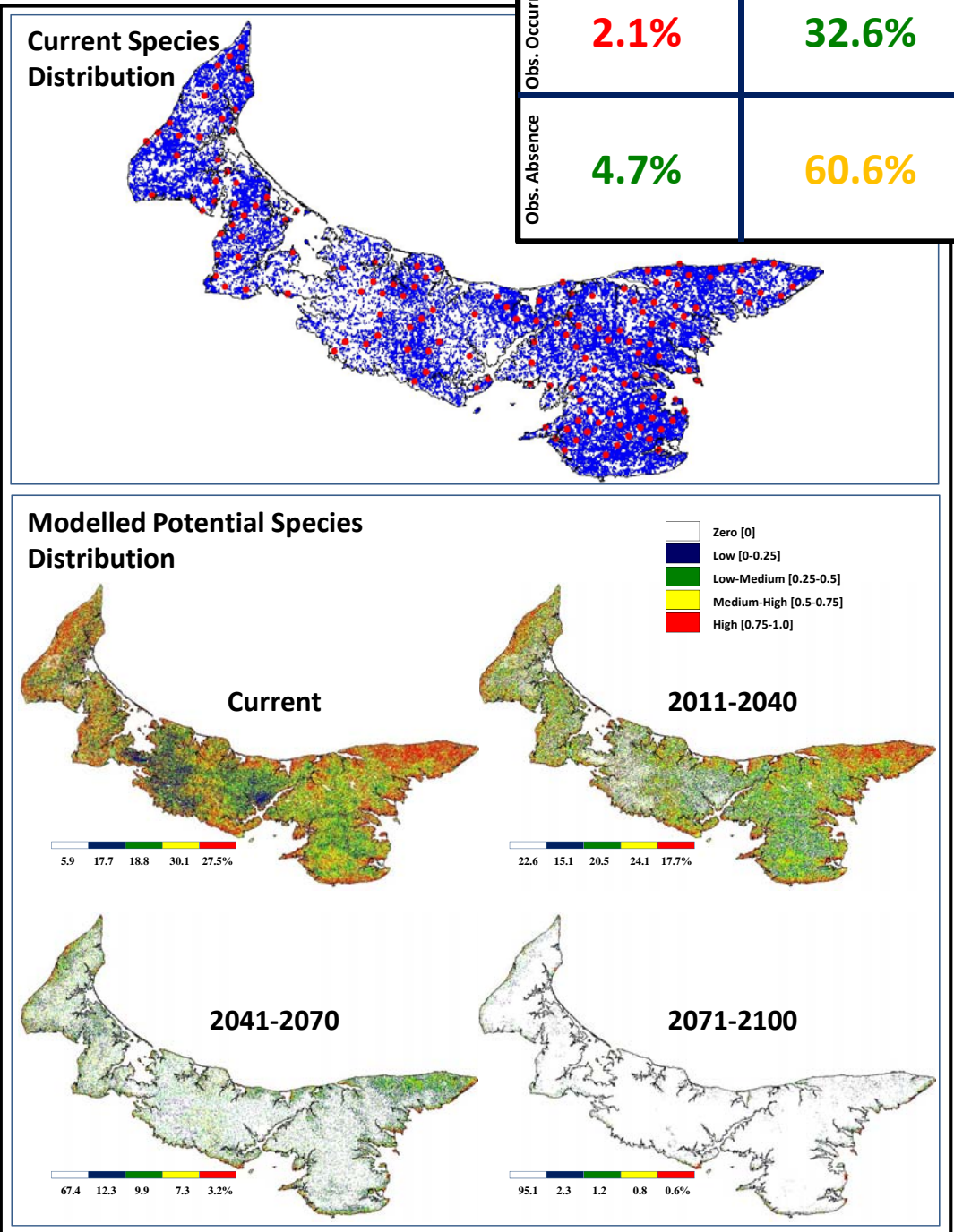
### 3.2. Species Distribution for Current and Future Climatic Conditions

Figures 20-32 provide actual and potential species distribution for the thirteen tree species for both current and future climatic conditions with CCGCM1-projected temperature shifts and 5%, 10%, and 15% increase in annual total precipitation. The Figures also provide comparisons of actual species occurrence in inventory plots with modelled PSD values for current conditions (inset); i.e., (i) *predicted vs. observed species occurrence*; (ii) *predicted vs. observed species absence*; (iii) *predicted occurrence vs. observed species absence*; and (iv) *predicted absence vs. observed species occurrence* (see Section 2.3.5 for outcome description). In all instances, the influences of forest-forming factors, beyond the ones introduced here, are quite large (yellow coloured values in the inset); predicted occurrence vs. species absence from the inventory plots ranges from 30.2-84.1%, giving a mean value of  $60.1 \pm 4.6\%$  (standard error), indicating a need to incorporate new factors in the current definition of PSD for a more accurate representation of actual species distribution in a highly disturbed landscape, like that of PEI. Dynamic factors associated with forest development processes like inter- and intra-species competition, species migration and extirpation, and disturbance (including harvesting and land conversion) are not easily addressed outside the scope of predictive models of forest succession, such as individual tree-based (e.g., Zelig; Urban, 1990) or cohort-based forest vegetation simulators. Slow-changing factors, like soil fertility and soil compaction can be added to the definition of PSD, but for this to happen the data must be available at the desired spatial resolution (10-50 m, or finer) and of sufficiently high quality. Outright model error (red coloured values) ranges from 0.0-3.3%, giving a mean of  $0.9 \pm 0.3\%$  (standard error). Agreement between model prediction and inventory-plot species presence/absence (sum of green coloured values, inset) ranges from 15.9-69.7%, giving a mean value of  $39.0 \pm 4.9\%$  (standard error).

We summarise the prominent features of the projected PSD (Figures 20-32) as follow:

- **White spruce** habitat is projected to decline progressively over the next 100 years with climate warming (Figure 20). Extent of high quality sites (red colour sites; Figure 20) is projected to decrease from 27.5% of PEI in the first (1971-2000) to 0.6% in the fourth tri-decade (2071-2100). Similar reductions are expected to occur in the other habitat-quality categories. At the end of the fourth tri-decade, 95.1% of PEI will be unfavourable for white spruce growth (an increase of 89.2% from current conditions). Isolated pockets of poor-to-high quality habitat are projected to persist in the cooler areas of the Island by 2100. Current proliferation of white spruce on the Island is associated with the historical conversion of PEI's forestland to agriculture and its subsequent abandonment.
- **White pine** habitat is predicted to improve in the first two tri-decades into the future (Figure 21) with a 27.9% increase in high-quality sites at the end of the third tri-decade (red colour sites; Figure 21). In the fourth tri-decade, model projections indicate a gradual decline in both habitat extent (80.6% to 69.4% of PEI) and quality (from 69.5% of high to moderately-high quality sites to 38.7%). During this same time, low to moderately-low quality habitat (blue and green colours) will cover 30.8% of the Island.
- **Eastern white cedar**, as a cold-hardy species, is projected to undergo gradual decline over the next 100 years (Figure 22). Extent of high quality sites (red and yellow coloured sites; mostly in the western third of the Island) is expected to decrease from a current value of 22.3% to 1.8% overall coverage of the Island. As in white spruce, eastern white cedar will be confined to the cooler areas of the landscape as the climate warms.
- **Eastern hemlock** high-quality habitat (red coloured sites) is projected to increase slightly over the first tri-decade into the future, from an initial coverage of 16.6% to 23.5% of the Island (Figure 23). In successive tri-decades, the extent (18.1%) and quality of the sites is modelled to decrease (from 38.2% of red and yellow coloured sites to 11.4%). Unfavourable habitat will increase from 48.1% to 76.1% of the Island from the second to the fourth tri-decade.
- **Balsam fir** is an aggressive species that grows practically everywhere on the Island as in the other Atlantic Provinces (Ritchie, 1996); this is borne out by the distribution of potential species habitat (98.3% of the Island; Figure 24, current conditions) and number of inventory plots with balsam fir as the primary species (PEI DEEF, 2009). Under current climatic conditions, balsam fir habitat is most suitable (red and yellow colours; Figure 24) in the central region of the Island and the other cooler parts of the province (e.g., along the Northumberland Strait and Gulf of St. Lawrence; accounting for 55.3% of PEI). In the warmer and potentially wetter parts of the landscape (e.g., either side of the central hills of the Island) balsam fir is not expected to fare as well; sub-optimal PSD index values (represented by the blue and white colours) occur on 26.0% of PEI land base. Inaccuracies in modelled projections for current conditions accounts for 2.2% of PSD values generated for the inventory-plot locations (Figure 24, inset). Under projected climate change in 2011-2040 (Figure 24), balsam fir is predicted to be restricted mostly to the eastern third of the Island and to some extent, the far western portion of the Island. In 2011-2040, balsam fir habitat occupancy is predicted to diminish from a current value of 98.3% of PEI to 73.4%. With continued warming (2041-2070 and 2071-2100), species habitat is predicted to persist mostly along the cooler, coastal regions of the province.

## White Spruce



**Figure 20.** Distribution of **white spruce** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

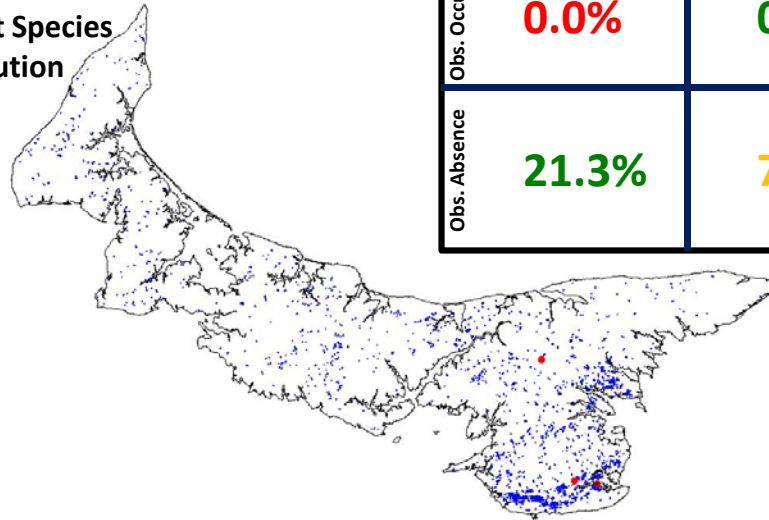


## White Pine

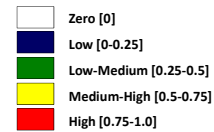
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	0.0%	0.4%
Obs. Absence	21.3%	78.3%

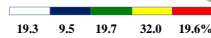
#### Current Species Distribution



#### Modelled Potential Species Distribution



#### Current



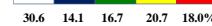
#### 2011-2040



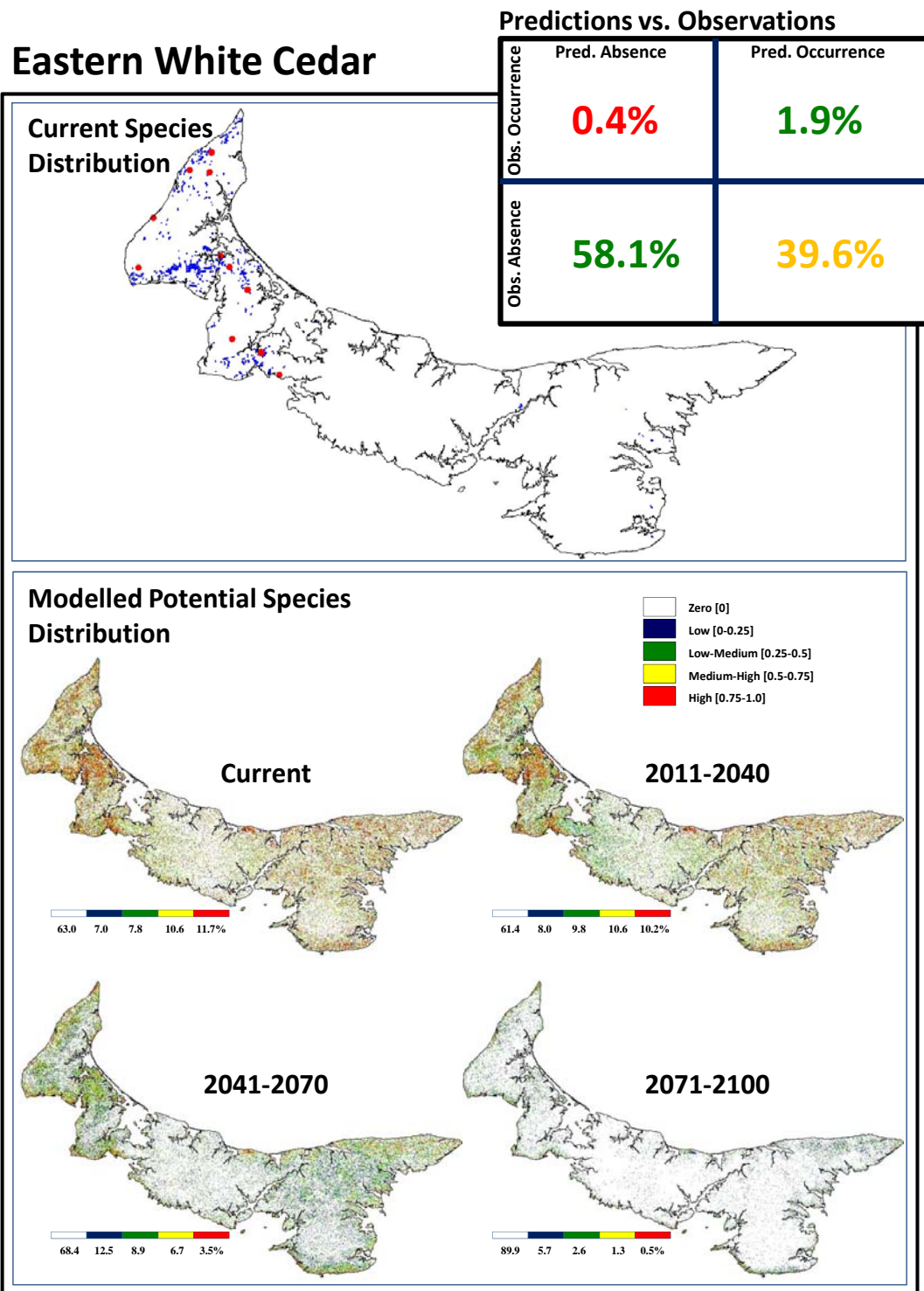
#### 2041-2070



#### 2071-2100



**Figure 21.** Distribution of **white pine** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).



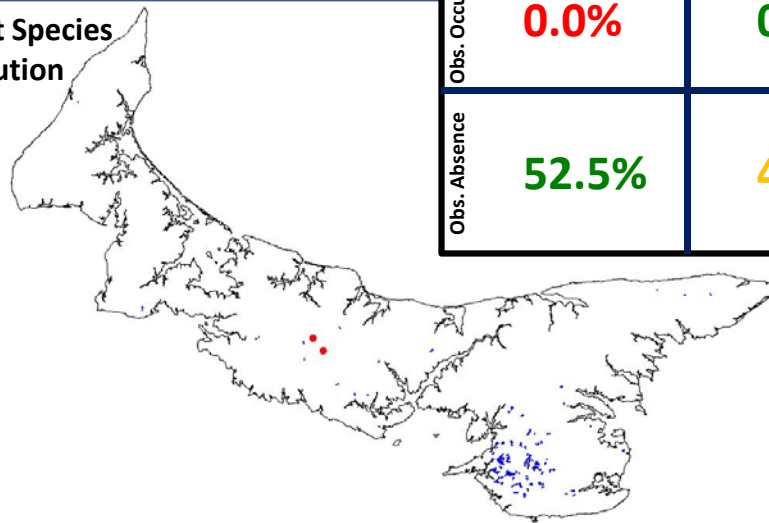
**Figure 22.** Distribution of **white cedar** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## Eastern Hemlock

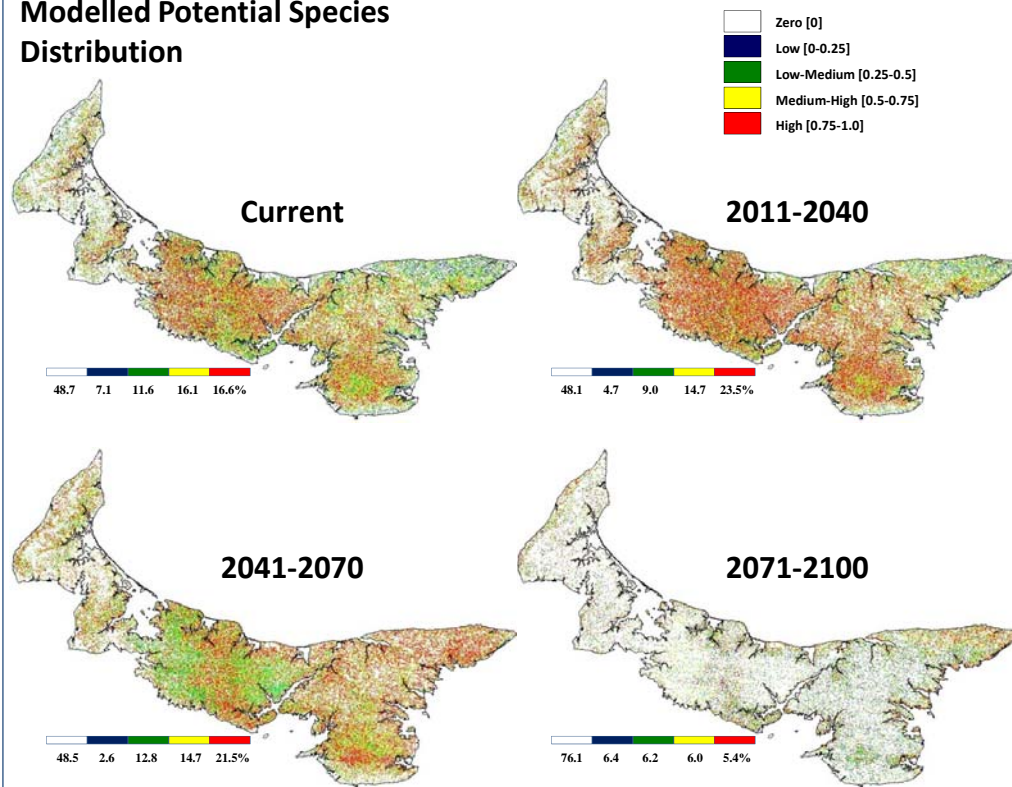
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	0.0%	0.3%
Obs. Absence	52.5%	47.2%

### Current Species Distribution

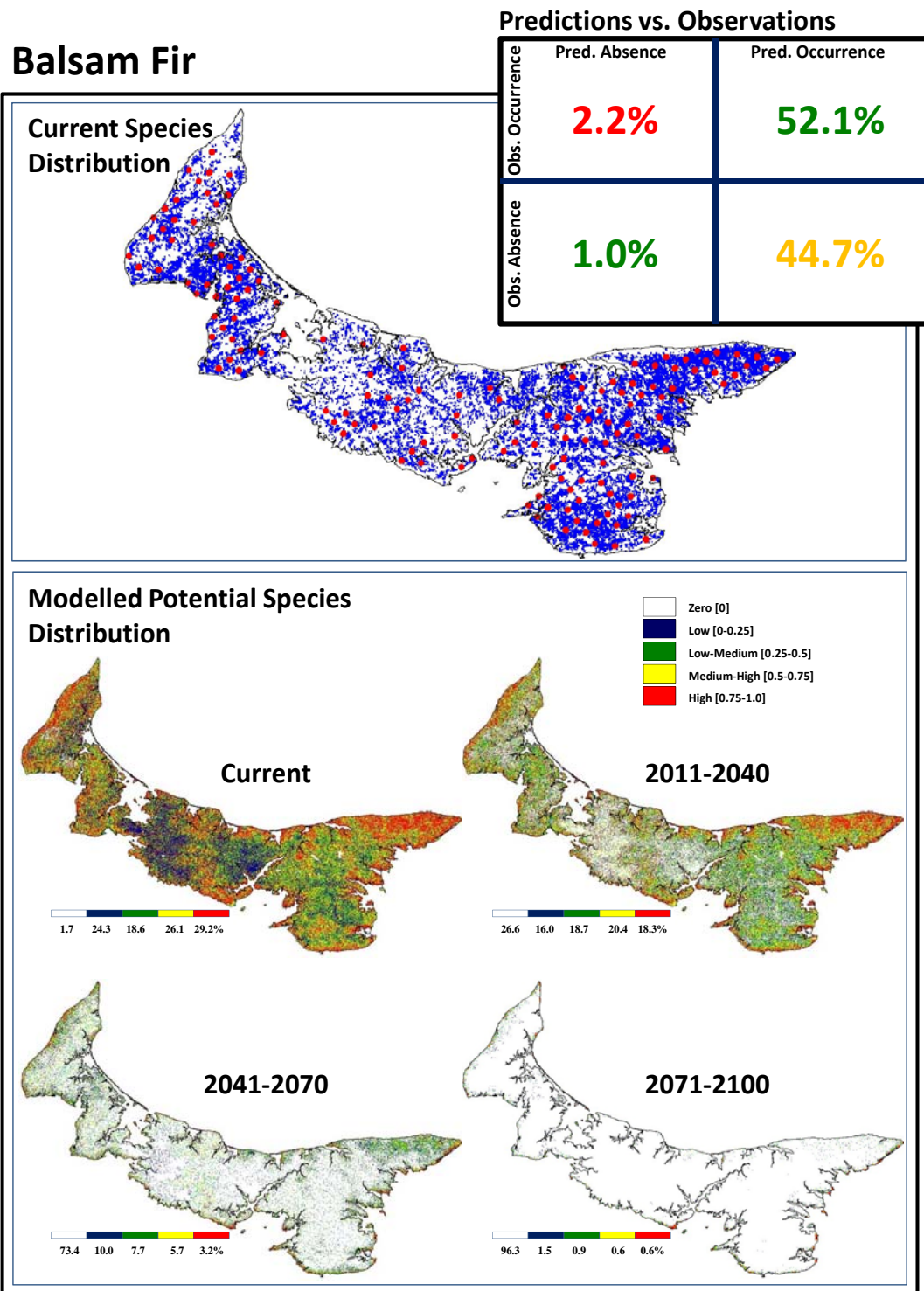


### Modelled Potential Species Distribution



**Figure 23.** Distribution of *hemlock* for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

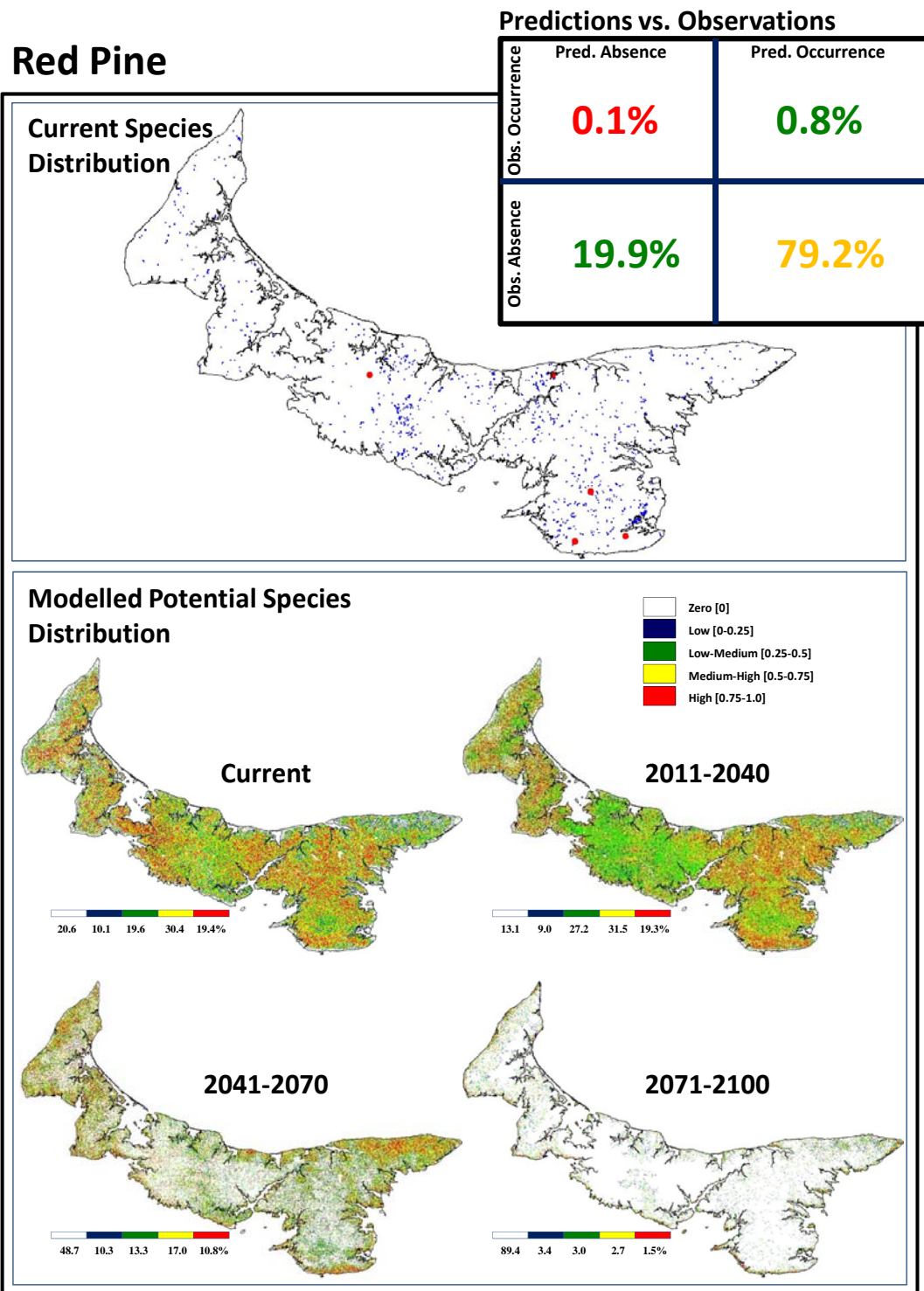




**Figure 24.** Distribution of *balsam fir* for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

By 2100, balsam fir habitat is projected to persist on only 3.7% of PEI. Greatest determinant of species-habitat change with climate change is GDD; however, slight increases in SWC can also be expected to have some influence on the distribution of balsam fir over the next 100 years, albeit at reduced levels.

- Current **red pine** habitat is predicted not to fare as well as white pine habitat with climate change, where a 45.6% reduction is projected in high to moderately-high quality habitat by the fourth tri-decade (Figure 25). This decline is associated with the narrower response of red pine to increasing GDD in comparison to white pine.
- **Red spruce** habitat for current conditions is calculated to occupy 87.2% of PEI land base. Under projected climate, red spruce habitat is projected to continue to benefit with warming temperatures on 87.2% of PEI land base during the second tri-decade (2011-2040) and begin declining in subsequent tri-decades (2041-2070 to 2071-2100; Figure 26). Amount of high quality habitat (red coloured sites, with 0.75-1.0 index values), is projected to decrease from 55.0% of PEI in the second tri-decade (2011-2040) to 33.0% and 6.8% in the third (2041-2070) and fourth tri-decade (2071-2100), respectively. In the fourth tri-decade, red spruce habitat is predicted to be limited to the cooler areas of PEI, occupying about 43.3% of PEI; mostly as low to low-medium quality habitat (on 25.3% of the Island).
- **White ash** habitat is predicted to improve/expand with climate warming. Current habitat accounts for 49.9% of the Island, with 1.5% as medium-high to high quality sites (Figure 27). By the end of the fourth tri-decade, 62.3% of the Island will be suitable for growing white ash. The quality of the sites will improve from an initial value of 1.5% of medium-high quality sites to 42.2%, by the fourth tri-decade. Accordingly, unfavourable sites will decrease from 50.1% of the Island to 37.7%, by the fourth tri-decade.
- Projection of **yellow birch** habitat is predicted to ameliorate during the second tri-decade (2011-2040; Figure 28). Species range in PEI is projected to remain mostly unchanged during the second tri-decade (85.6% of PEI to 85.9%), while high to moderately-high quality habitat is projected to increase from 64.7% of PEI to 70.5% during the same time period. In following tri-decades, yellow birch habitat is predicted to undergo significant decline in the third (2041-2070) and fourth tri-decade (2071-2100), losing about 42.5% of its range and 51.0% of medium-high to high quality sites (red and yellow coloured sites) in 60 years.
- **White birch** habitat, like balsam fir and eastern white cedar, will undergo significant decline from 1971-2000 to 2071-2100 (Figure 29). In 100 years, white birch habitat is projected to decrease from an initial coverage of 92.7% to 14.6%. In the fourth tri-decade localised persistence of species' habitat in the cooler areas of the Island is projected, but at greatly reduced quality. By the fourth tri-decade (2071-2100), amount of medium-high to high quality sites is projected to decrease from an initial (current) value of 65.2% to 1.9% of PEI.
- Range of **sugar maple** is projected to remain mostly unaffected during the first 40 years (Figure 30). In the third and into the fourth tri-decade, sugar maple habitat is predicted to undergo significant decline, from an initial (current) coverage of the Island of 70.0% to 33.0%. High quality sites (red and yellow sites) will decrease from 50.5% to 8.3% of PEI over the next 100 years.



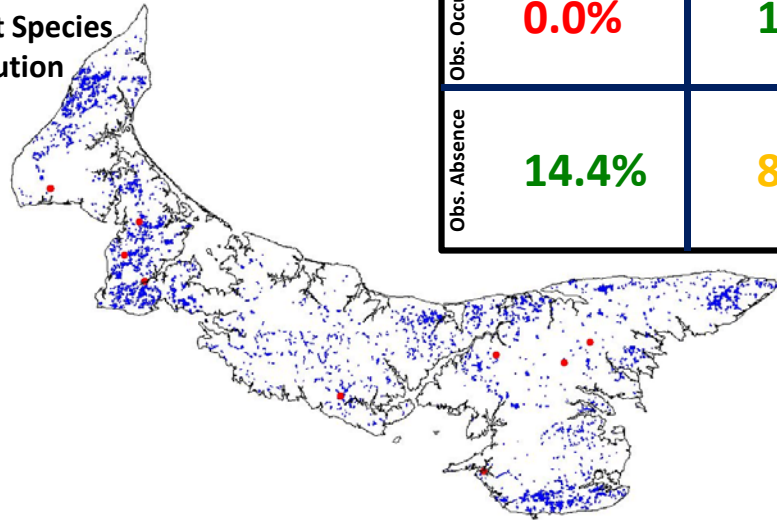
**Figure 25.** Distribution of **red pine** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## Red Spruce

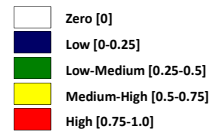
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	0.0%	1.5%
Obs. Absence	14.4%	84.1%

#### Current Species Distribution



#### Modelled Potential Species Distribution



#### Current

12.8 2.3 8.3 26.5 50.1%

#### 2011-2040

12.8 2.4 6.4 23.4 55.0%

#### 2041-2070

13.4 4.5 22.9 26.2 33.0%

#### 2071-2100

56.7 12.9 12.4 11.2 6.8%

**Figure 26.** Distribution of **red spruce** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

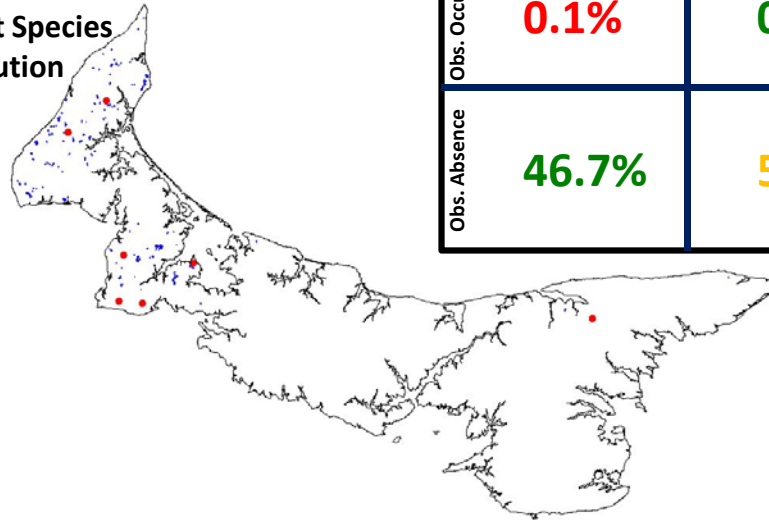


## White Ash

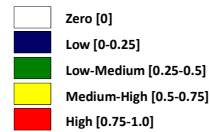
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	0.1%	0.8%
Obs. Absence	46.7%	52.4%

### Current Species Distribution



### Modelled Potential Species Distribution



#### Current



#### 2011-2040



#### 2041-2070



#### 2071-2100



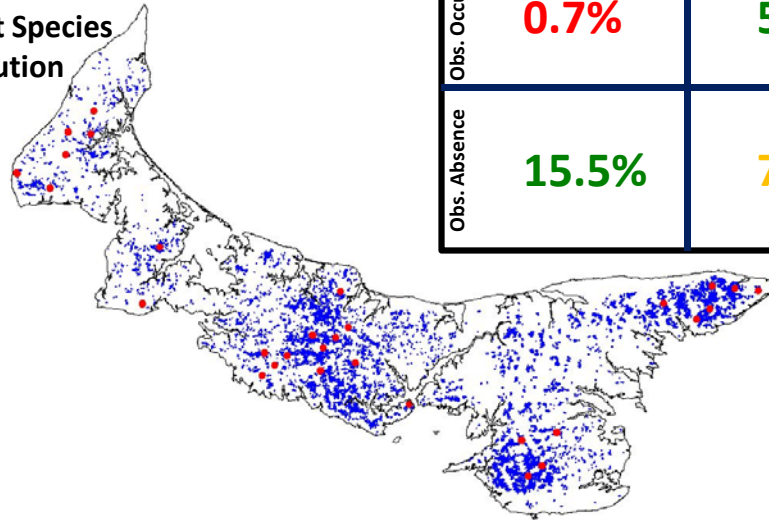
**Figure 27.** Distribution of **white ash** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## Yellow Birch

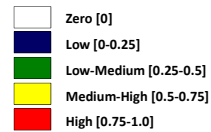
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	0.7%	5.3%
Obs. Absence	15.5%	78.5%

#### Current Species Distribution



#### Modelled Potential Species Distribution



#### Current



#### 2011-2040



#### 2041-2070



#### 2071-2100



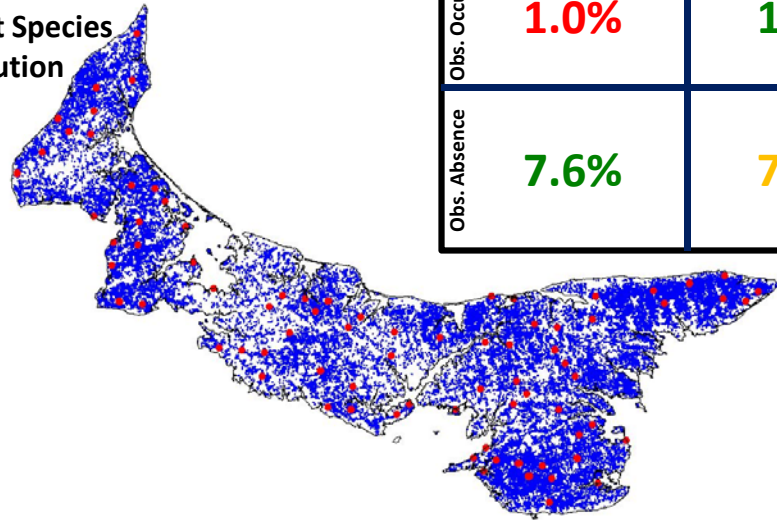
**Figure 28.** Distribution of **yellow birch** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## White Birch

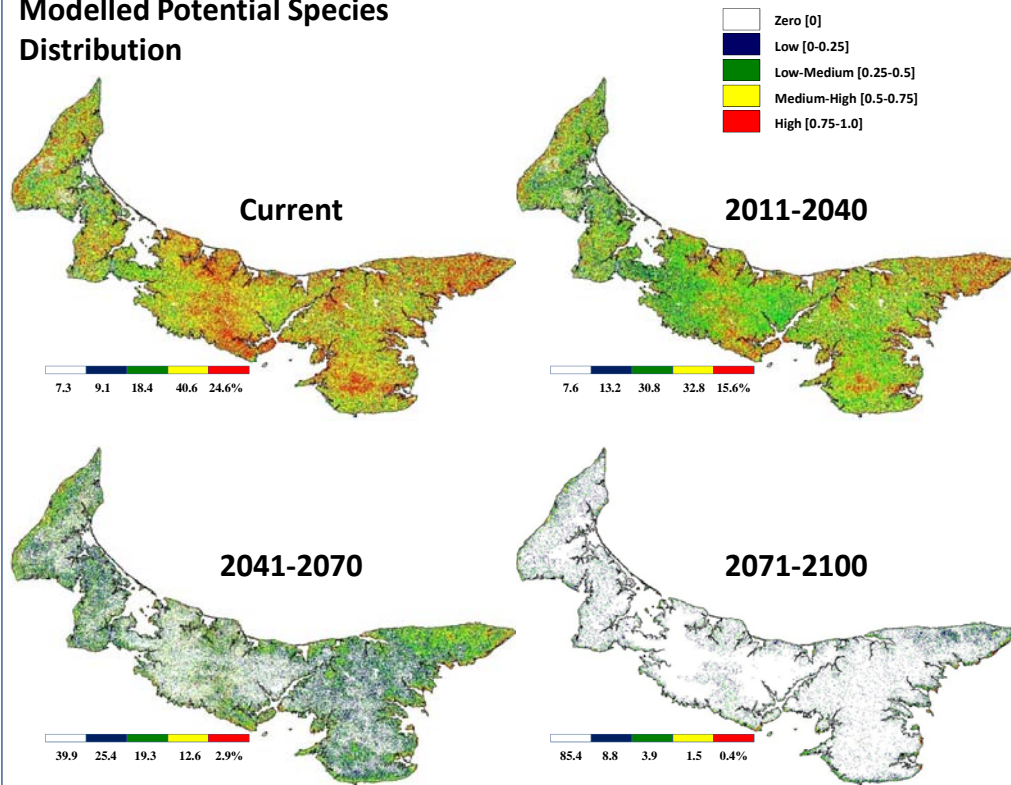
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	1.0%	13.9%
Obs. Absence	7.6%	77.5%

#### Current Species Distribution



#### Modelled Potential Species Distribution



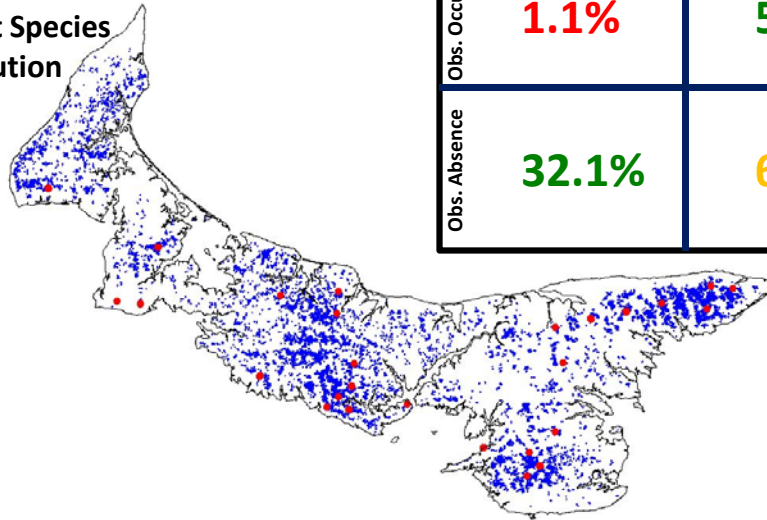
**Figure 29.** Distribution of **white birch** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## Sugar Maple

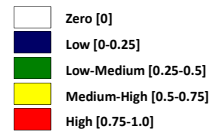
### Predictions vs. Observations

	Pred. Absence	Pred. Occurrence
Obs. Occurrence	1.1%	5.7%
Obs. Absence	32.1%	61.1%

### Current Species Distribution



### Modelled Potential Species Distribution



#### Current



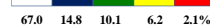
#### 2011-2040



#### 2041-2070



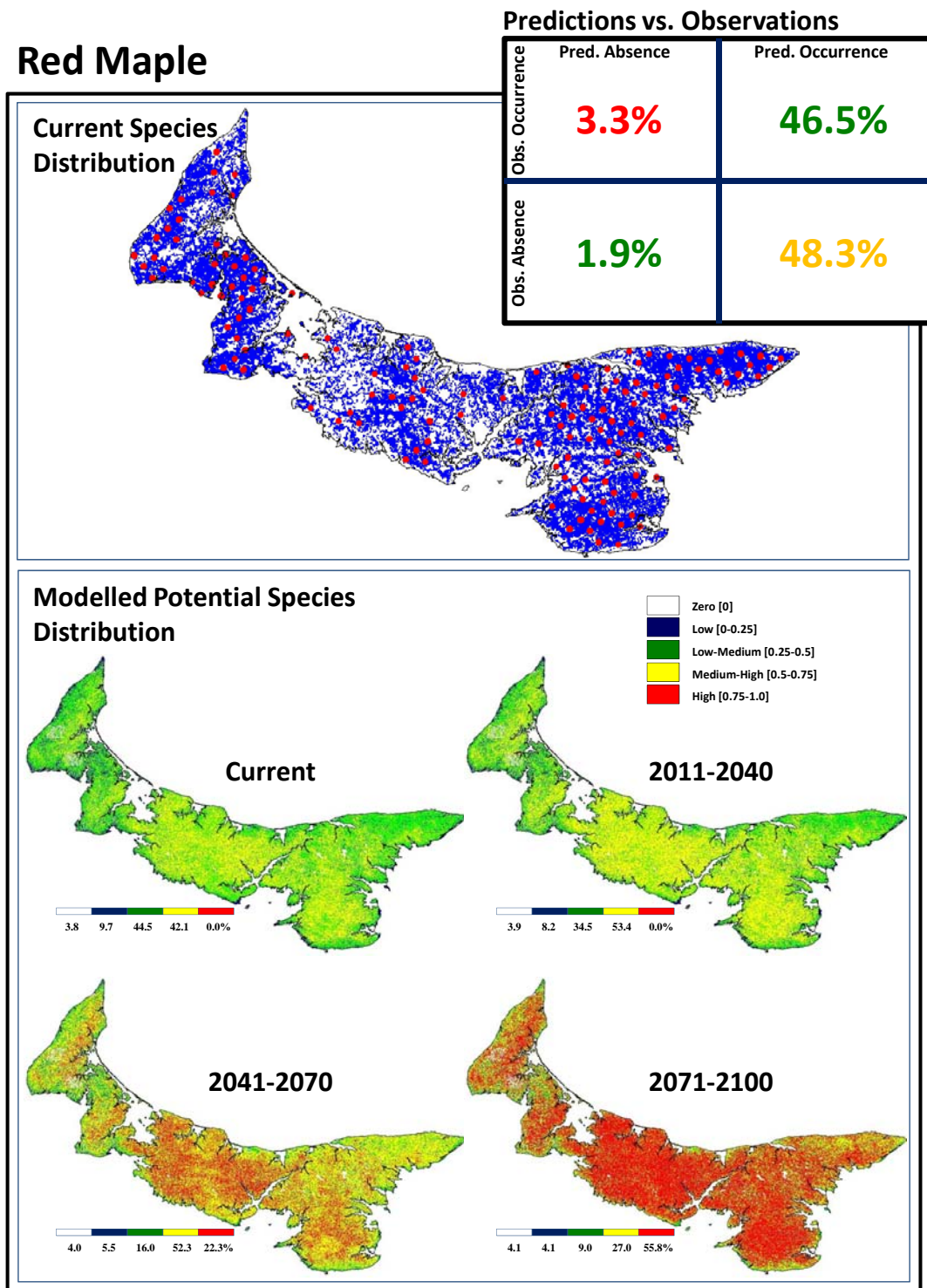
#### 2071-2100



**Figure 30.** Distribution of **sugar maple** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

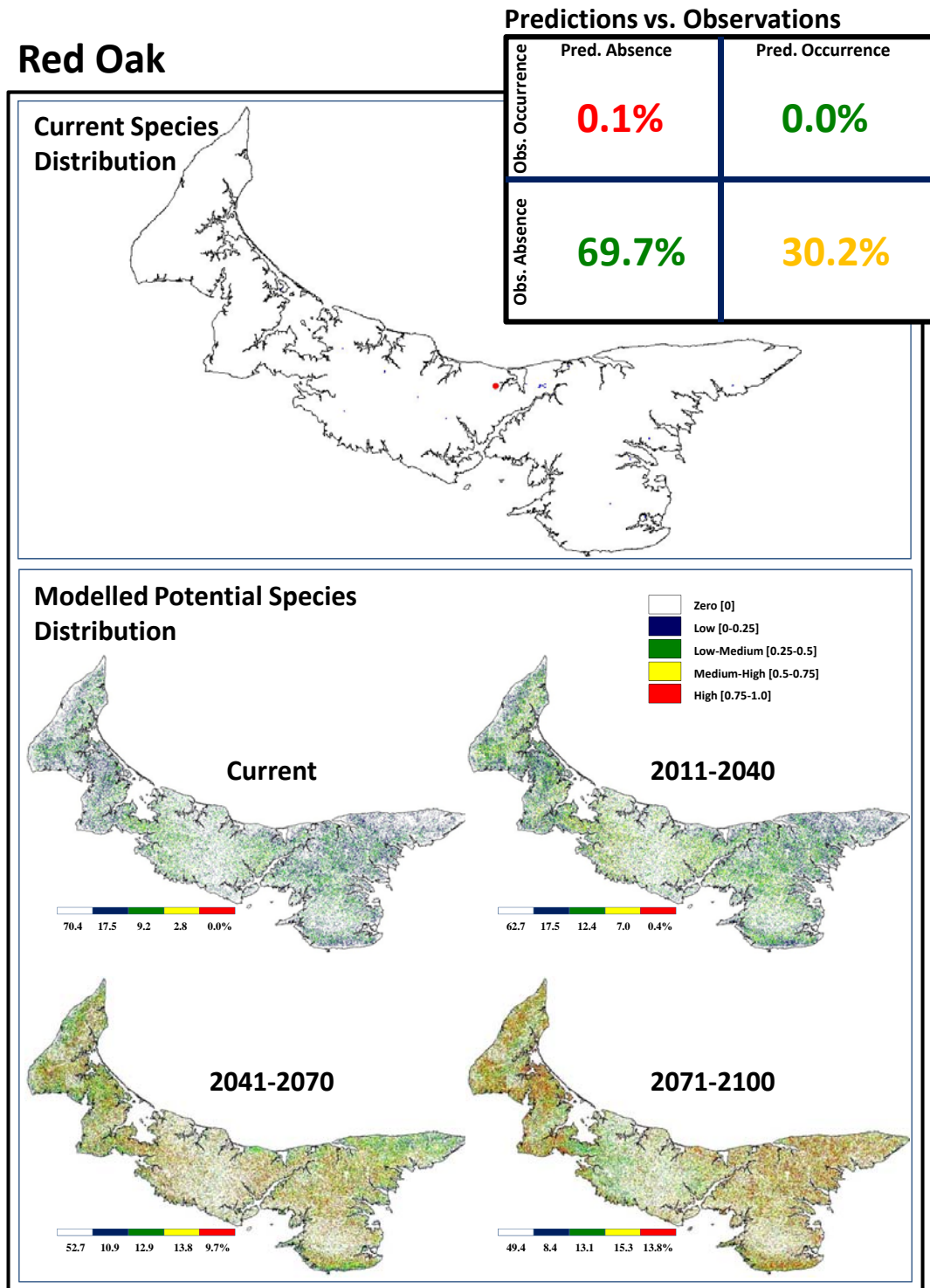


- **Red maple** habitat will benefit with climate warming (Figure 31). Over 100 years, medium-high to high quality red maple habitat will increase from an initial (current) coverage of PEI of 42.1% to 82.8%. The range of red maple on the Island (96.1% of PEI) is projected to remain mostly unaffected.
- **Red oak** habitat is predicted to ameliorate/expand over the next 100 years (Figure 32) with increases in mean temperature and GDD (from 2.8% of medium-high to high quality habitat to 29.1%, with an overall expansion of 21% across PEI) because of improved species response to high temperatures.



**Figure 31.** Distribution of **red maple** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

## Red Oak



**Figure 32.** Distribution of **red oak** for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100. In the current species distribution map (top panel), the red dots and blue polygons represent inventory plots and GIS polygons with  $\geq 10\%$  of the target species. Inset to the top right compares inventory plot observations of species presence/absence with modelled occurrence values for current conditions. In the legend, white represents unfavourable conditions and potential absence of species, while red represents the most favourable conditions and probable presence of the species; blue, green, and yellow represent intermediate conditions and associated species presence. The horizontal colour bar associated with modelled PSD (lower panel) indicates % of PEI occupied by individual habitat categories (legend).

Projected shifts in tree species distribution illustrated in Figures 20-32 are consistent with species response and projected habitat shifts from similar climate change-tree species impact studies for eastern Canada and continental USA using different GCMs and emission scenarios, e.g., McKenny *et al.* (2007), Bourque *et al.* (2008), Mohan *et al.* (2009), and Dombroskie *et al.* (2010).

#### 4. Concluding Remarks

In this report, we demonstrate a simple protocol for projecting species distribution for Prince Edward Island, Canada, by integrating modelled species-specific response to largely modelled biophysical variables of incident photosynthetically active radiation, growing degree days, and soil water content. Photosynthetically active radiation and soil water content are based on model calculations with the **LandSET** model and growing degree days, from remote sensing MODIS data. Average temperature and interpolated surfaces of mean annual precipitation serve as input to **LandSET** in its calculations of SWC. Despite the importance of soil fertility to plant growth, we ignore its impact here, as the available soil fertility maps for PEI are at a significantly coarser resolution. Adding soil fertility to the definition of PSD at the appropriate resolution may help provide better species description at the local scale. Its incorporation in PSD calculations is possible given the modular structure of the modelling framework.

More work is required to validate the species response functions both at local and regional scales for current climate conditions. Currently, the function parameters are based on values compiled from the scientific literature. A comprehensive evaluation of parameter values would require using inventory plots and biophysical data from as many sites (plots) in the *natural ranges* of target species as is feasibly possible. Likely other forest-forming factors, like minimum temperatures, thaw-freeze cycles, etc., may need to be incorporated to improve calculations for some species. Dynamic factors that also influence species distribution (e.g., species interaction and succession associated with disturbance) must be dealt within the context of stand development models.

The current report does not examine the impact of non-native tree species to PEI with the potential to move northward with climate change. Their presence in PEI and the extensive historical disturbance on the Island due to agriculture and other forest-forming practices can potentially change the dynamics of forest development processes on the Island and are elements worth investigating.

#### 5. Acknowledgements

This study was funded by Prince Edward Island (PEI) Department of Environment, Energy, and Forestry. We are particularly grateful to Mary-Lynn McCourt, Jon Hutchinson, and Mike Montigny of PEI DEEF for use of a recently acquired LiDAR-based DEM of the province and tree species presence/absence information used in our assessment of current potential species distribution. We would like to acknowledge Gary Lines of Environment Canada, Dartmouth, NS, for the statistical downscaling analysis and data projections of future monthly maximum and minimum air temperatures and growing season lengths used in the study. We would also like to acknowledge the National Aeronautics and Space Administration (NASA), USA, for providing the MODIS and Landsat-7 ETM+ data free of charge.

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## Appendix A

### Climate Station Location and Recorded Long-Term Mean Annual Total Precipitation

Station Name	Double Stereographic, X coordinate (m)	Double Stereographic, Y coordinate (m)	Elevation (m)	Annual Precipitation (mm)
ALBANY	355031.6	690860.4	24.86	1000.1
ALBERTON	322467.4	756038.5	3.54	1071.0
ALLISTON	430948.6	668541.3	51.81	1182.2
ARGYLE SHORE	372969.4	679638.2	31.99	1070.8
BANGOR	424374.3	700005.6	42.31	1354.9
CHARLOTTETOWN	389724.6	692554.8	53.28	1173.3
EAST BALTIC	464043.9	709559.2	50.6	1226.3
ELLERSLIE	329789.9	730008.5	0.98	1148.8
ELMWOOD	374295.8	688895.5	68.35	1193.0
HUNTER RIVER	374342.9	700010.9	72.81	1216.8
KINGSBORO	469209.7	705910.7	22.6	1191.3
LONG RIVER	357782.7	716777.7	23.35	1046.2
MONTAGUE	425727.7	683337.8	20.54	1101.8
MONTICELLO	440963.2	713063.8	22.97	1164.5
NEW GLASGOW	373093.1	707426.8	19.58	1240.8
NEWTON CROSS	412879.6	675886.5	34.97	1250.1
O'LEARY	303133.1	739644.0	43.11	1140.7
ST NICHOLAS	328271.0	709645.6	3.94	1171.7
ST PETERS	432012.4	711157.0	22.54	1075.8
STANHOPE	393593.6	707370.3	8.97	1044.4
SUMMERSIDE A	335956.1	709559.2	19.46	1078.0
TIGNISH	318805.9	767204.7	26.86	1105.6
TYNE VALLEY	328469.3	726318.4	17.4	1160.8
WELLINGTON	319354.7	713463.9	46.11	1142.3