Modelled Potential Species Distribution for Current and Projected Future Climates for the Acadian Forest Region of Nova Scotia, Canada

Charles P.-A. Bourque[1], Quazi K. Hassan[2], and D. E. Swift[3]

[1] Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, New Brunswick, E3B 6C2, Canada. Email: cbourque@unb.ca

[2] Department of Geomatics Engineering, Schulich School of Engineering, University of Calgary, 2500 University Dr., Calgary, Alberta, T2N 1N4, Canada. Email: qhassan@ucalgary.ca

[3] Canadian Wood Fibre Centre, Canadian Forest Service-Atlantic Forestry Centre, Natural Resources Canada, P.O. Box 4000, 1350 Regent Street South, Fredericton, New Brunswick, E3B 5P7, Canada. Email: eswift@nrcan.gc.ca

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 site conditions and how the variables may respond with changes in climate. In this report, we provide a description of a spatially explicit modelling framework that relates modelled climatic factors and potential species response to potential species distribution. As a demonstration of the method, we apply it to twelve plant species (i.e., ten tree species and two shrub species) native to the Acadian forest region of Nova Scotia (NS), 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), (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 **Lan**dscape **D**istribution of **S**oil moisture, **E**nergy, and **T**emperature model (**LanDSET**). GDD and average air temperature are estimated from remote sensing data derived primarily from MODIS and Landsat-7 ETM+ optical and thermal (infra-red) image data. Average air temperature and annual precipitation (presented as an interpolation of climate station precipitation measurements) serve as input to the calculation of SWC in **LanDSET**. In this assessment, the influence of hydraulic conductivity in the re-distribution of water in the landscape is assumed to vary with soil texture, % bedrock exposure, soil water content, slope position, and flow accumulation. In areas of the landscape where exposed bedrock appears, the water is channeled downslope without first infiltrating into the ground. Due to inadequate soil fertility information for NS, soil fertility is not included in the 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 disappearance, and disturbance in the calculation of PSD.

Climate change scenarios for future environmental conditions and species distribution for NS are based on statistical downscaling of coarse-grid climate projections from the first generation Canadian Coupled Global Climate Model (CGCM1) 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 results for current and future climates indicate that boreal species in the Acadian forest of NS (e.g., balsam fir, black spruce) would be restricted to the cooler areas of the landscape, i.e., adjacent to cold water bodies (e.g., Bay of Fundy in the northwest and Atlantic Ocean on the south-to-northeast of the province) and high elevation areas, such as the Cape Breton Highlands and Cobequid Hills. Under similar climatic conditions, temperate hardwood species (e.g., red oak, beech) are projected to benefit from elevated GDD in the second (2011-2040) and third tri-decade (2041-2070), and experience some decline in the fourth tri-decade (2071-2100). The report does not examine the impact of tree species currently south of NS as they move northward and begin to interact with tree species in the Acadian forest region of NS with climate warming.

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 bio-diversity, and (iv) regulating climate and atmospheric composition. As Canada possesses ~10% of global forests (Anonymous, 2007), developing further understanding of the geo-biophysical and ecological processes of forests and forested landscapes is important. The focus of this report is to relate a number of vital attributes of selected tree and shrub species and their modelled response to potential distribution in Nova Scotia (NS), 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), (ii) soil water content (SWC), (iii) growing degree days (GDD: a temperature related index), 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 soil water-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 characterization using RS data is done through vegetation indices, such as normalized 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 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 **Lan**dscape **D**istribution of **S**oil moisture, **E**nergy, and **T**emperature 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 northwest New Brunswick (NB), Canada (Hassan, 2008). 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.

In this report, we employ the formulation described in Bourque *et al.* (2000) and Hassan (2008) to provide PSD surfaces for ten commercial tree species and two shrub species native to NS, Canada (between 43^{o} 27' N to 46^{o} 01' N latitudes and 59^{o} 38' W to 66^{o} 16' W longitudes) for current (1971-2000) and projected climate scenarios for 2011-2040, 2041-2070, and 2071-2100. The species investigated include (1) five softwood species, i.e., balsam fir, black spruce [*Picea mariana* (Mill.) B.S.P.], red spruce (*Picea rubens* Sarg.), white pine (*Pinus strobus* L.), and red pine (*Pinus resinosa* Ait.); (2) five hardwood species, red oak (*Quercus rubra* L.), yellow birch (*Betula alleghaniensis* Britton), American beech (*Fagus grandifolia* Ehrh.), trembling aspen (*Populus tremuloides* Michx.), and black cherry (*Prunus serotina* Ehrh.); and (3) two shrub species, lambkill (*Kalmia angustifolia*) and witch hazel (*Hamamelis viginiana*). We exclude soil fertility (SF) in our formulation of PSD because currently no suitable map of SF exists for NS with our particular resolution needs. In this report, we make no attempt to examine the northward movement of tree species non-native to the Acadian forest region. Interaction between these species and those native to the Acadian forest (those not eliminated by climate change) will define the future dynamics of forest development in NS in a changing climate.

2. Methods

2.1. Study Area

Canada is divided into fifteen terrestrial ecozones, generalized 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 NS (Figures 1a, 1b) falls in the Atlantic Maritime Ecozone of eastern Canada (Figure 1a), and is characterized by a forest-dominated landscape and variable topography (i.e., elevations ranging from 0-540 m above mean sea level, asl). The landscape is distinguished by its temperate evergreen-deciduous Acadian forests, where a mixture of various coniferous species (e.g., balsam fir, red spruce) and deciduous species (e.g., yellow birch, red maple) dominate. Forests occupy about 79% of the province's land base (Hassan *et al.*, 2007b). Provincial climate is largely influenced by the region's proximity to the Bay of Fundy in the north and Atlantic Ocean to the south-to-northeast of the province. The province experiences a cool-moist climate with an annual mean temperature and total precipitation range of 5-7 °C and 900-1500 mm (NS Museum, 1996).

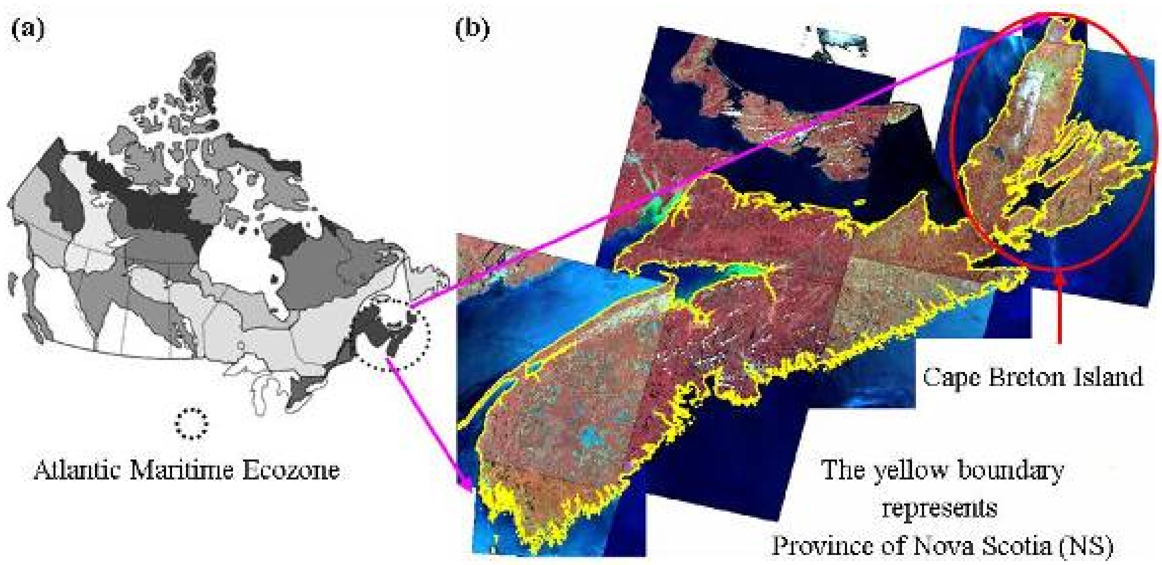

Figure 1. Atlantic Maritime ecozone of eastern Canada (a) and a mosaic of Landsat-7 ETM+ images depicting the Province of Nova Scotia (b).

2.2. Species Attributes and Habitat

1. **Balsam fir** develops best in the eastern part of its natural range, including in NB and NS. The provinces are distinguished by their cool temperatures and abundance of moisture. Growth of balsam fir is most favorable in areas with a mean temperature of 2 to 4 ^{o}C and annual precipitation of 760 to 1100 mm. The species grows on a broad range of inorganic and organic soils characterized 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 and topography 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, white spruce (*Picea glauca*), white birch (*Betula papyrifera*), trembling aspen, yellow birch, American beech, red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), eastern hemlock (*Tsuga canadensis*), eastern white pine, tamarack (*Larix laricina*), black ash (*Fraxinus nigra*), and northern white-cedar (*Thuja occidententalis*; Farrar, 1995). Red spruce is frequently associated with balsam fir in NB, NS, and Maine (Burns and Honkala, 1990a).

2. **Black spruce** is a wide-ranging species in northern North America (Farrar, 1995). Climate for black spruce is described as cold with moisture regimes ranging from humid to dry sub-humid (Burns and Honkala, 1990a). Mean annual temperatures range from -11 to 7 ^{o}C from its northern to southern limits. Generally, annual precipitation decreases from east to west, from as high as 1520 mm in the Maritime Provinces to 150 mm in western Alaska. Annual precipitation ranges from 380 to 760 mm in most of the species' range. The species usually grows on wet organic soils, but on occasion can be found to grow on soil types ranging from deep humus soils to shallow soil over bedrock. Lowest productivity occurs on partially decomposed sphagnum peat. Local topography and drainage characteristics appear to affect its distribution more than elevation. Black spruce commonly grows in pure stands

on organic soils and mixed stands on mineral soils. It is moderately shade tolerant (Farrar, 1995).

3. **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 to 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 to 5.5. Lack of proper aeration in poorly drained sites constrains the growth of red spruce. Red spruce can grow both in pure and mixed stands.

4. **White pine** grows in a cool and moist climate. Distribution of white pine coincides with the mean July temperature range of 18 to 23 ^{o}C. Annual precipitation ranges from 510 to about 2030 mm across its range. Throughout its range, precipitation is about 1-1.5 times the evaporation rate (promoting water surplus conditions). 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.

5. **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 to 1010 mm throughout the species' range. The northern limit of red pine coincides with the 2 ^{o}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 the borders of swamps. Productivity in red pine, in general, increases from ridges to plains to uplands.

6. **Red oak** grows from Cape Breton to Ontario, in Canada. Mean annual temperature across its range is about 4 ^{o}C in the north to 16 ^{o}C in its extreme south. Mean annual precipitation varies from about 760 to 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 to water table (Burns and Honkala, 1990b).

7. **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 ^{o}C average annual temperature isotherm and the southern and western limits with the 30 ^{o}C maximum temperature

isotherm. Annual precipitation across its range varies from about 1270 to 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 characteristics because of reduced competition from other species. Yellow birch appears in all stages of succession.

8. **American beech** grows from Cape Breton Island to southern Ontario westward to eastern Texas in the south. A strain of beech occurs in the mountains of northeastern Mexico. Within its range, mean annual temperature ranges from 4 to 21 ^{o}C and annual precipitation ranges from 760 to 1270 mm. Beech occurs in greater numbers on coarse-textured, dry soils in the northern part of its range. Beech may grow where the water table is within 15 to 25 cm of the surface. Beech is seldom found on alkaline soils (soils with pH > 7.0).

9. **Trembling aspen** has the largest natural range of any native tree species of North America. The range extends westward from Newfoundland to British Columbia. In the south, trembling aspen is found in the mountains of Mexico. Climate varies greatly over the range, specifically the minimum temperature and annual precipitation. Part of trembling aspen's range lies within northern Canada's permafrost zone; however, growth only occurs on the warmest sites, free of permafrost. Trembling aspen is found on a variety of soils from shallow and rocky to deep loamy sands and heavy clays (Burns and Honkala, 1990b). Growth on sandy soils is generally poor owing to insufficient moisture. Best aspen growth occurs on soils with a silt + clay content > 80%.

10. **Black cherry** grows best from NS-NB to southern Quebec and Ontario in the west to Texas, in the south. Black cherry and its various strains grow under a wide range of climatic conditions. In the core of its range, climate is temperate and moist with an average annual precipitation of 970 to 1120 mm. It will grow on a variety of soil types if the soils are cool and moist. Best development of black cherry occurs on the Allegheny Plateau at elevations of 300 to 790 m asl. Growth is constrained on very wet and very dry sites (Burns and Honkala, 1990b).

11. **Lambkill** is found from central Labrador, Newfoundland, south to Georgia, and from Newfoundland west to northern Ontario (Hinds, 2000). It can appear on acidic barrens and as an understory shrub in dry to moist coniferous woods with poor, sandy to rocky soils. Most commonly found in peat bogs and openings provided by forest clearings, abandoned pasturelands, and barren lands (Hinds, 2000). Within its natural range, the average number of growing degree days range from about 500 (Environment Canada, 2008) in the north of its range to about 2900, in the south (http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliGCStG.pl?va3071, site last visited September, 2008).

12. **Witch hazel** is found from NS (particularly in the southwest of the province) to Minnesota and south to Florida and Texas, mainly on moist, acidic forest soils and in shore tickets (Hinds, 2000). Witch hazel is shade-tolerant, a mid-to-late seral species that grows well as an understory species preferring deep, moist well-drained soils. It is known to grow along streams and forest edges, where it can grow taller with additional light. Witch hazel is known to be drought tolerant (http://tccswcd.vaswcd.org/witch-hazel.htm, site last visited

September, 2008). Within its natural range, the average number of growing degree days range from about 1400 along its northern limit (Hassan *et al.*, 2007b) to about 7025 along its southern limit (http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliGCStG.pl?fl6078, site last visited September, 2008).

2.3. Data Requirement and Processing

Data required to generate maps of PSD, included (i) a Digital Elevation Model (DEM) of NS, (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. The DEM of NS was generated from 3-arc second resolution point-data (~70 m at 45^{o} N latitude) acquired from the NASA Shuttle Radar Topography Mission. Supplementary datasets used in confirming current species distributions included inventory plots from which species presence were recorded. All inventory plot data were in GIS format; courtesy of the NS Department of Natural Resources (NS DNR).

2.3.1. Precipitation

In order to construct a mean annual total precipitation surface for NS (mm), a generalized (trained) artificial neural network (ANN) was employed. Training of the ANN was based on the generalized 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 in UTM (NAD83) co-ordinates, m], and elevation (m; Figure 2). The target output consisted of annual total precipitation at all Environment Canada climate stations in NS (61, altogether) and an estimated, imposed value at the centre of the Cape Breton Highland Plateau because of missing data (Appendix A).

Normally a small fraction of the dataset is used to train the ANN. The other fraction is normally used to check the reliability of model calculations. However, because of the limited number of samples, the entire dataset was utilized 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 2). The trained ANN was then applied to the individual cells of the DEM to obtain the required precipitation surface. Figure 3 shows the relative location and elevation (in m asl) of the climate stations that provided precipitation data.

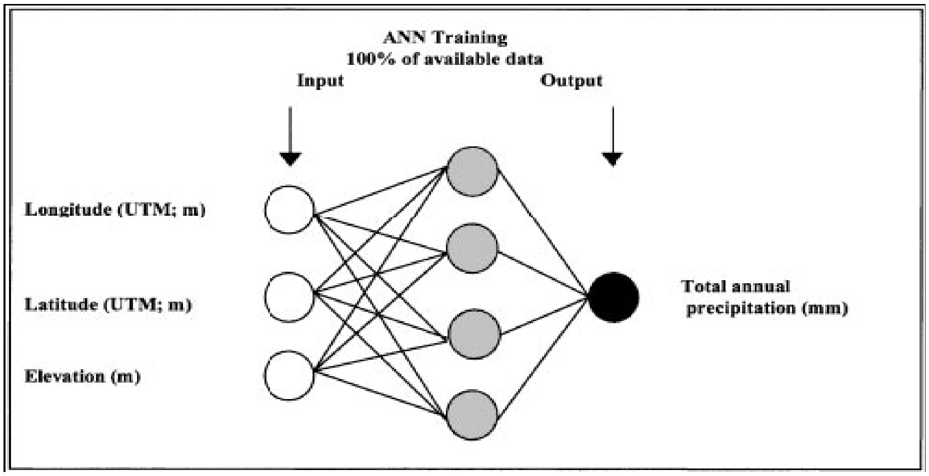

Figure 2. Representation of artificial neural network constructed to model average annual precipitation (mm). Inputs are based on DEM UTM coordinate transformation of longitude and latitude (NAD83, zone=20), and elevation (m asl).

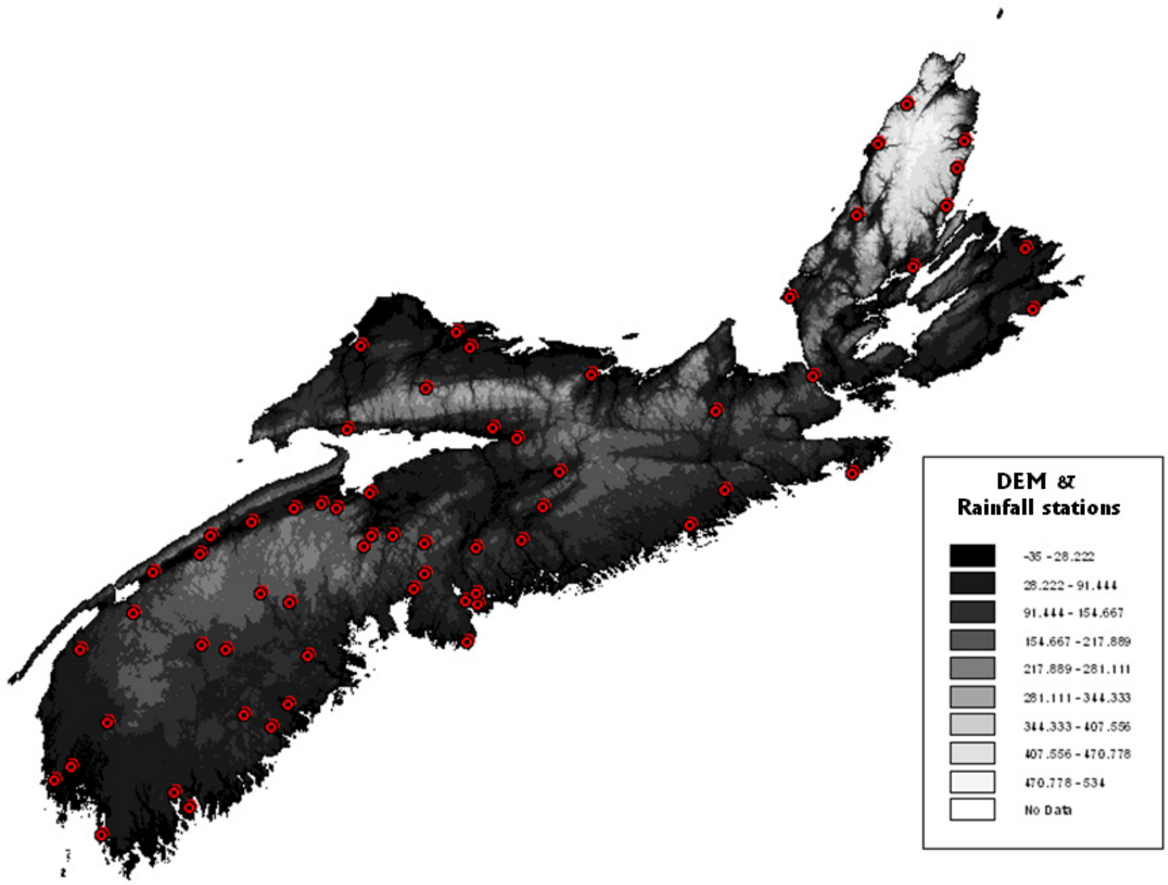

Figure 3. Geographic distribution of 61 Environment Canada climate stations in the province of NS providing precipitation data (denoted by red symbols; Appendix A). Gray scale colours correspond to variation in elevation (m asl), with white being the higher elevations, gray the intermediate elevations, and black the lower elevations (see legend).

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.,

$$\mathrm{GDD} = \sum_{i=1}^{i=n} \left(\overline{T} - T_{base}\right), \text{ when } \overline{T} - T_{base} > 0, \tag{1}$$

where $\overline{T}$ is the average temperature, T_{base} the base temperature at 5 ^{o}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 snow accumulation 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 NS 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^{-1}; Figure 4). Input to the model included topography, by way of DEM height values and cellsize specification (70 m), net radiative fluxes (in MJ m^{-2}), 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 permenant 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 texture and % bedrock exposure. In areas of the landscape where sufficient exposed bedrock occurred (≥ 50% in any GIS bedrock exposure polygon; NS DNR; Figure 5), the water was channeled downslope without first infiltrating into the ground. Soil texture, from very coarse to very fine (Figure 5) were assigned hydraulic conductivities based on values reported in the literature, e.g., Clapp and Hornberger (1978). These values (Table 1) controlled the rate in which water passed through the soil during the unsaturated and saturated phases.

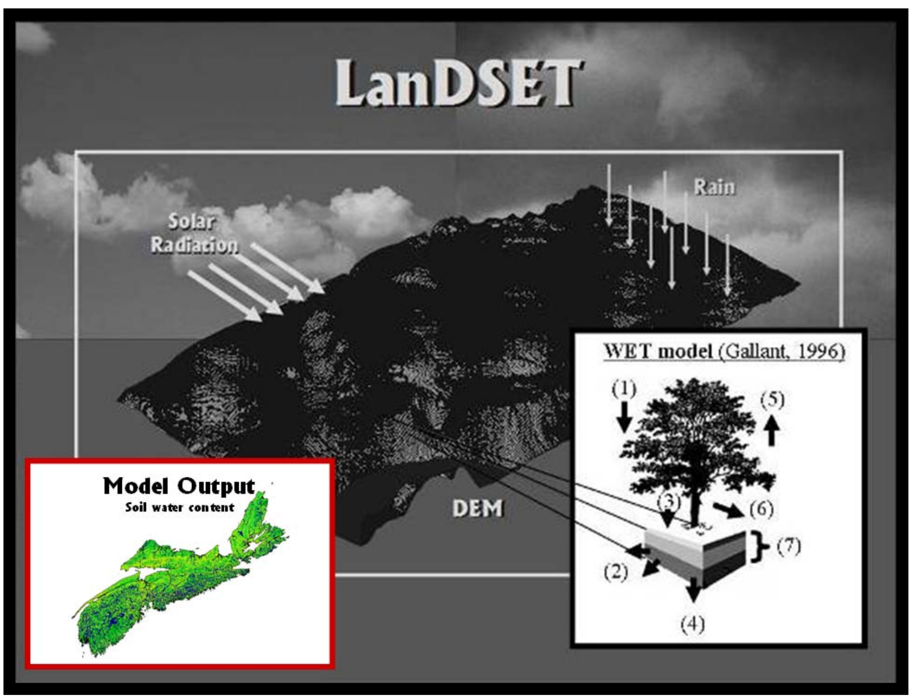

Figure 4. The **LanDSET** model simulates soil water content (SWC; inset) in the landscape according to cell-by-cell assessments of hydrological fluxes and storage. Input to the calculation of SWC includes available solar radiation and hydrological inputs of annual mean precipitation (1; inset) and lateral flow from upslope regions (2; inset). Hydrological outputs are infiltration (3; inset), deep seepage (4; inset), evapotranspiration (5; inset), surface runoff (6; inset), and changes in soil-water storage (7; inset).

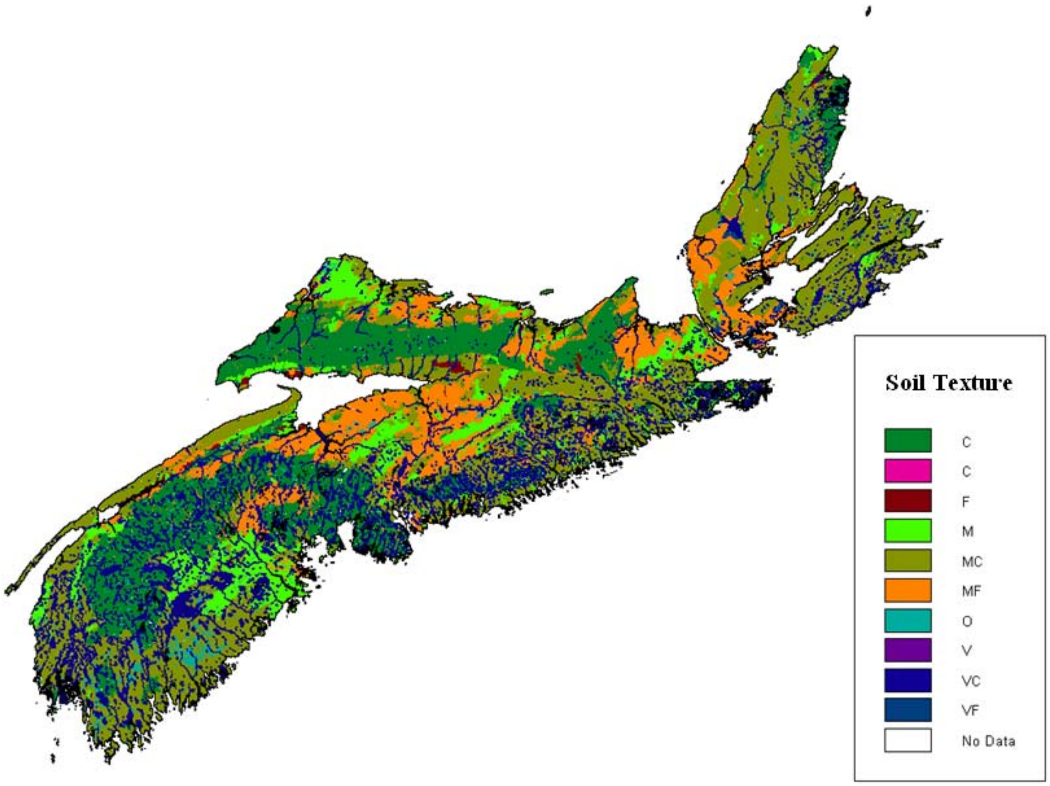

Figure 5. Soil texture map of NS (courtesy of NS DNR). The black polygons on the map are areas of significant bedrock (≥ 50% exposure; BR). The blue polygons are water bodies. Legend: C=coarse textured soils; F=fine textured soils; M=medium textured soils; MC=moderately coarse textured soils; MF=moderately fine textured soils; O=organic soils; V & VC=very coarse textured soils; and VF=very fine textured soils.

Table 1: Hydraulic conductivity of (1) soils of various texture and (2) areas of exposed bedrock.

Soil Texture	Nomenclature	Maximum Conductivity[1] (mm d^{-1})
Very coarse	VC	5.0
Coarse	C	4.5
Moderately coarse	MC	3.0
Medium	M	2.5
Moderately fine	MF	2.0
Fine	F	1.0
Very fine	VF	0.5
Organic	O	3.5
Consolidated Bedrock	BR	0.0

[1] 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); so for SWC=0, the hydraulic conductivity is zero. For BR, conductivity is always zero.

2.3.5. Evaluating Modeled PSD for Current Climate

Species occurrence in NS permanent sample plots (PSPs; NS DNR, 2004) was used as an indication of current species distribution across the province. The assessment included over 3000 PSPs measured from 2003-2007. The number of inventory plots available for individual species varied with species abundance. In an attempt to investigate the degree to which current PSD reflected actual species distribution, inventory plots containing the target species were compared with the species' PSD values. For purpose of assessment, several assumptions were made:

- Tree species were considered to have occurred in a PSP if the species represented at least 20% of the observed basal area in that plot.
- Shrub species were considered to have occurred in a PSP if the species represented at least 10% of the observed ground cover in that plot.
- Raster cells representing the landscape were considered to have the biophysical attributes needed for species occurrence where the predicted PSD was > 0.

Locations of plots were linked to the corresponding raster-based prediction of PSD for current climate conditions (1971-2000) to summarize the correlation between observed and predicted occurrences for each species. The analysis summarized 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 PSP ground observations.
2. **Predicted vs. Observed Species Absence**: This outcome demonstrates positive agreement between predicted species absence and PSP ground observations.
3. **Predicted Occurrence vs. Observed Species Absence**: This outcome is indeterminate with respect to model predictions, as species absence from the PSPs maybe the result of other forest-forming factors not addressed in the current definition of PSD (e.g., species migration, succession, disturbance, 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). One source of modelled inaccuracy is associated with the coarse resolution of the DEM.

2.3.6. Projected Future Climates

Climate change scenarios for NS were based on Environment Canada's statistical downscaling of coarse-grid climate projections generated with the first generation Canadian Coupled Global Climate Model (CGCM1) 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 (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 CGCM1 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 NS were based on fine-scale projections at 14 representative climate stations distributed across Atlantic Canada, including (1) Goose Bay, 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 Prince Edward Island. 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 6-8 monthly mean temperatures) and GDD (based on a monthly application of eq. 1 and a base temperature of 5 ^{o}C) for current and future 30-year time slices for NS (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 70 m resolution. Figure 6 provides an example of projected proportional changes in growing season mean temperature from current conditions (1971-2000) to 2011-2040.

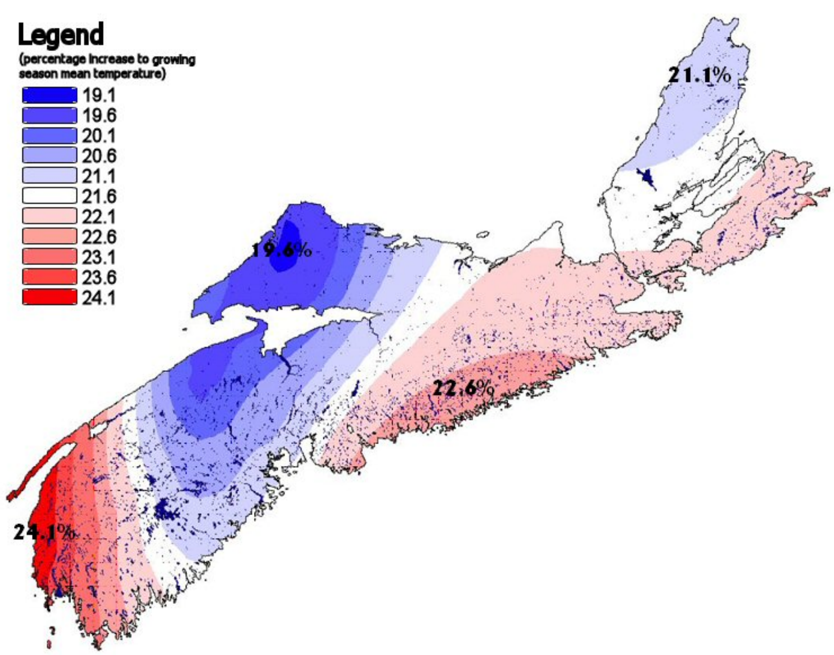

Figure 6. Proportional increases in growing season mean air temperature from current climate conditions (1971-2000) to 2011-2040 based on averaging 6-8 monthly mean temperature surfaces derived from statistically downscaled monthly maximum and minimum air temperatures. Similar surfaces were developed for each tri-decade, 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 (Environment Canada, 2007).

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, and Appendix B). Index values of relative PSD for individual DEM grid-points were obtained by multiplying individual grid-point evaluations of species environmental response (Figure 7). 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 utilize 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 7a) is modelled with

$$\mathrm{R(PAR)} = c_1 \cdot \left\{ 1 - \exp\left[-c_2 \left(\frac{\mathrm{PAR}}{\mathrm{PAR_{max}}} - c_P \right) \right] \right\}, \tag{2}$$

where c_1 is a scaling factor, c_2 is the slope of the response curve (Figure 7a), c_P is the light-compensation point, and 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 7b) assumes a parabolic function, i.e.,

$$\mathrm{R(GDD)} = \frac{4(\mathrm{GDD} - \mathrm{GDD_{min}}) \cdot (\mathrm{GDD_{max}} - \mathrm{GDD})}{(\mathrm{GDD_{max}} - \mathrm{GDD_{min}}) \cdot (\mathrm{GDD_{max}} - \mathrm{GDD_{min}})}, \tag{3}$$

where GDD_{min} and GDD_{max} are the minimum and maximum values of GDD (e.g., Bourque *et al.*, 2000; Hassan, 2008). The mid-point between GDD_{min} and 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 7c) is modelled after Bourque *et al.* (2000), i.e.,

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

where

$$\xi = \frac{SWC - SWC_{min}}{SWC_{max} - SWC_{min}},$$

$$\chi = \frac{\Psi - SWC_{min}}{SWC_{max} - SWC_{min}},\ SWC_{min} < \Psi < SWC_{max}, \qquad (4)$$

$$\kappa = \frac{1}{\chi^{\alpha}(1-\chi)^{\frac{1}{\alpha}}}, \text{ and}$$

$$\alpha = \sqrt{\frac{\chi}{1-\chi}}.$$

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

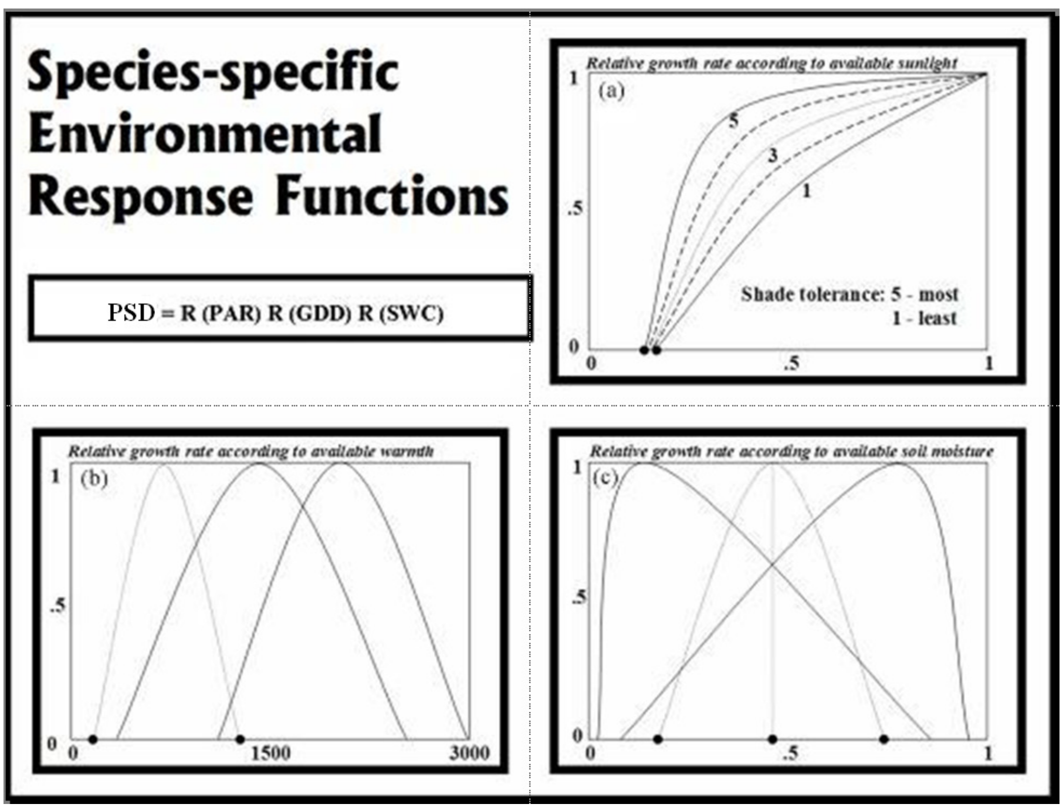

Figure 7. Generic species-specific environmental response functions for photosynthetically active radiation (PAR; a), growing degree days (GDD; b), and soil water content (SWC; c, after Bourque *et al.*, 2000). PSD is obtained by *multiplying* the individual response values constrained between 0 and 1. Definition of response curves for PAR, GDD, and SWC for a particular species is based on the species vital attributes in Table 2. Species environmental response curves for the 12 target species appear in Appendix B.

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

Species	Shade-tolerance class[1]	PAR[2]			GDD[3]		SWC[4]		
		c_1	c_2	c_P	GDD_{min}	GDD_{max}	SWC_{min}	SWC_{max}	Ψ
Balsam fir	4	1.05	3.29	0.06	563	2011	0.1	1	0.5
Black spruce	3	1.13	2.44	0.09	300	2200	0.27	1	0.8
Red spruce	4	1.05	3.29	0.06	800	2900	0.2	0.8	0.6
White pine	2	1.26	1.79	0.12	1100	3400	0.01	0.76	0.53
Red pine	1	1.58	1.19	0.15	1400	2300	0.2	0.95	0.7
Red oak	2	1.26	1.79	0.12	1525	3878	0.58	0.95	0.73
Yellow birch	3	1.13	2.44	0.09	1100	2900	0.01	0.76	0.67
American beech	5	1.02	4.17	0.03	1300	3500	0.01	0.70	0.58
Trembling aspen	1	1.58	1.19	0.15	800	3000	0.01	0.92	0.75
Black cherry	1	1.58	1.19	0.15	1700	4400	0.2	0.95	0.75
Lambkill	1	1.58	1.19	0.15	500	2900	0.1	0.87	0.5
Witch hazel	4	1.05	3.29	0.06	1400	7025	0.2	0.99	0.6

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

As a comparison, predictions based on a multiplication of individual response values (Figure 7; Bourque *et al.*, 2000) will be compared with a new definition based on the minimum of these same values.

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 8. 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 (29.9) and the slope (0.99) of the regression line fitted to the data were not statistically different from zero and unity at the 5% significance level.

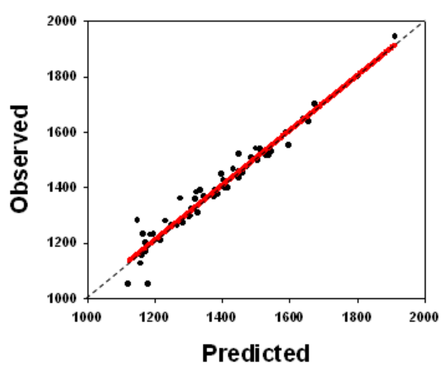

Figure 8. Scatter diagram of predicted vs. observed mean annual total precipitation (in mm). Level of agreement, as shown by the alignment of prediction-to-observation data points along the 1:1 correspondence line (diagonal dashed line), was 0.95 (adjusted-r^2). The slope and y-intercept of the regression 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 ± 37 mm.

The results show that, for the most part, the trained ANN was able to produce annual precipitation totals within 37 mm (standard error of estimate). The ANN was able to explain about 95% of the variability in the data (adjusted-r^2=0.95). Analysis of internal weights of the trained ANN revealed that longitude contributed 36% towards the calculation of precipitation, followed by latitude (35%), and elevation (29%). Spatial distribution of current annual total precipitation for NS is given in Figure 9.

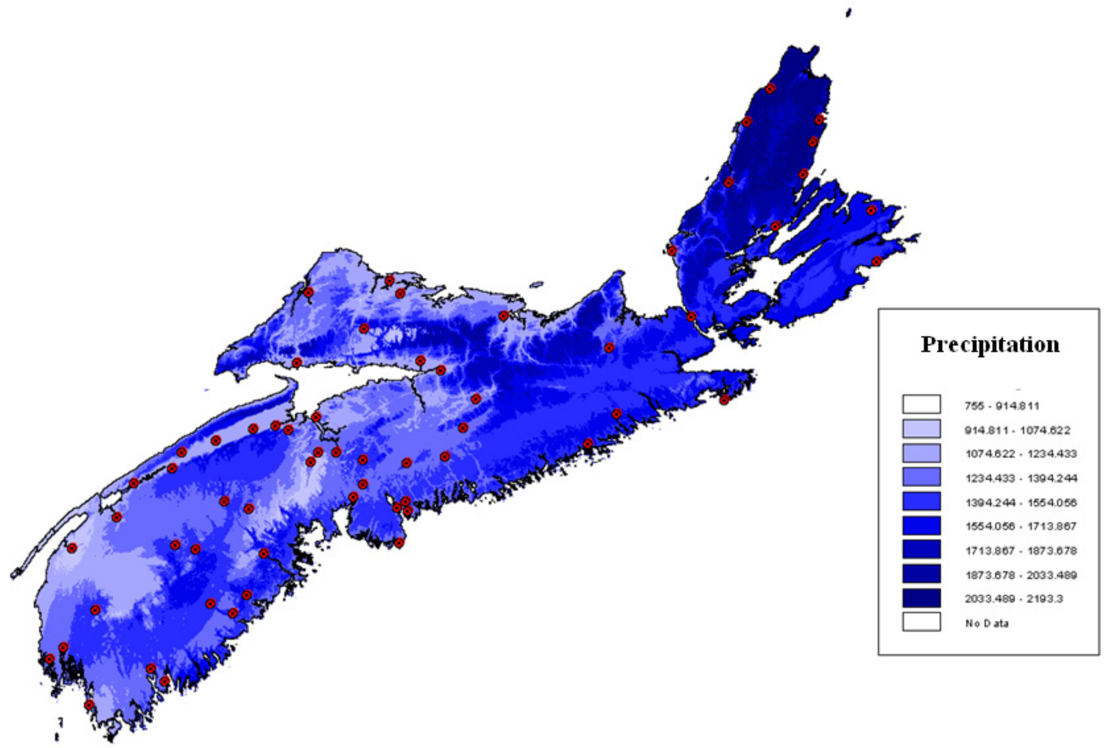

Figure 9. Distribution of mean annual total precipitation (in mm) for current conditions (1971-2000). The red symbols represent the locations of 61 Environment Canada climate stations used in the study (Appendix A).

Figures 10 and 11 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).

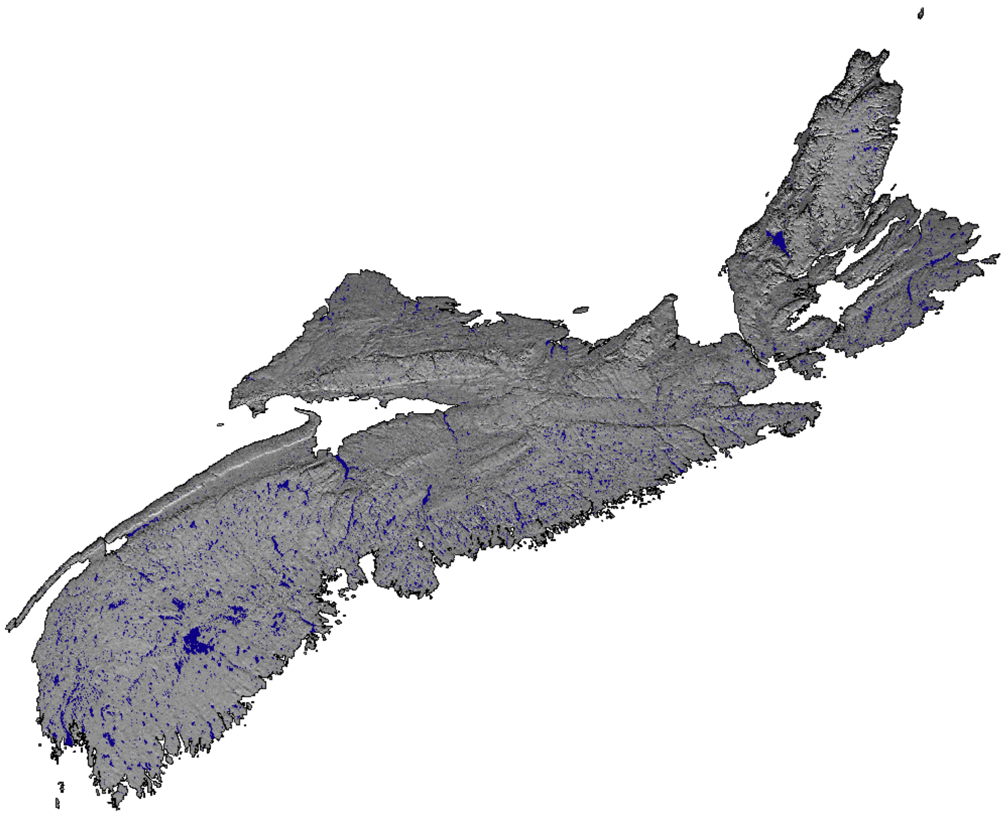

Figure 10. Distribution of **LanDSET**-modelled growing-season accumulated photosynthetically active radiation (PAR) for cloud-free conditions and an assumed mean mid-afternoon atmospheric transmissivity of 0.7. Light gray colours denote high incident PAR, especially on south-facing slopes, and the darker grays, low PAR. Blue areas represent lakes and other water bodies.

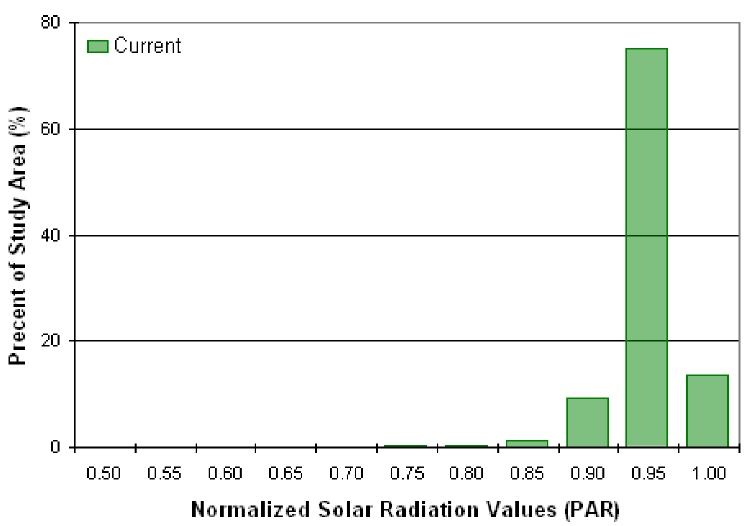

Figure 11. PAR frequency distribution (% of study area) for current climatic conditions (1971-2000). PAR values are based on normalized values (i.e., PAR/PAR_{max}).

Figure 12 shows the distributions of GDD for both current and future climatic conditions. GDD values for current conditions were in between 800 to 1989 from the coolest to the warmest locations in the landscape. These values are consistent with values reported by Environment

Canada for GDD calculated with a base temperature of 5 ^{o}C (Canadian Climate Normals for NS, 1971-2000; http://climate.weatheroffice.ec.gc.ca/climate_normals, site last visited September, 2008). Figure 13 shows the frequency distribution of GDD as a function of current and future climatic states. As expected, the distribution peaks shift towards higher values as climate warms. Projected increases in GDD from current conditions are on average 399 degree-days higher in 2011-2040 (ranging from 186-612, across NS), 871 higher in 2041-2070 (ranging from 489-1253), and 1323 higher in 2071-2100 (ranging from 620-1865), as a result of increased average temperatures and longer growing seasons compared to current conditions. Also, the range of GDD increases with climate warming, causing the distributions to flatten out from 1971-2000 to 2071-2100 (Figure 13). GDD projections over the next 100 years indicate that the temperature regime of NS will gradually converge to a temperature regime very similar to present-day conditions in the Commonwealth States of Kentucky and Virginia, USA.

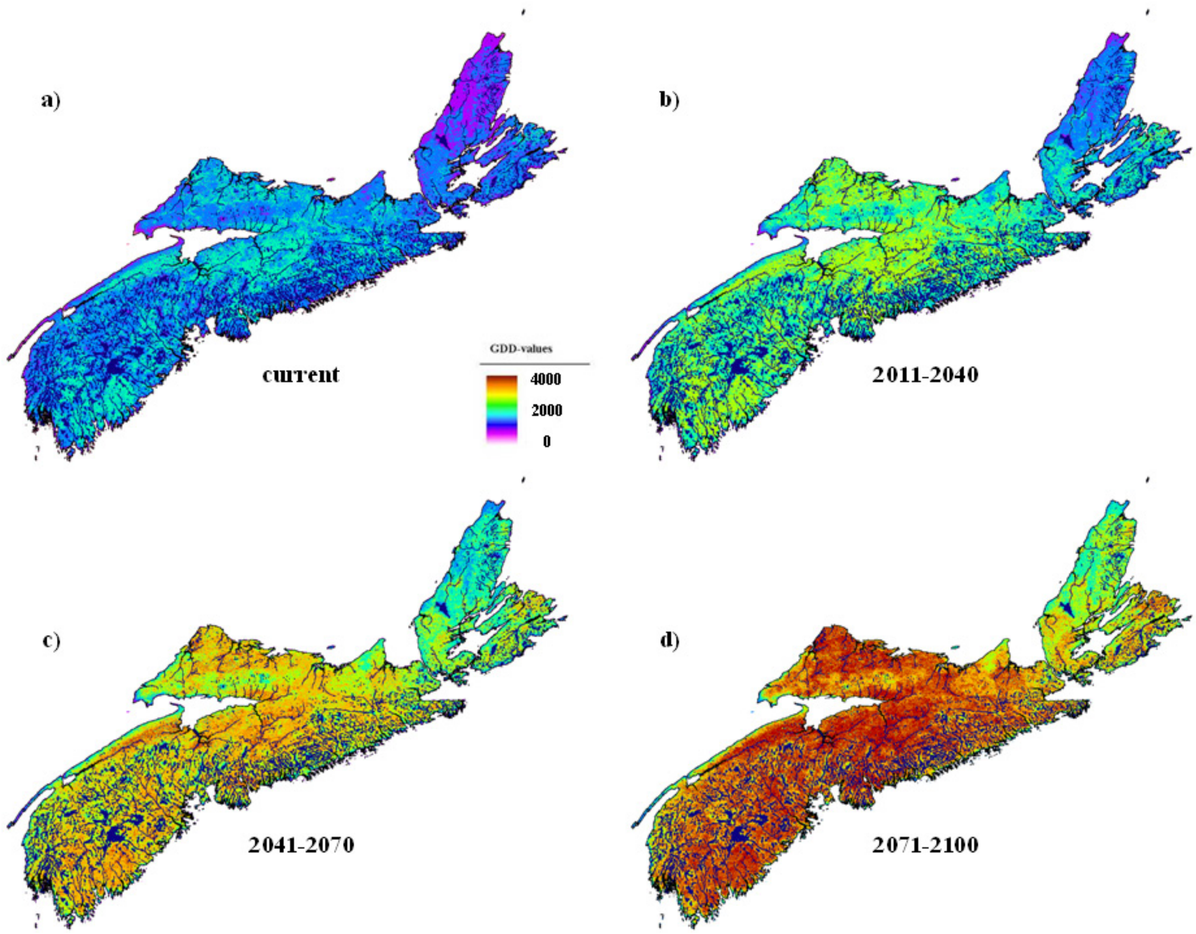

Figure 12. Spatial distribution of growing degree days (GDD) for current climatic conditions, 1971-2000 (a) and future conditions for 2011-2040 (b), 2041-2070 (c), and 2071-2100 (d).

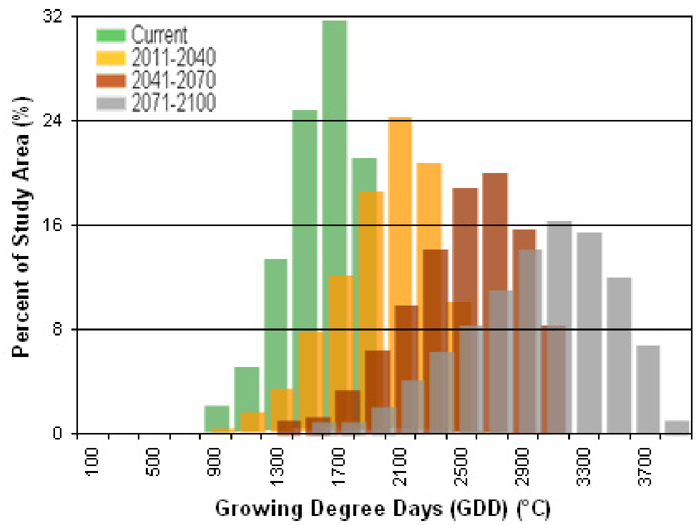

Figure 13. GDD frequency distributions (% of study area) for current climatic conditions (1971-2000) and future conditions for 2011-2040, 2041-2070, and 2071-2100. GDD are based on values from Figures 12a-12d.

Some features of the current GDD map (Figure 12a) worth highlighting include (Hassan *et al.*, 2007a):

(i) High elevation areas, such as in northeastern NS (i.e., the Highlands located in the northern most sections of Cape Breton Island; Figure 1b) had lower GDD, typically in the 800-1400 range. This is consistent with the fact that high elevation areas are normally cooler than low elevation areas in summer.

(ii) The areas along the coastlines had lower GDD at around 800-900, due to their proximity to cold ocean water.

(iii) Forested areas exhibited relatively cooler GDD compared to agricultural lands, due to the cooling effect associated with higher evapotranspiration rates by forests. Pattern in current land use has potential to impact GDD determined by remote sensing techniques. This effect is potentially carried forward with each successive calculation of future climate regimes.

Figure 14a shows the distribution of SWC for current climatic conditions. Figures 14b-14d show % difference of future soil water conditions for 2011-2040, 2041-2070, and 2071-2100 as a function of the previous tri-decade with a 5%, 10%, and 15% increase in current annual precipitation and projected increase in mean temperature. The pinkish-red colours in the map indicate land areas predicted to undergo drying, while bluish colours, areas to undergo wetting. The frequency distributions of SWC as a function of % of study area are given in Figure 15 for current and future climates. Greatest wetting of the soils is predicted to occur in the northern section of Cape Breton Island and Cobequid Hills, especially in the initial tri-decade (i.e., from 2000 to 2011-2040). In following tri-decades, wetting of these areas decrease as potential and actual evapotranspiration (and mean temperatures) start to increase at a greater rate than precipitation (Figures 14b-14d). In terms of SWC distribution for current conditions, 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 for NB (i.e., r^2=0.96; Figure 16).

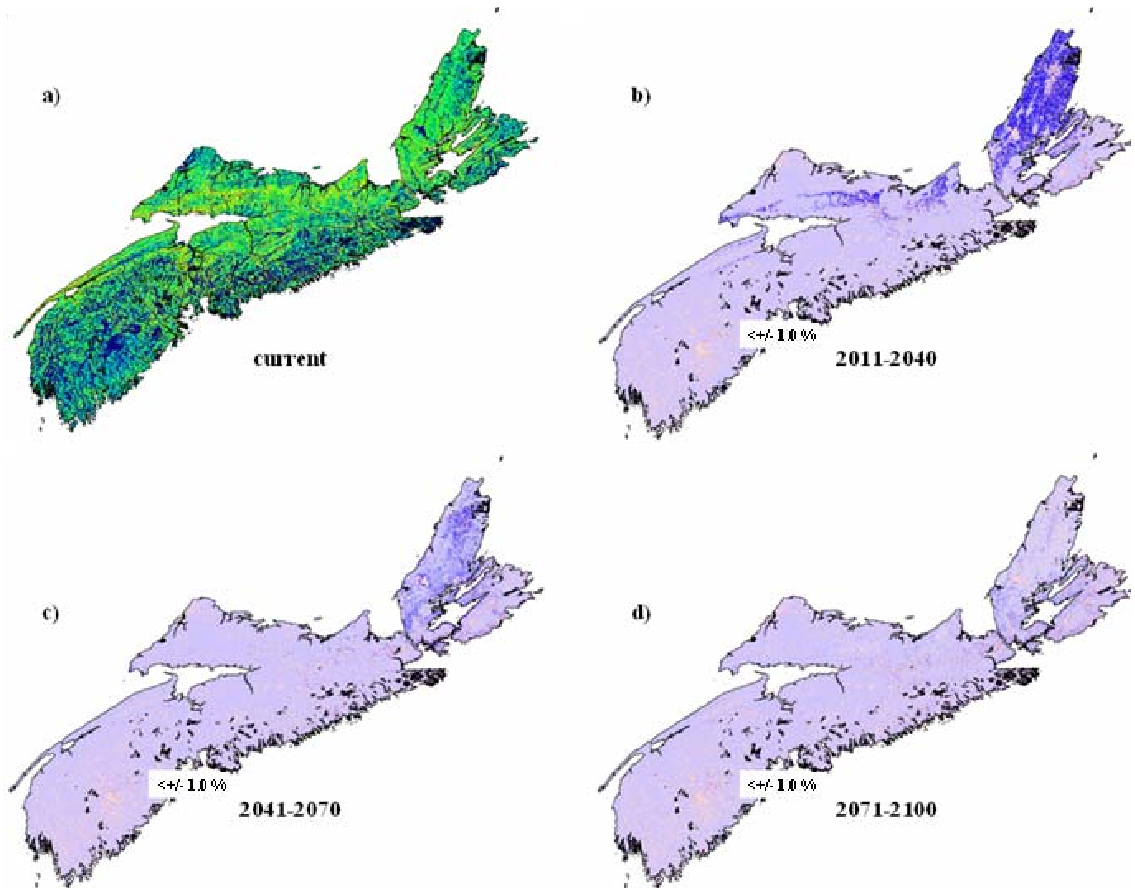

Figure 14. LanDSET-derived soil water content for current (a) and future conditions for 2011-2040, 2041-2070, and 2071-2100 as % difference maps from previous tri-decades [i.e., (current tri-decade minus previous tri-decade)/previous tri-decade*100%; b-d]. Average temperature increases across tri-decades are calculated from the monthly maximum and minimum temperatures derived from statistical downscaling. Pink colours in the difference maps (b-d) represent a net decrease (drying), while blue represents a net increase in soil water content, wetting the soils (the darker the blue, the greater is the wetting from the previous tri-decade). White colours to light pink and blue in the difference maps (b-d) represent nominal change in soil water content (< ±1.0%), especially in the flat, saturated areas of the landscape; denoted by dark blue-green colours in (a). The black areas denote exposed bedrock (with >50% coverage) and SWC=0.0.

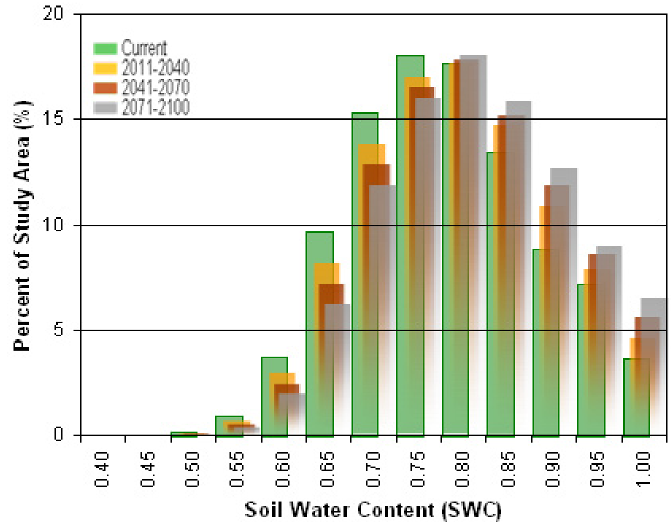

Figure 15. SWC frequency distributions for current climatic conditions (1971-2000) and future conditions for 2011-2040, 2041-2070, and 2071-2100. SWC are based on values from Figure 14a for current conditions; SWC for future climates are not shown.

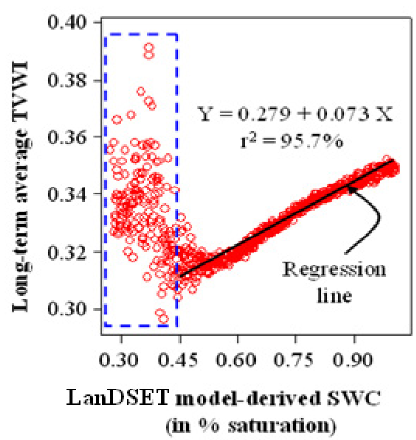

Figure 16. Comparison of **LanDSET**-generated SWC with long-term averages of wetness index calculated from MODIS surface reflectance data and greenness index, i.e., NDVI; after Hassan *et al.* (2007c). Points that deviate from the regression line (i.e., LanDSET model-derived values < 0.45) account for < 0.5% of all points.

3.2. Species Distribution for Current and Future Climatic Conditions

Figures 17-28 provide species distribution and corresponding % area histograms for the ten tree species and two shrub species for both current and future climatic conditions with CGCM1-projected temperature shifts and 5%, 10%, and 15% increase in annual total precipitation. The Figures also provide comparisons of (1) species environmental response functions with corresponding frequency distributions of GDD, SWC, and PAR for both current and future conditions, and (2) actual species occurrence in PSPs with modelled PSD values for current conditions (bottom right inset). In all instances, the influences of forest-forming factors, beyond the ones introduced here, were quite large [predicted occurrence vs. species absence from the PSPs ranged from 73.0-25.8%, giving a mean value of 49.5 ± 4.5% (standard error); Figures 17-28], indicating a need to incorporate new factors in the current definition of PSD. Dynamic factors associated with forest development processes like inter- and intra-species competition, species migration and extirpation, and disturbance (including harvesting) 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 simulators. Slow-changing factors, like soil fertility and soil compaction can be added to the definition of PSD, but for this to occur the data must be available and of sufficiently high quality at the desired spatial resolution (~100-70 m, or higher).

We summarize the prominent features of the projected distributions (Figures 17-28) as follow:

- **Balsam fir** is an aggressive species that grows practically everywhere in NS (Ritchie, 1996); this is borne out by the distribution of potential species habitat (99% of the study area; Figure 17, current conditions) and number of PSPs with balsam fir as the primary species (NS DNR, 2004). Under current climatic conditions, balsam fir habitat is most suitable (red and yellow colours; Figure 17) on Cape Breton Island and the other cooler parts of the province (e.g., Cobequid Hills, along the south-central and southeast coast, and along the Bay of Fundy; accounting for 45% of NS). In the warmer and wetter parts of the landscape (e.g., in the Annapolis Valley and inland) balsam fir is not expected to fare as well; sub-optimal PSD index values (represented by the blue and gray colours) occurs on 27% of the NS land base. Inaccuracies in modelled projections for current conditions accounts for 5.5% of PSD values generated for the PSP locations (bottom right; Figure 17). Under projected climate change in 2011-2040 (Figure 17), balsam fir is predicted to be restricted mostly to Cape Breton Island and to mainland areas close to cool water bodies and in high elevation areas (e.g., along the Bay of Fundy and, to some extent, in the Cobequid Hills). In 2011-2040, balsam fir habitat occupancy is predicted to diminish from a current value of 99% of NS to 46%. With continued warming (2041-2070 and 2071-2100), species habitat is predicted to persist mostly along the cooler, coastal regions of the province and to a lesser extent, along the edge of significant inland water bodies. In the latter part of the third tri-decade, habitat for balsam fir regeneration and growth is predicted to worsen with increase mean temperatures and GDD throughout NS (insets of Figure 17). By 2100, species habitat is projected to persist on only 7% of NS. 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 habitat over the next 100 years, albeit at much reduced levels.

- As in balsam fir, **black spruce** habitat is most suitable on Cape Breton Island and other high elevation areas (represented by mostly red colours of high PSD values; Figure 18) and near water bodies under current climatic conditions. Currently, black spruce habitat occupies 99% of NS, with 73% of NS having high to moderately-high PSD values. Modelled inaccuracies accounts for 3.2% of PSPs. Over time, black spruce habitat is also predicted to decline mostly as a function of mean temperature increase with climate change (from 2011-2040 to 2071-2100; Figure 18). In 2041-2070, black spruce habitat is predicted to deteriorate on most of mainland NS, potentially relegating black

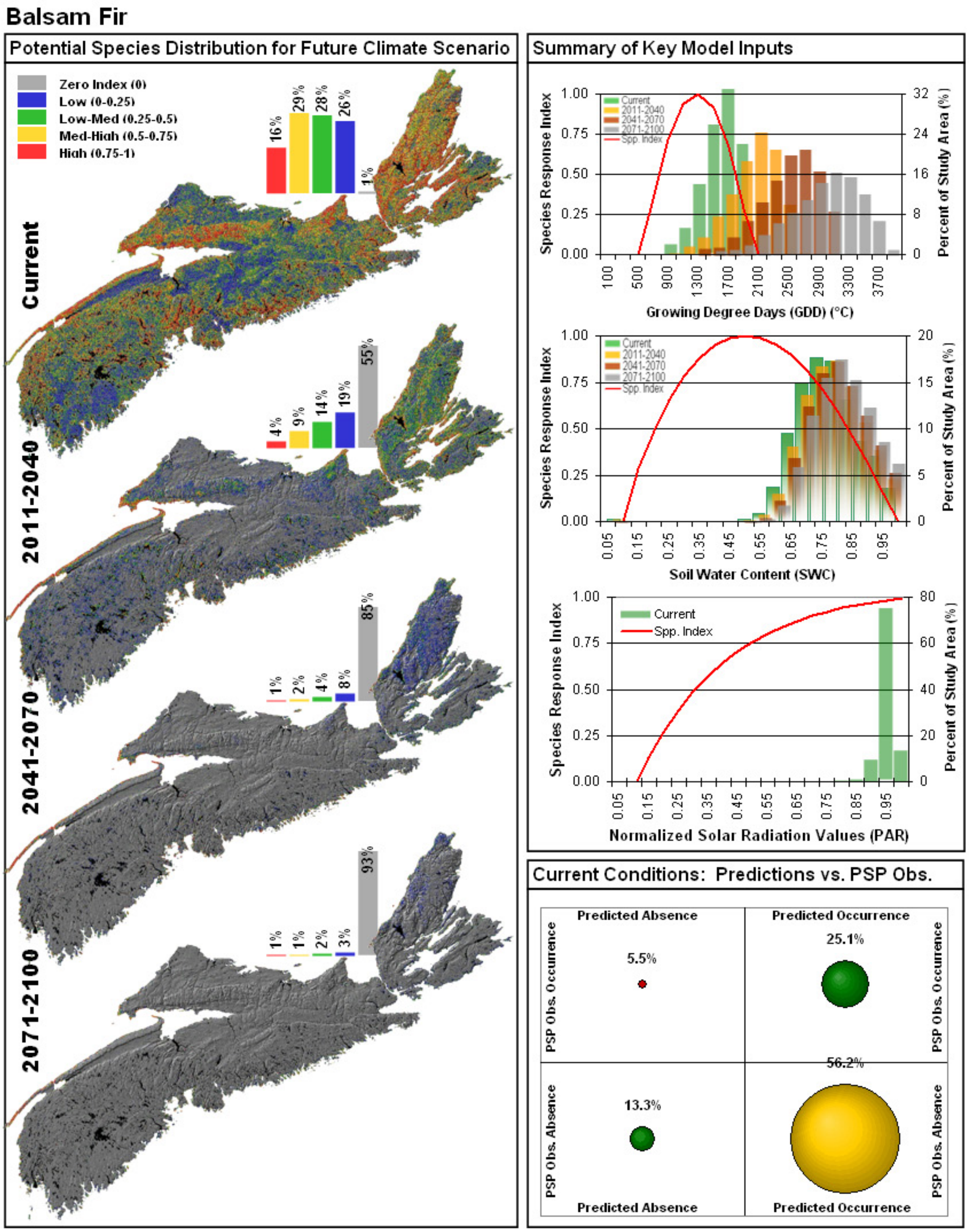

Figure 17. Distribution of balsam fir for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

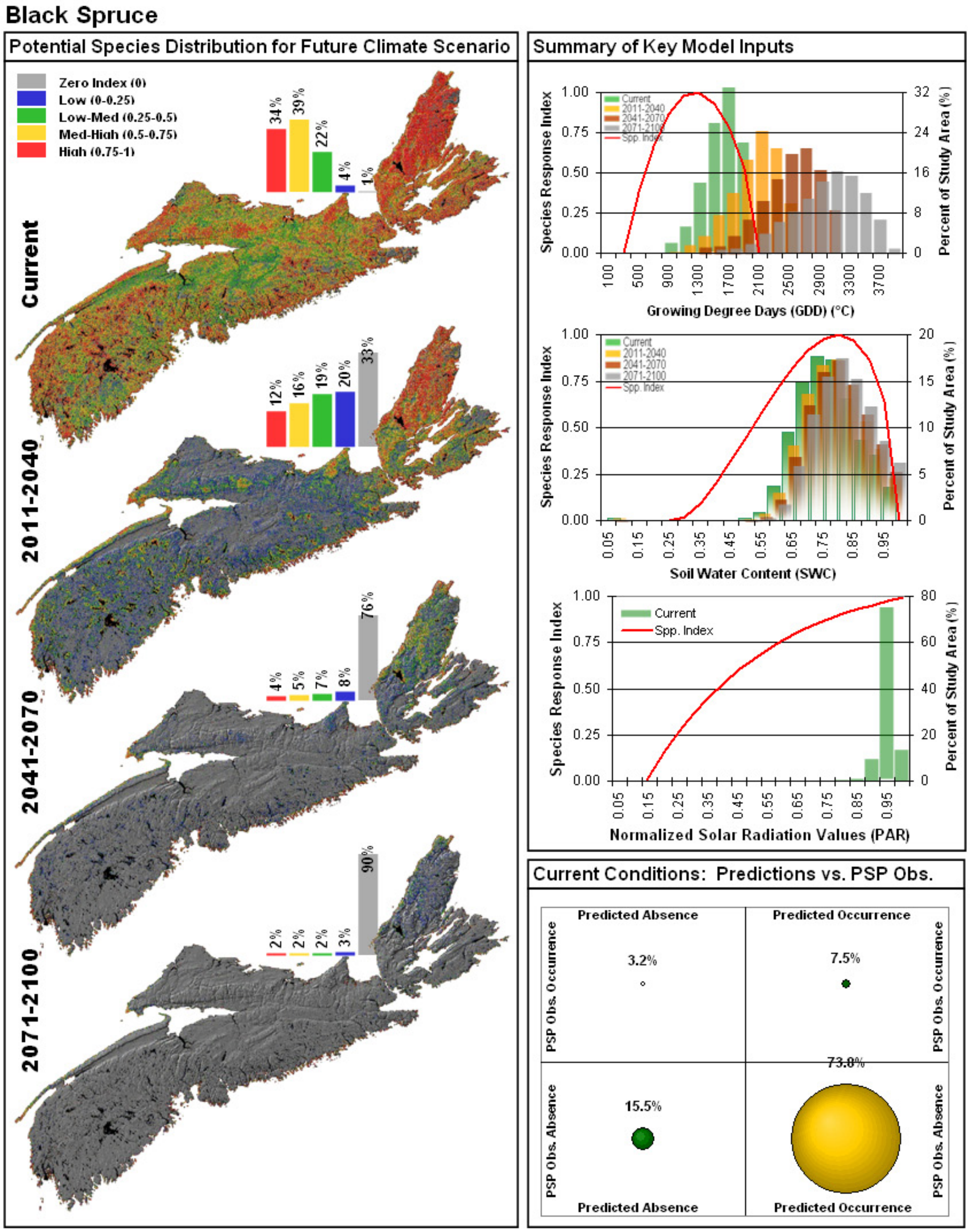

Figure 18. Distribution of black spruce for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

spruce to the cooler portions of the Cape Breton Island landscape. By 2041-2070, 24% of NS is projected to have suitable habitat for black spruce regeneration and growth. In the following tri-decade (2071-2100), black spruce habitat is projected to occupy < 11% of NS, mostly in pockets along the coast of mainland NS and plateau and coastal areas of Cape Breton Island.

- Under current climate conditions, **red spruce** is a dominant tree species on most of mainland NS, where GDD and SWC are most favourable (see summary statistics, Figure 19). Some red spruce habitat is found on Cape Breton Island, but mostly in the lowlands of the Island. Altogether, red spruce habitat for current conditions is calculated to occupy 65% of the NS land base. The cooler temperatures in the north restrict its potential presence northward, except for a small region northeast of the Cape Breton Highlands (Figure 19). Inaccuracies in modelled PSD values account for 10.8% error. Because red spruce often hybridizes with black spruce, separating the two species from each other in the field is sometimes problematic, resulting in mislabeling and increased error. Under projected climate, red spruce habitat is projected to continue to benefit with warming temperatures on 61% of the NS land base during the second tri-decade (2011-2040) and begin declining, in the order of 14-17%, in subsequent tri-decades (2041-2070 to 2071-2100; Figures 19). In the third tri-decade (2041-2070), red spruce habitat is predicted to be limited to Cape Breton Island and the cooler areas of mainland NS, occupying about 47% of NS. In the fourth tri-decade, habitat for red spruce is projected to occupy 20% of NS.

- **White pine** habitat is predicted to improve in the first tri-decade into the future (Figure 20) with a 13% increase in high-quality sites (red colour sites; Figure 20). During this time, the total white pine habitat (all habitat categories) will actually decrease from a current value of 52% of the total land base to 49%. In the following tri-decade, model projections indicate a gradual decline in both habitat extent (49% to 46% of NS) and quality (from 34% of high to moderately-high quality sites to 28%). Greatest decline is projected in the third tri-decade into the future (2071-2100), where white pine habitat is anticipated to occupy 33% of NS, most of low to moderately-low quality (blue and green colours; accounting for 22% of NS).

- Current **red pine** habitat is predicted not to fare as well as white pine habitat with climate change, where a 9% reduction is projected in high to moderately-high quality habitat in the first tri-decade into the future, and a 6% reduction, overall (Figure 21). This decline is clearly associated with the narrower response of red pine to increasing GDD in comparison to white pine. There is an indication that habitat for red pine will undergo significant deterioration from 2011-2040 to 2071-2100, with habitat lost > 50% with additional atmospheric warming and surface wetting, however small, over the 60 years (Figure 21).

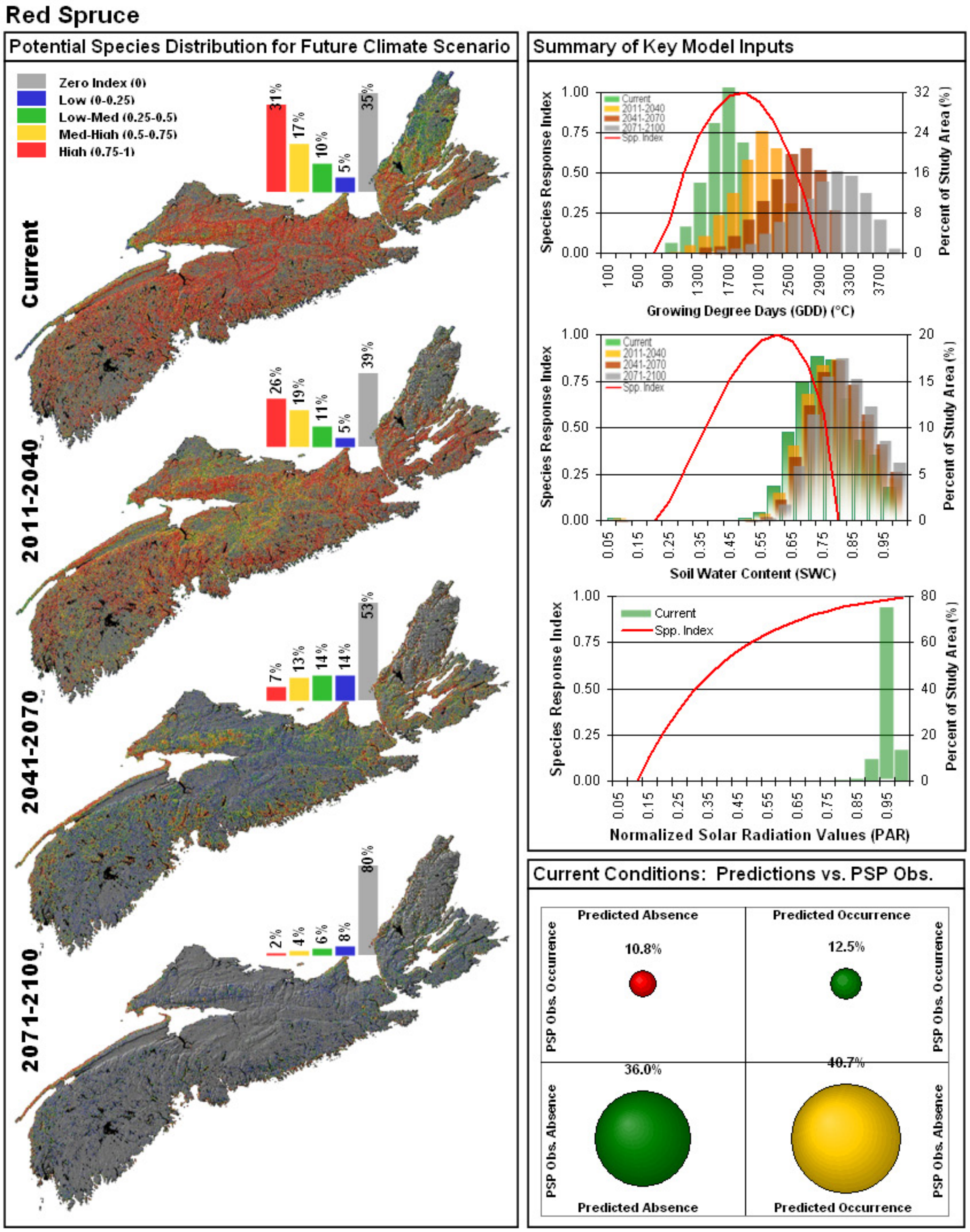

Figure 19. Distribution of red spruce for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

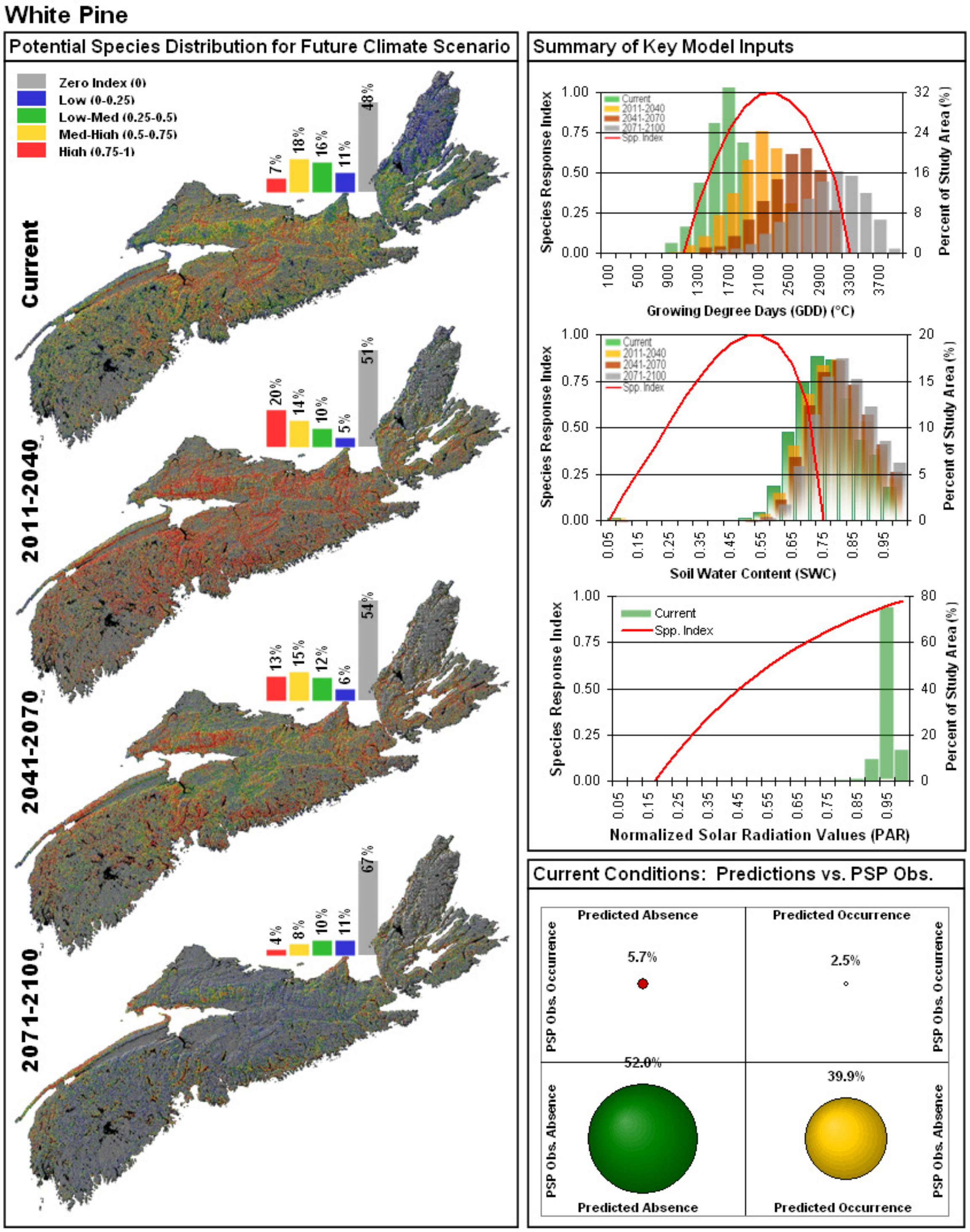

Figure 20. Distribution of white pine for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

Red Pine

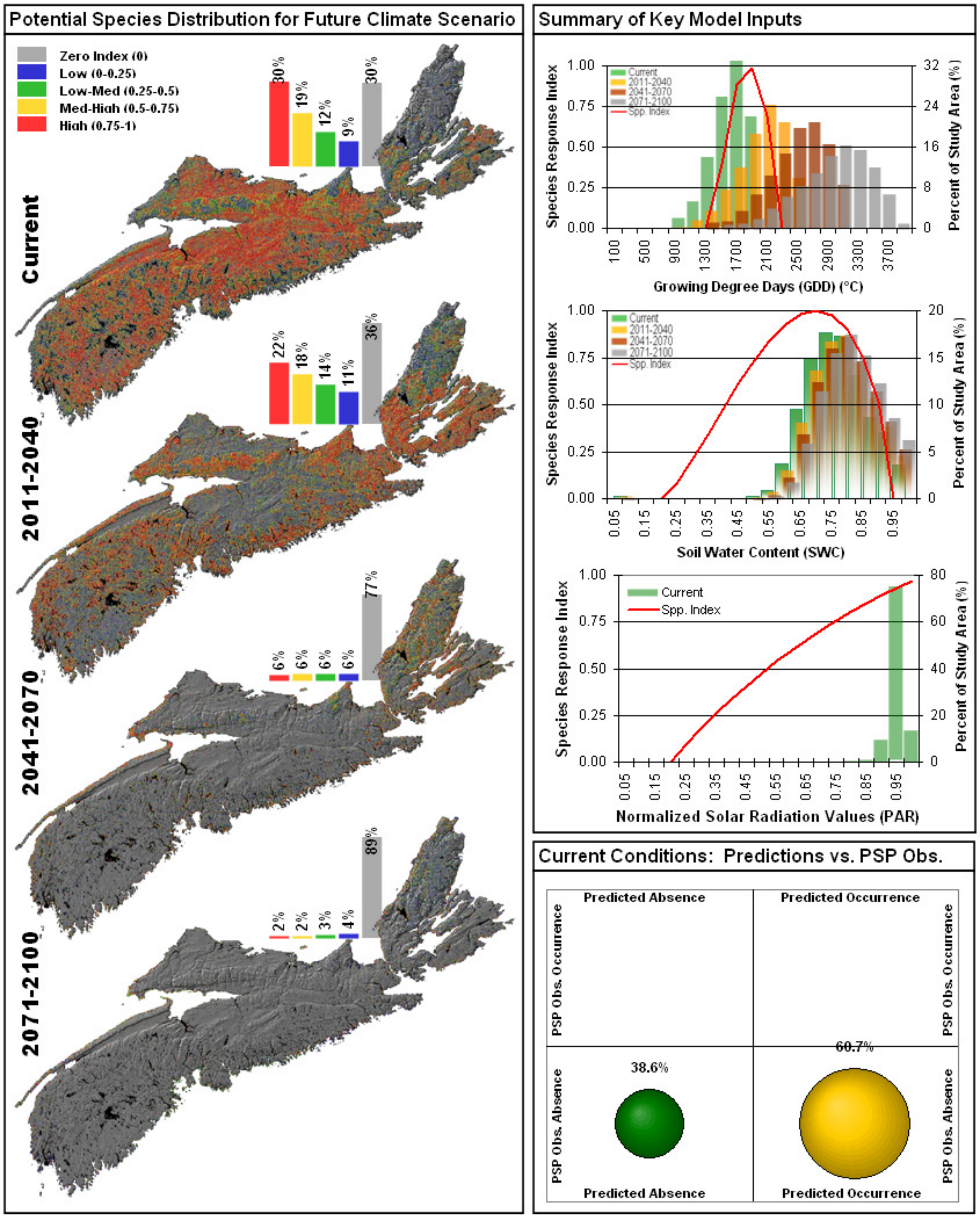

Figure 21. Distribution of red pine for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

- **Red oak** habitat is predicted to ameliorate/expand in the second and third tri-decade with increases in mean temperature and GDD (from 4% of high to moderately-high quality habitat to 37%, with an overall expansion of 21% across NS) because of improved species response to high temperatures (inset; Figure 22). This benefit, however, is projected to wane with further warming (Figure 22) in the fourth tri-decade with a 10% increase in low to moderately-low habitat quality and an 11% decrease in high quality habitat; no significant lost is projected for red oak across habitat quality categories from 2041-2070 to 2071-2100 (83% of NS to 82%). At the end of the fourth tri-decade, red oak is predicted to do well across most of NS (46% of high to moderately-high habitat quality), but generally at reduced levels from 2041-2070, when 34% of NS is projected as high quality habitat. High quality habitat in 2071-2100 is projected to occupy 23% of NS.

- Projections of PSD for **yellow birch** reveal that it may not fare as well as other hardwood species with climate change because of a narrower response function to increasing GDD and, to some extent, moistening of the soils (inset; Figure 23). Yellow birch habitat is predicted to ameliorate in some areas of NS (e.g., Cobequid Hills and areas of sloped terrain) and decline (downgrade in habitat quality) in others (e.g., in central NS) during the second tri-decade (2011-2040). Species range in NS is projected to decrease from 52% of NS to 49% during the second tri-decade, while high to moderately-high quality habitat is projected to increase from 38% of NS to 43% during the same time period. In following tri-decades, yellow birch habitat is predicted to undergo a significant decline in the third (2041-2070) and fourth tri-decade (2071-2100), losing about 33% of its range in 60 years.

- **American beech** habitat quality is predicted to ameliorate with climate warming during the first two tri-decades into the future (yielding a 12% increase in high to moderately-high quality habitat; Figure 24). Coupled to this amelioration is an overall reduction in the range of beech in NS, from a current value of 33% of NS to 32% in 2011-2040, to 30% in 2041-2070. A 14% decrease in high to moderately-high quality habitat and an 8% reduction in species range is predicted to occur in the fourth tri-decade (2071-2100; Figure 24).

- **Trembling aspen** habitat is predicted to experience a significant level of deterioration in the third and fourth tri-decade with climate warming; from 86% in 1971-2000 and 2011-2040, to 76% in 2041-2070, and 38% in 2071-2100 (Figure 25). High to moderately-high quality habitat is expected to improve slightly from 1971-2000 to the second tri-decade; i.e., from 76% of NS to 78%. In following tri-decades, high to moderately-high quality habitat is projected to decline by about 34% during the 2011-2040 to 2041-2070 period and an additional 26%, during the 2041-2070 to 2071-2100 period.

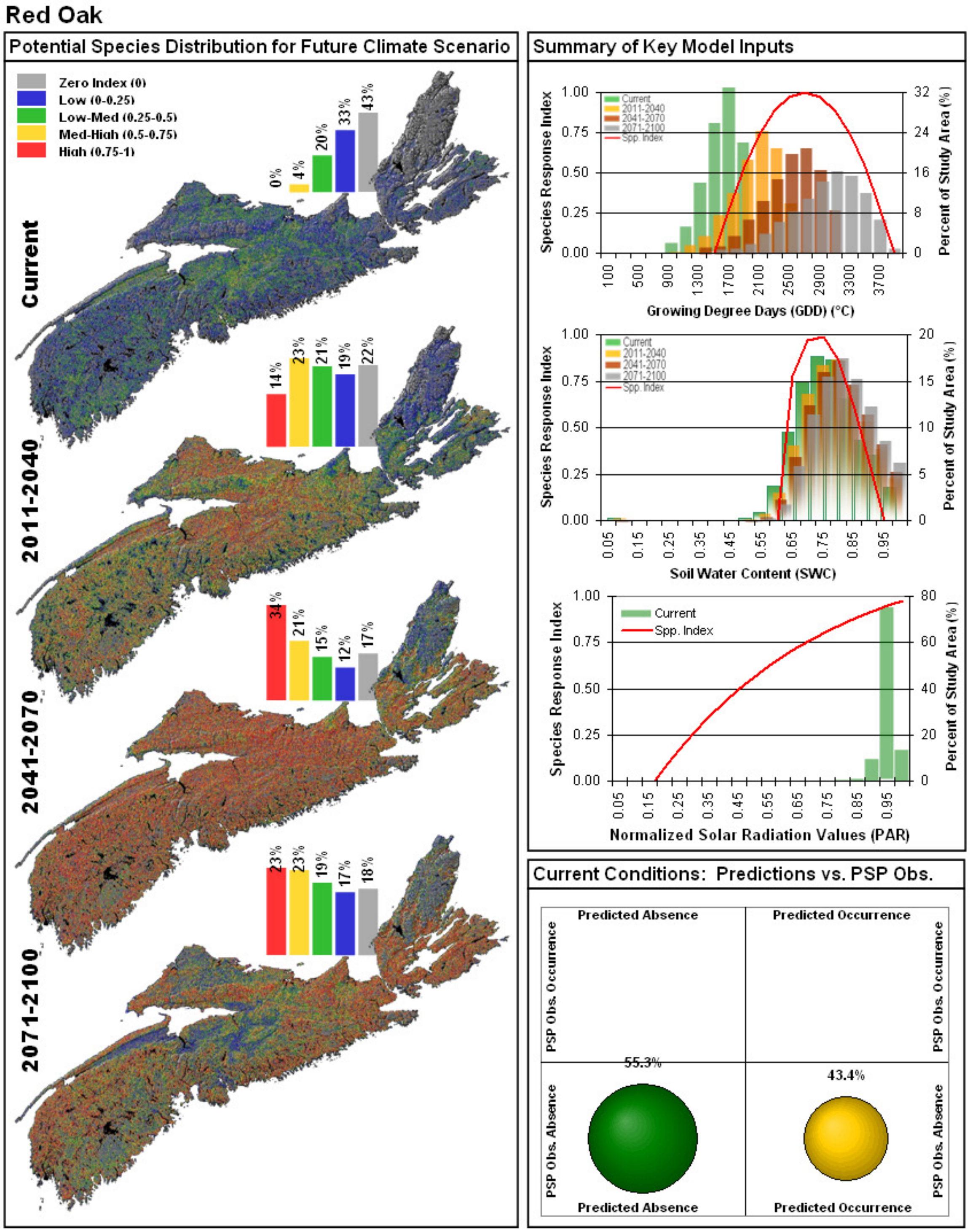

Figure 22. Distribution of red oak for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

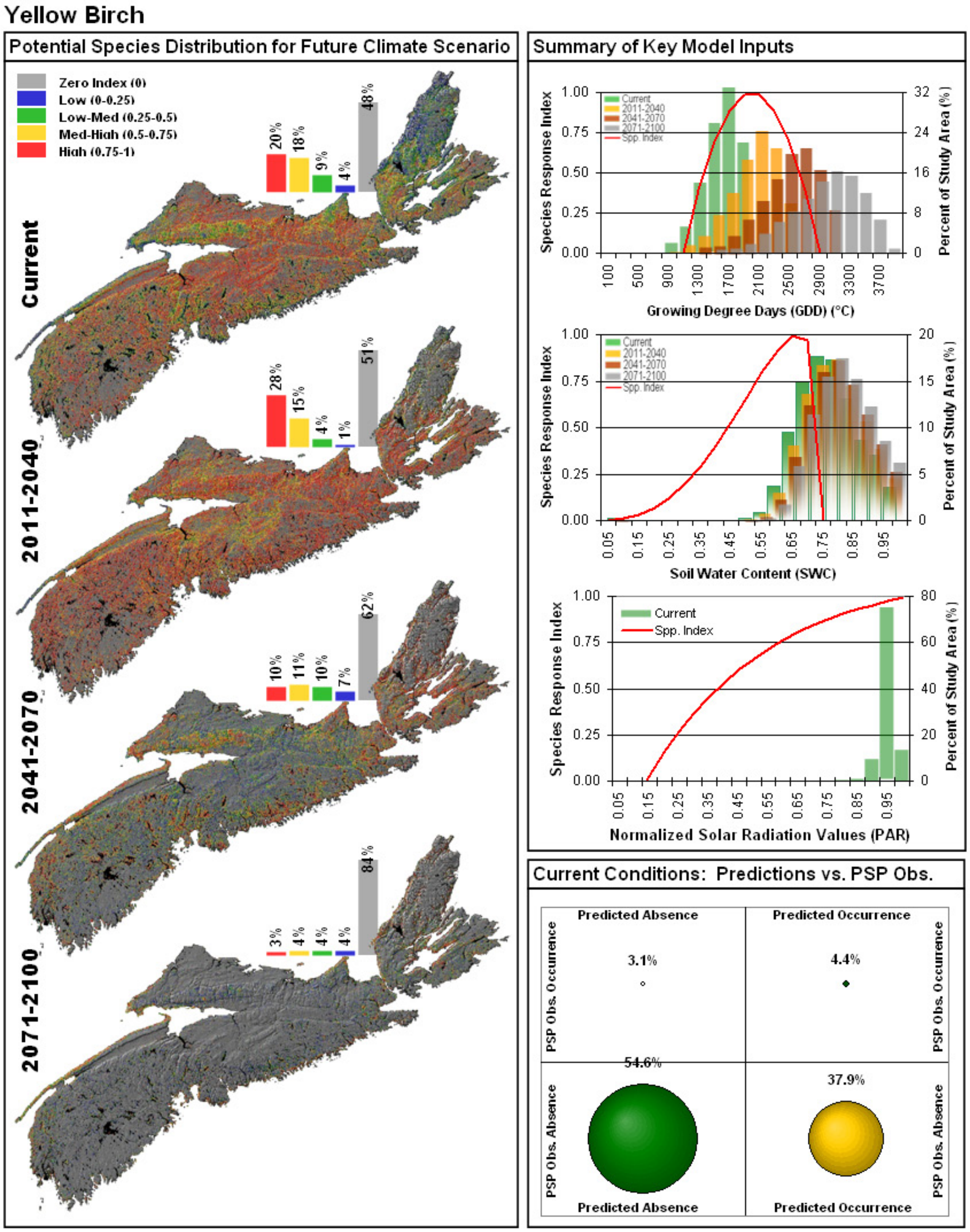

Figure 23. Distribution of yellow birch for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

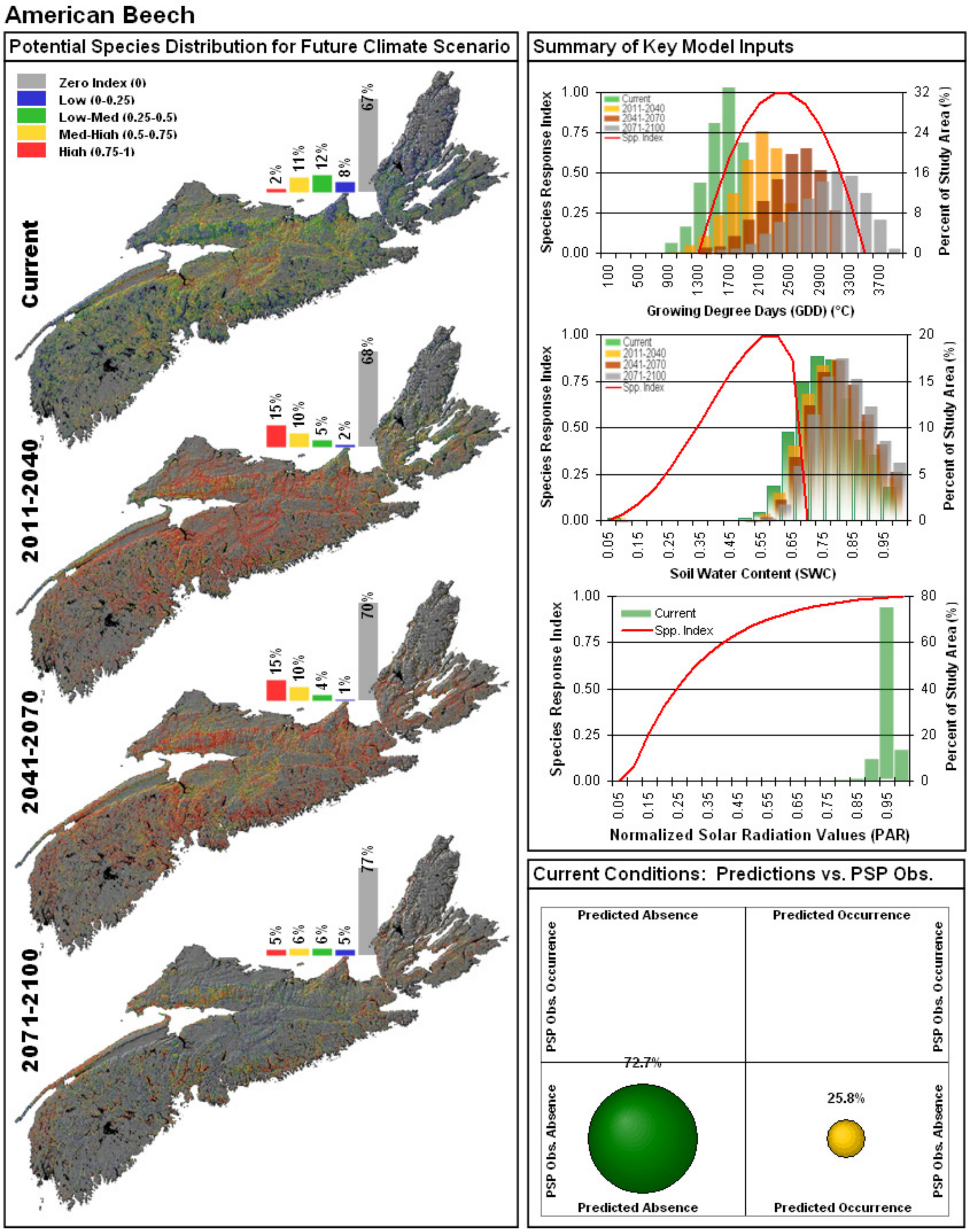

Figure 24. Distribution of American beech for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

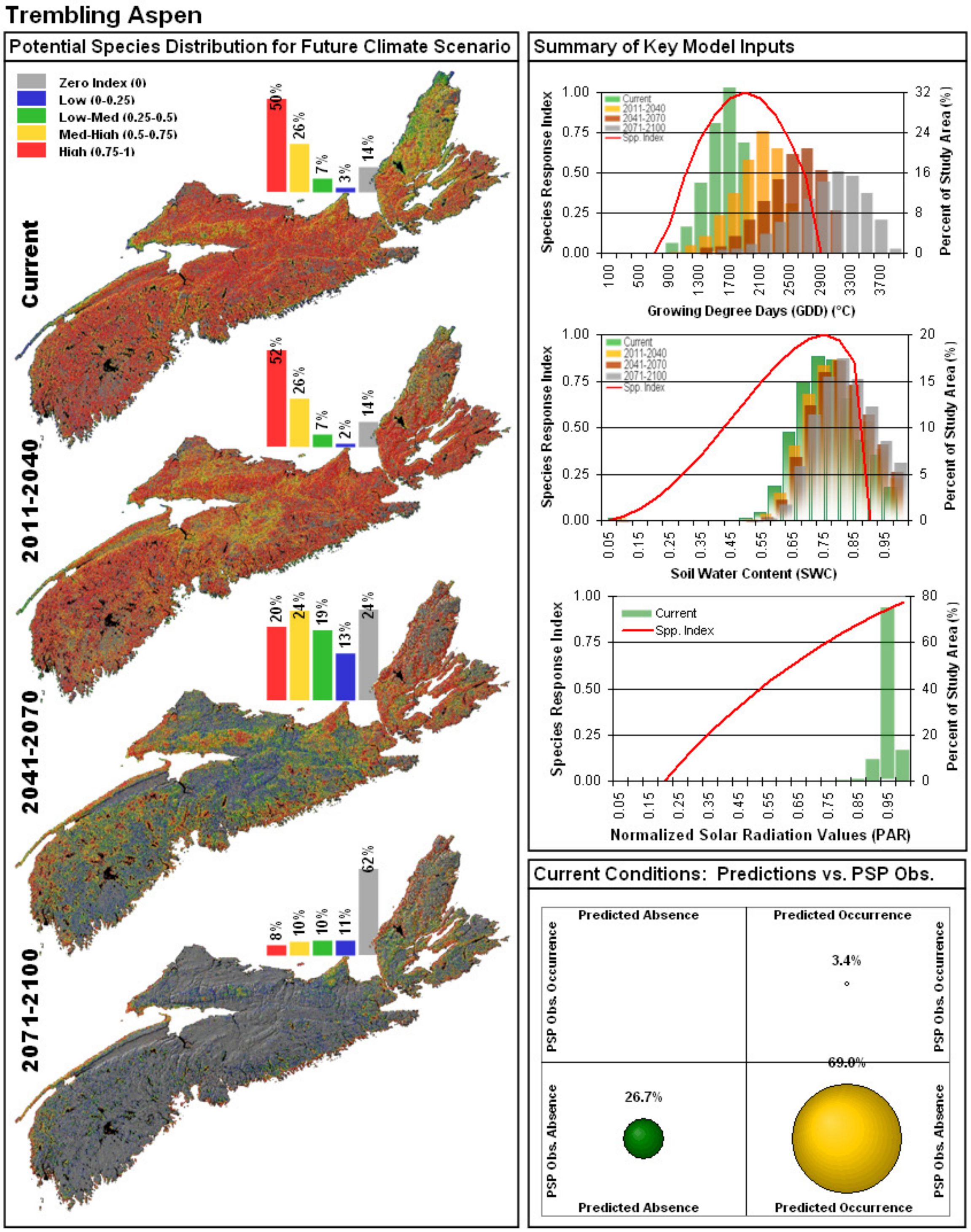

Figure 25. Distribution of trembling aspen for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

- **Black cherry** habitat and its range are predicted to ameliorate/expand with climate warming due to the species broad response function to GDD. From the first to second tri-decade, high to moderately-high quality habitat is predicted to increase from 0% of the land base to 28%. In successive tri-decades, high to moderately-high quality habitat is projected to increase an additional 35%, during the 2011-2040 to 2041-2070 period, and 8 %, during the 2041-2070 to 2071-2100 period. The species range in NS is projected to increase from a current value of 34% of the NS land base, to 71% of the land base in the second tri-decade (2011-2040), to 82% in the third tri-decade (2041-2070). Range expansion is predicted to stabilize after the third tri-decade. In the fourth tri-decade, black cherry habitat is projected to occupy most of NS (~82% of the total land base), except in the northern portion of Cape Breton Island (Figure 26). Of this area, 39% is projected as high quality habitat.

- **Lambkill** habitat is currently abundant in NS; modelled PSD values indicate a species range that covers approximately 81% of the entire province. Twenty two percent of the land base is projected as high quality habitat. The range is predicted to gradually decline with atmospheric warming and, to some extent, wetting of the soils, from its initial distribution of 81% of NS to 28% in the final tri-decade (Figure 27). A similar decline is projected in high quality habitat from an initial value of 22% of NS to 1% in the fourth tri-decade.

- **Witch hazel** habitat and its range are predicted to ameliorate/expand with climate warming, mainly as a function of the species' broad response function to GDD (inset; Figure 28). High quality habitat is projected to increase from an initial value of 0% of NS to 24%, by the fourth tri-decade. Although, the current range covers roughly 75% of NS, most of this habitat is of poor to medium quality (PSD values < 0.5). As GDD increases, the range increases by 13% by the second tri-decade, 2% by the third tri-decade, and 2% by the fourth tri-decade. By the final tri-decade, high to moderately-high quality witch hazel habitat is projected to occupy 56% of NS. Habitat quality in northern Cape Breton Island is expected to remain poor (low to unsuitable) over the next 100 years (Figure 28).

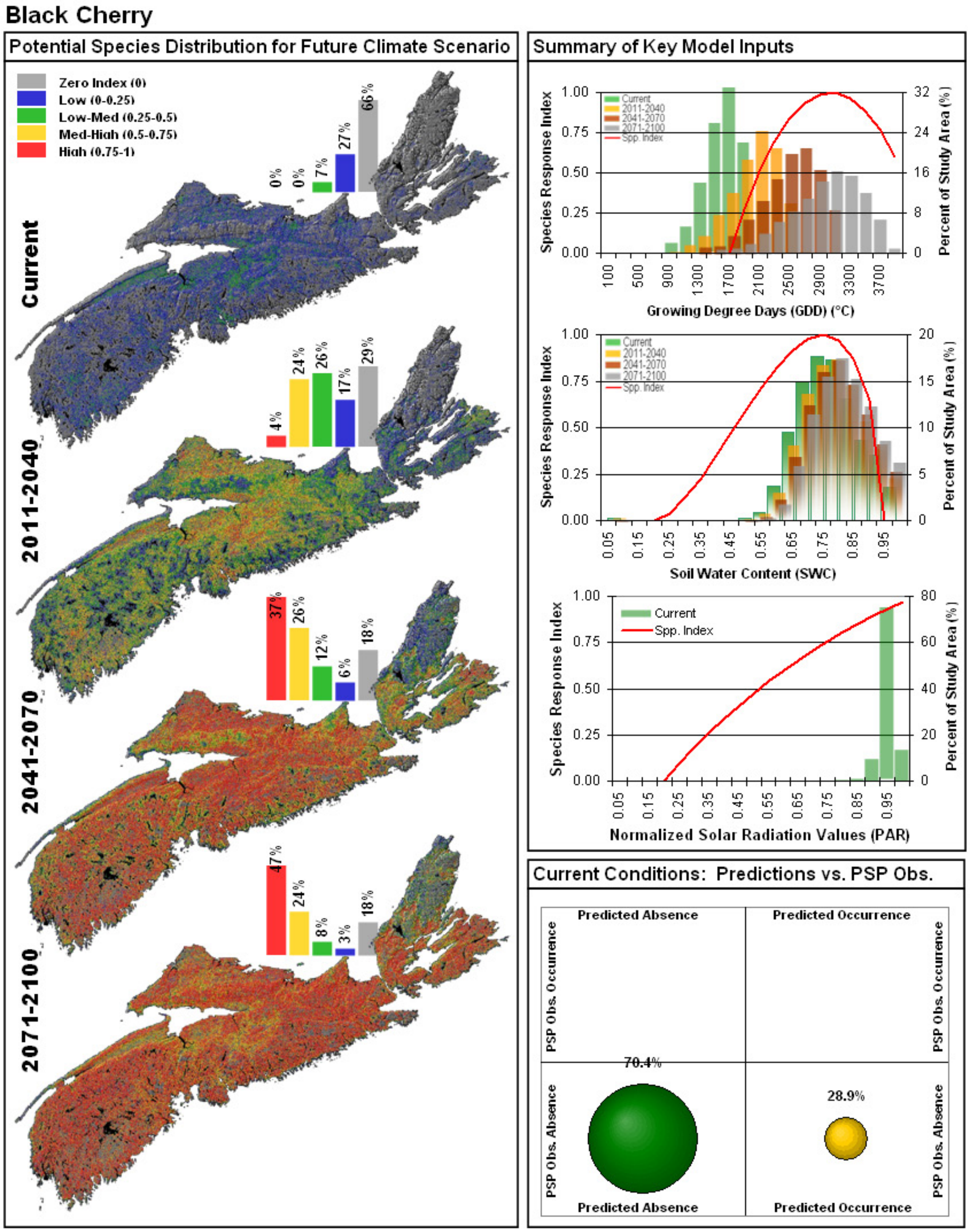

Figure 26. Distribution of black cherry for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

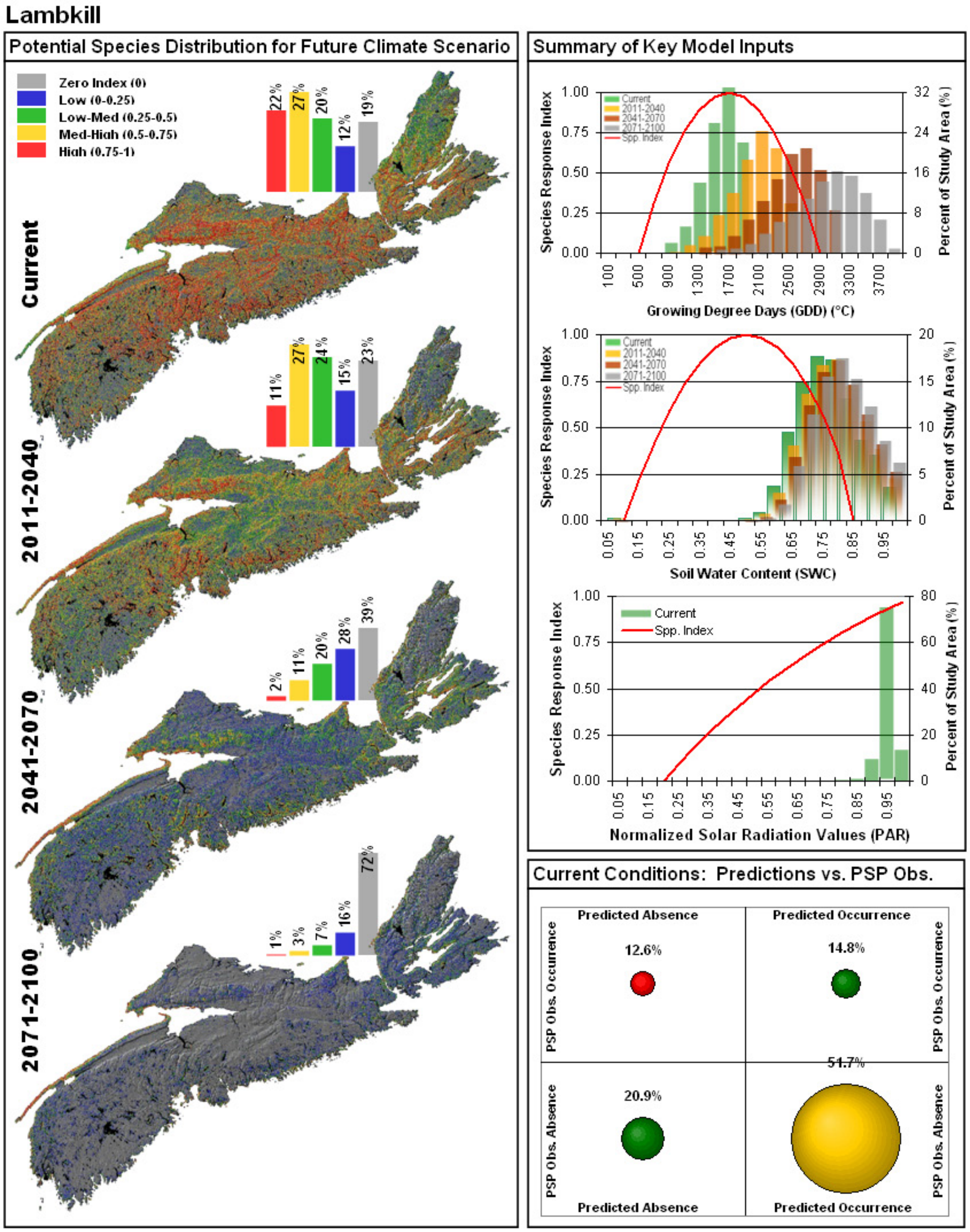

Figure 27. Distribution of lambkill for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

Witch hazel

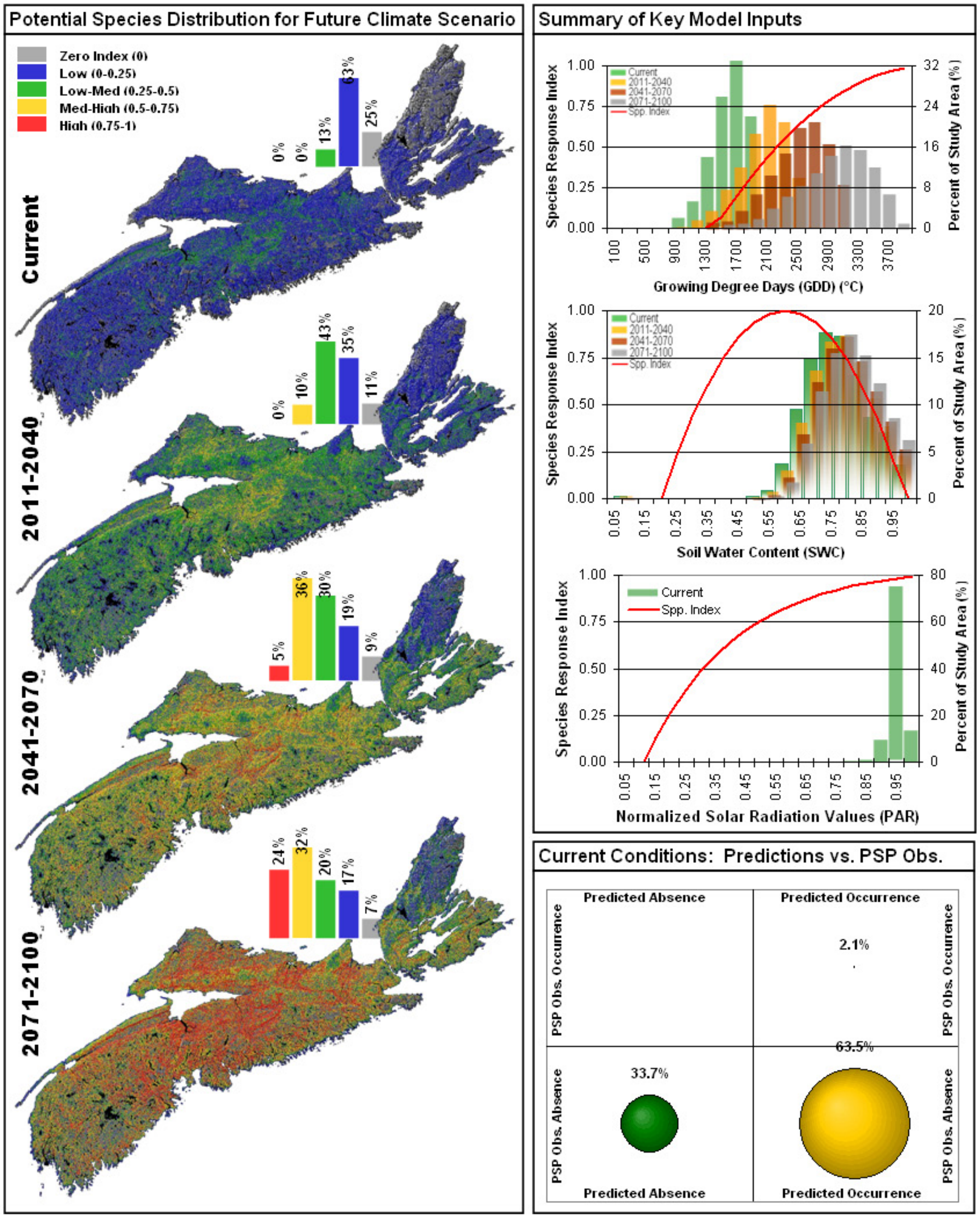

Figure 28. Distribution of witch hazel for current climatic conditions and future conditions for 2011-2040, 2041-2070, and 2071-2100 (maps on the left). Gray colours represent unfavourable conditions and potential absence of species, while red represent the most favourable conditions and probable presence of the species (legend); blue, green and yellow represent intermediate conditions and associated species presence. Black areas represent exposed water. Included are % coverages of species habitat categories for NS. Insets to the right provide comparisons of species response functions with corresponding frequency distributions of GDD, SWC, and PAR as function of % of study area. Inset at the right hand bottom of the Figure compares permanent sample plot (PSP) observations of species presence/absence with modelled occurrence values for current conditions.

Figure 29 provides a comparison of PSD values calculated as a function of (i) the product (Figure 7; and Figure 29a) and (ii) minimum (Figure 29b) of individual species response for balsam fir (bF) and red oak (rO). Both calculation methods give near similar spatial distributions at the regional level; however, some difference exists locally. Multiplication generally downgrades PSD values by at least one suitability class (0.25) when values are near the threshold of a lower class. This downgrading is illustrated in the frequency distributions with an obvious shift towards lower values when multiplication of species response is used.

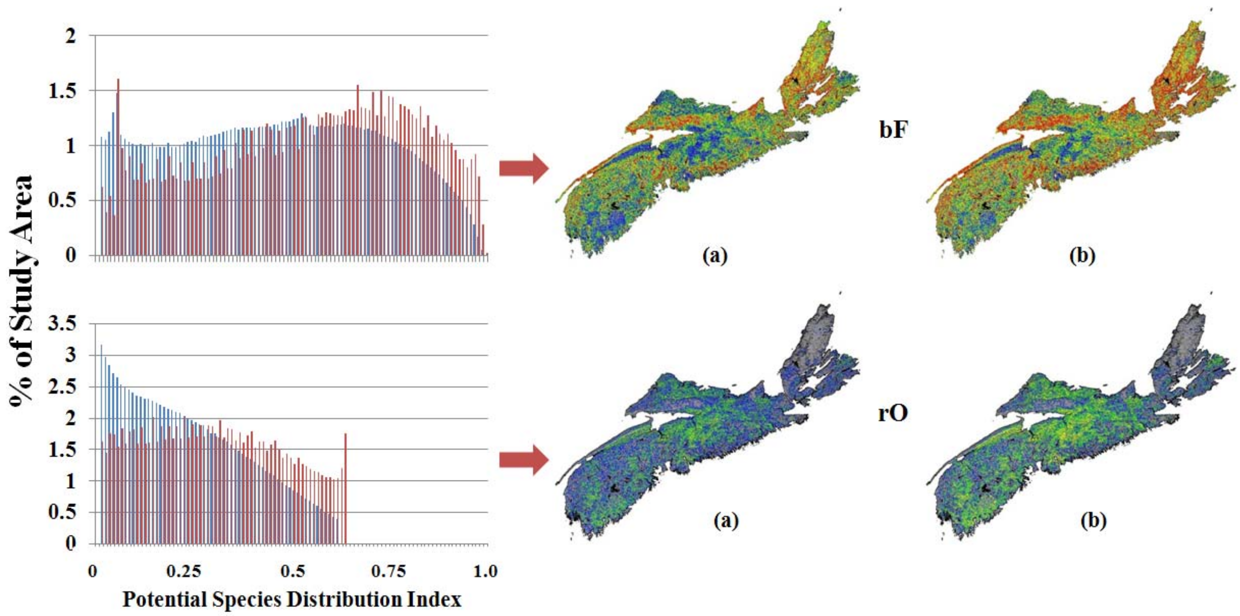

Figure 29. PSD as a function of the product (a; Figure 7) and minimum (b) of individual species response for balsam fir (bF) and red oak (rO). On the left are the frequency distributions of PSD values for both species and calculation methods (PSD on the x-axis are in increments of 0.01). The light blue distribution (left) coincides with the product of response values and the light red distribution, minimum of response values.

4. Concluding Remarks

In this report, we demonstrate a simple protocol for projecting species distribution for the Province of NS by integrating modelled species-specific response to largely modelled biophysical variables of incident solar radiation (and photosynthetically active radiation), soil water content, and growing degree days. Photosynthetically active radiation and soil water content are based on model calculations with the **LanDSET** model and growing degree days, from remote sensing 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 NS are at a significantly reduced 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 PSP and biophysical data from as many sites (PSPs) in the *natural ranges* of target species as is 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) must be dealt within the context of stand development models.

The current report does not examine the impact of non-native tree species south of NS with the potential to move northward with climate change. Their presence in NS can potentially change the dynamics of forest development processes in NS and is an element worth investigating.

5. Acknowledgements

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6. References

Anonymous. Global Forest Watch. http://www.gnb.ca/0079/Forest/trees-e.asp, 2007.

Aussenac, G. Interactions between forest stands and microclimate: Ecophysiological aspects and consequences for silviculture. *Ann. For. Sci.* 2000, Vol. 57, 287-301.

Bourque, C.P-A; Cox, R.M.; Allen, D.J.; Arp, P.A.; Meng, F.-R. Spatial extent of winter thaw events in eastern North America: Historical weather records in relation to yellow birch decline. *Global Change Biol.* 2005, 11(9), 1477-1492.

Bourque, C.P.-A.; Gullison, J.J. A technique to predict hourly potential solar radiation and temperature for a mostly unmonitored area in the Cape Breton Highlands. *Can. J. Soil Sci.* 1998, Vol. 78, 409-420.

Bourque, C.P.-A.; Meng, F-R.; Gullison, J.J.; Bridgland, J. Biophysical and potential vegetation growth surfaces for a small watershed in northern Cape Breton Island, Nova Scotia, Canada. *Can. J. For. Res.* 2000, Vol. 30, 1179-1195.

Burns, R.M.; Honkala, B.H. *Silvics of North America: 1. Conifers*. Agriculture Handbook 654. US Department of Agriculture, Forest Service, Washington, DC. 1990a, Vol. 1, 675 pp.

Burns, R.M.; Honkala, B.H. *Silvics of North America: 2. Hardwoods*. Agriculture Handbook 654. US Department of Agriculture, Forest Service, Washington, DC. 1990b, Vol. 2, 877 pp.

Clapp, R.B.; Hornberger, G.M. Empirical equations for some soil hydraulic properties. Water Resour. Res. 1978, Vol. 14(4), 601-604.

Ecological Stratification Working Group. *A National Ecological Framework for Canada.* Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research and Environment Canada, State of Environment Directorate, Ottawa/Hull, Canada, 1996, 125 pp.

Farrar, J.L. *Trees of Canada*. Fitzhenry and Whiteside Ltd. and Canadian Forest Service, Markham, Ontario, 1995, 502 pp.

Gallant, J. *Complex wetness index calculations, WET documentation version 2.0.* Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia, 1996.

Gustafson, E.J.; Lietz, S.M.; Wright, J.L. Predicting the spatial distribution of aspen growth potential in the upper Great Lakes region. *For. Sci.* 2003, Vol. 49, 499-508.

Hassan, Q.K. Species-specific site quality index based on environmental data generated from remote sensing imagery and a process-based model. *Unpublished PhD Thesis, UNB*, 2008.

Hassan, Q.K.; Bourque, C.P.-A.; Meng, F.-R. Estimation of daytime net ecosystem CO_2 exchange over balsam fir forests in eastern Canada: Combining averaged tower-based flux measurements with remotely sensed MODIS data. *Can. J. Remote Sens.* 2006, Vol. 32, 405-416.

Hassan, Q.K.; Bourque, C.P.-A.; Meng, F.-R.; Richards, W. Spatial mapping of growing degree days: An application of MODIS-based surface temperatures and enhanced vegetation index. *J. Appl. Remote Sens.* 2007a, Vol. 1, 013511, 12p.

Hassan, Q.K.; Bourque, C.P.-A.; Meng, F.-R. Application of Landsat-7 ETM+ and MODIS products in mapping seasonal accumulation of growing degree days at an enhanced resolution. *J. Appl. Remote Sens.* 2007b, Vol. 1, 013539, 10p.

Hassan, Q.K.; Bourque, C.P.-A.; Meng, F.-R.; Cox, R.M. A wetness index using terrain-corrected surface temperature and normalized difference vegetation index: an evaluation of its use in a humid forest-dominated region of eastern Canada. *Sensors*, 2007c, Vol. 7, 2028-2048.

Hinds, H.R. *Flora of New Brunswick, 2nd edition*. Biology Department, University of New Brunswick, Fredericton, New Brunswick, 2000, 694 pp.

Kimmins, J.P. *Forest ecology: a foundation for sustainable management*. Prentice Hall, NJ, 1997, 596 pp.

Ma, M.; Jiang, H.; Liu, S.; Zhu, C.; Liu, Y.; Wang, J. Estimation of forest-ecosystem site index using remote-sensed data. *Acta Ecologica Sinica*. 2006, Vol. 26, 2810-2816.

Monserud, R.A.; Huang, S.; Yang, Y. Predicting lodgepole pine site index from climatic parameters in Alberta. *For. Chron.* 2006, Vol. 82, 562-571.

Moore, I.D.; Norton, T.W.; Williams, J.E. Modelling environmental heterogeneity in forested landscapes. *J. Hydrology.* 1993, Vol. 150, 717–747.

Nova Scotia Museum. *The natural history of Nova Scotia*: *Topics and habitats*. Nimbus, Nova Scotia, 1996; 518 pp.

NS DNR. 2004. Forest Inventory Permanent Sample Plot Field Measurement Methods and Specifications. Forest Inventory Section, Nova Scotia Department of Natural Resources, Truro Nova Scotia. Forest Inventory Report Version 2004-1.2. 66 pp.

Nilsen, E.T.; Orcutt, D.M. *Physiology of plants under stress: abiotic factors*. John Wiley & Sons, Inc., NY, 1996, 689 pp.

Oliver, C.D.; Larson, B.C. *Forest stand dynamics*. John Wiley & Sons, Inc., NY; 1996, 520 pp.

Planchon, O.; Darboux, F. A fast, simple and versatile algorithm to fill the depressions of digital elevation models. *Catena*, 2001, Vol. 46, 159–176.
Priestley, C.H.B.; Taylor, R.J. On the assesment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*. 1972, Vol. 100, 81-92.
Ritchie, G.A. *Trees of Knowledge: A handbook of Maritime trees*. Canadian Forest Service-Atlantic Forestry Centre, 1996, 41 pp.
Smith, D.M.; Larson, B.C.; Kelty, M.J.; Ashton, P.M.S. *The practice of silviculture: applied forest ecology*. John Wiley & Sons, NY, 1997, 537 pp.
Smith, M.J. *An examination of forest succession in the Cape Breton Highlands of Nova Scotia*. Unpublished M.Sc. thesis, University of New Brunswick, Canada, 1998.
Ung, C.-H.; Bernier, P.Y.; Raulier, F.; Fournier, R.A.; Lambert, M.-C.; Regniere, J. Biophysical site indices for shade tolerant and intolerant boreal species. *For. Sci.* 2001, Vol. 47, 83-95.
Urban, D.L. *A user's guide to Zelig version 2.0, with notes on upgrades from version 1.0.* Environmental Sciences Department, University of Virginia-Charlottesville, VA, 1993.
Urban, D.L. *A versatile model to simulate forest pattern: a user's guide to Zelig, version 1.0*. Environmental Sciences Department, University of Virginia-Charlottesville, VA, 1990.
Waring, R.H.; Milner, K.S.; Jolly, W.M.; Philips, L.; Mcwethy, D. Assessment of site index and forest growth capacity across the Pacific and Inland Northwest U.S.A. with a MODIS satellite-derived vegetation index. *For. Ecol. Manage.* 2006, Vol. 228, 285-291.

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

Station Name	UTM X coordinate (m)	UTM Y coordinate (m)	Elevation (m)	Annual Precipitation (mm)
ANNAPOLIS ROYAL	300786.9	4958260	8	1209
AVON	403913.6	4970710	24	1427.8
BADDECK	673906.9	5107619	8	1500.9
BEAR RIVER	290893.4	4938188	8	1377.5
BRIDGEWATER	376567.7	4917470	27	1523
CHARLESVILLE	275288.5	4829361	3	1263.7
CHETICAMP	656865.4	5168312	11	1391.1
CLARENCE	328986	4975977	52	1263.8
COLLEGEVILLE	576847.3	5037115	76	1384.3
DEBERT	467399.2	5029323	38	1169.5
DEMING	564384.5	4981423	15	1541.3
ECUM SECUM	367805.8	4943571	152	1377.2
FARMINGTON	348893.5	4982886	28	1127.3
GREENWOOD A	453745.4	4944237	70	1508
HALIFAX CITADEL	459196.2	4970120	145	1452.2
HALIFAX INT'L A	336796.9	4920197	107	1460.9
HARMONY	689731.4	5137745	13	1639.5
INDIAN BROOK	698949.7	5169555	8	1700.3
INGONISH BEACH	434990.5	5048092	91	1454.5
JACKSON	324904.9	4922358	127	1399.1
KEJIMKUJIK PARK	278492.8	4884851	76	1497.8
KEMPTVILLE	383226.3	4991426	49	1211
KENTVILLE CDA	345343.3	4888499	50	1517.4
LIVERPOOL BIG FALLS	358556.7	4882646	29	1647.6
LIVERPOOL MILTON	732711.8	5087314	46	1598.8
LOUISBOURG	481583.1	4973720	41	1451.2
LOWER MEAGHERS GRANT	515583.8	5055181	29	1232.9
LYONS BROOK	646234.2	5132838	23	1400.6
MARGAREE FORKS	492127.6	4990361	48	1369.9
MIDDLE MUSQUODOBOIT	455937.6	5068279	31	1233
MIDDLEBORO	366788.1	4893586	15	1435.2
MILL VILLAGE	434206.4	4972180	159	1552.6
MOUNT UNIACKE	402803.8	5068883	20	1175.2
NAPPAN CDA	323469.3	4966862	46	1279.9
PARADISE	395646.8	5028252	24	1281.6
PARRSBORO	670367.7	5187213	29	1450.1
PLEASANT BAY GRAND ANSE	434054.5	4957368	165	1529.3
POCKWOCK LAKE	624707.2	5054555	23	1538.5
PORT HASTINGS	613601.1	5093241	27	1298.2

PORT HOOD	449518.1	5075735	5	1052.4
PUGWASH	310904.2	4850493	15	1523.6
ROSEWAY	418463.1	4976064	84	1360.1
SABLE ISLAND	454925.6	4923863	10	1361.2
SALMON HOLE	460341.8	4942341	51	1421.4
SANDY COVE NRC	318749.9	4842865	30	1393.1
SHEARWATER A	353348.4	4947587	167	1468.2
SHELBURNE	428697	4950019	17	1363.8
SPRINGFIELD	581253.3	4998282	14	1517.2
ST MARGARET'S BAY	406924.7	4996592	38	1054
STILLWATER SHERBROOKE	729021.1	5116844	62	1504.9
SUMMERVILLE	479117.1	5023718	40	1202.1
SYDNEY A	260341.3	4863242	9	1367.8
TRURO	500000	5007020	23	1321.9
TUSKET	370067.9	4989829	31	1155.1
UPPER STEWIACKE	459055.1	4947904	68	1476.8
WATERVILLE CAMBRIDGE	265078.8	4920535	11	1295.2
WESTPHAL	391067	4989436	38	1230.8
WEYMOUTH FALLS	407942.2	4976207	38	1308.2
WHITE ROCK	695543.3	5156466	76	1944.6
WINDSOR MARTOCK	252031.5	4856133	43	1274.1
999[1]	**683579.1**	**5174882**	**534**	**1900.0**

[1] An added point value to address annual precipitation rates on the Cape Breton Highland Plateau because of missing data

Appendix B

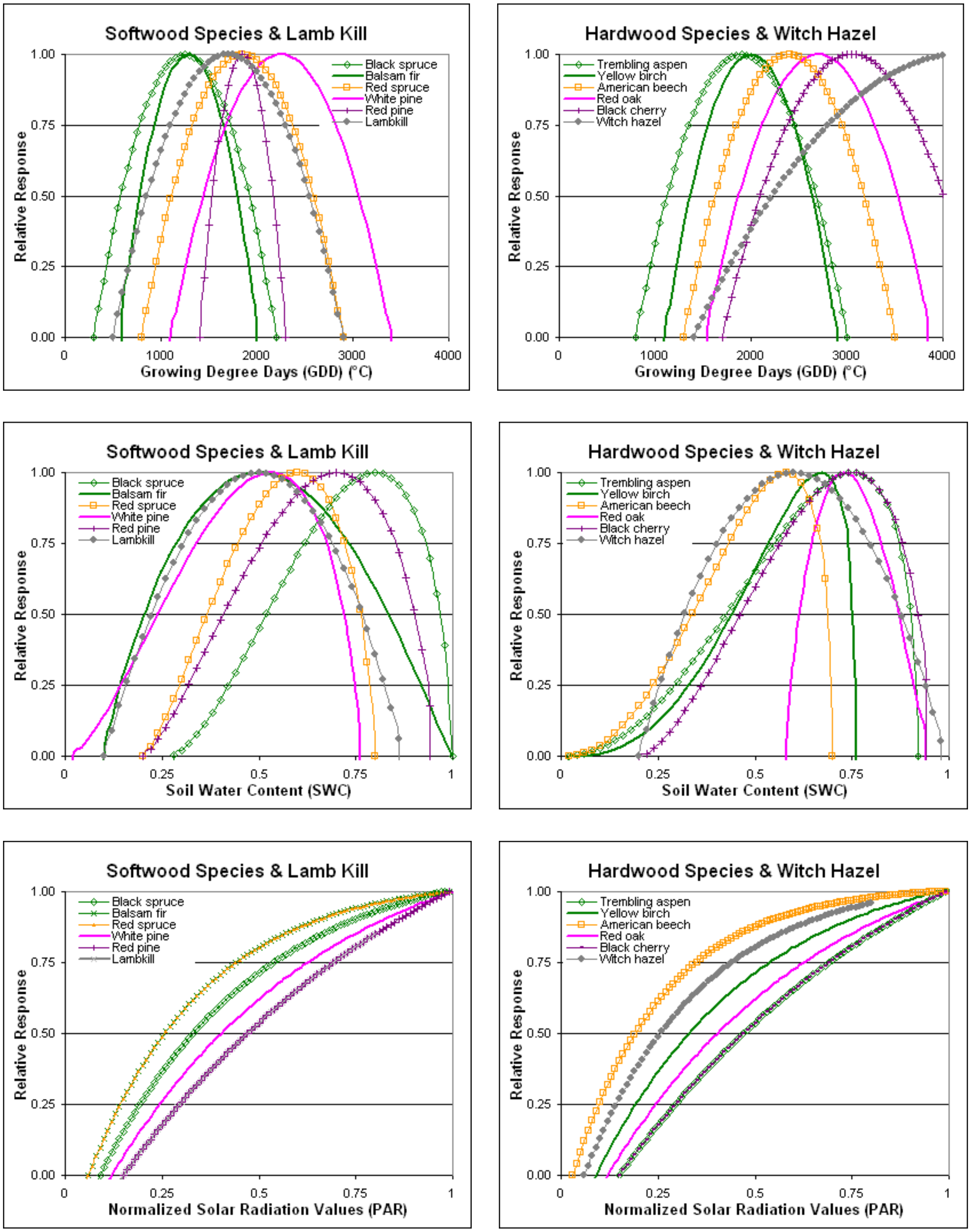

Figure B1. Species-specific environmental response curves as a function of normalized photosynthetically active radiation, growing degree days, and soil water content. Relative response varies from 0-1. Curves are based on eq.'s 2-4 of the main text and parameter values from Table 2.