# Impact of projected land conversion on water balance of boreal soils in western Newfoundland

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## ABSTRACT

Conversion of boreal forest into agricultural land is likely to occur due to the shift of climatic zones and increasing food demand. However, any land conversion will affect the water balance and hence solute fluxes within the soil column and connected ecosystems. Understanding the consequences of land conversion on soil hydrology is essential to support an economically viable agriculture while minimizing its environmental footprint. Hydrological models can simulate these effects based on regionally adjusted climate scenarios. Here, we combined a local climate analysis with hydrological simulations (Hydrus-1D) of boreal soils before and after agricultural conversion. Historical climate analysis showed increasing temperatures and growing degree days while precipitation remains stable. Hydrological simulations revealed lower saturation and higher infiltration rates for unconverted soils, indicating lower runoff and increased infiltration and deep percolation. In contrast, agricultural soils have slower infiltration rates, particularly in the upper horizon. Over the long term, agricultural conversion consequently increases erosion risk and nutrient loss by runoff. This might further progressively limit groundwater recharge, affect hydrological processes and functions and future drought/flood conditions at catchment levels. Hence, conversion of boreal soils demands a primary identification of suitable areas to minimize its impacts.

**Key words** | climate change, Hydrus-1D, land use change, Newfoundland, podzol, soil hydrology

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## INTRODUCTION

The globally averaged temperature shows a warming trend associated with increasing frequency, intensity and amount of precipitation with warming trends more accelerated in boreal regions such as Alaska, Canada and Greenland (IPCC 2013; Osborn *et al.* 2016). It is expected that increasing temperature and irregular precipitation will affect soils by modifying soil moisture, drainage, groundwater recharge, surface runoff, erosion, or nitrogen and carbon kinetics (Diodato *et al.* 2011; IPCC 2013; Mullan 2013). The regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought (IPCC 2013) will consequently affect established agricultural areas. On the other hand, predicted northwards shift in climate warming (Koven *et al.* 2013) and extended growing degree days in the northern hemisphere might offer new prospects for expansion of agricultural areas into formerly unsuitable regions (Stralberg *et al.* 2015). Combined with accelerated food demand due to rapidly increasing world population, it is expected that parts of boreal ecosystems might need to be converted to agricultural use.

Boreal forests accumulate and store huge amounts of organic carbon (Pan *et al.* 2011; Bradshaw & Warkentin 2015) and cover a broad range of unique ecological habitats (Rae *et al.* 2014; Stralberg *et al.* 2015), which are highly sensitive to climate change (Nelner & Hood 2011; Frank *et al.* 2015). In addition, the dominant soil type in boreal areas

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likely to be converted to agriculture is podzol, prone to carbon and mineral loss by leaching particularly after clear-cutting (Lindroos *et al.* 2011; Augustin *et al.* 2015). Due to low fertility and unfavourable physical properties, podzols are generally unattractive for arable cropping (FAO 2017). Nevertheless, there are conversion plans for substantial areas of boreal forests into croplands, e.g. in Newfoundland, Canada (Government of Newfoundland and Labrador 2017). Land conversion from boreal forest to agricultural use requires clear cutting and is therefore expected to impact the above-ground carbon stocks and consequently the ecosystem (Grünzweig *et al.* 2015). Land conversion will also affect the hydrological water balance and thus the carbon and nutrient fluxes from the soil column to field scale and to connected ecosystems. Given that the plant cover on podzols influences water flow and solute transport and redistribution in a soil profile (Nikodem *et al.* 2010), it is expected that boreal agricultural activities will influence leaching processes to groundwater, lakes and river systems (Bayley *et al.* 2013; Marttila *et al.* 2013). Moreover, the expected change of regional climate as linked to global climate change (IPCC 2013) will additionally affect the hydrological status of boreal soils through altered rainfall and snow melting kinetics, and their nutrient availability (Sanborn *et al.* 2011; D'Orangeville *et al.* 2014; Augustin *et al.* 2015). For example, the translocation of soluble organic materials into the mineral layer is most pronounced during snowmelt, comprising up to 50% of the annual flux of water at 100 cm depth (Redding & Devito 2011; Schaetzl *et al.* 2015). The projected increasing temperatures will further lead to higher evapotranspiration rates in summer and lower groundwater levels (Okkonen *et al.* 2010; Ge *et al.* 2013).

Hydrological models can help to assess and understand the effects of land use change under changing climate conditions (Hormann *et al.* 2005; Wang *et al.* 2008; Alaoui *et al.* 2014). Since local weather patterns become more variable, reliable hydrological simulations demand climate scenarios with the highest possible spatial resolution. Though future climate simulation from several general circulation models (GCMs) and regional climate models (RCMs) are available for the entire globe, commonly these predictions lack sufficient spatial resolution for boreal areas (e.g. Finnis 2013). A potential approach to predict climate conditions at a higher spatial resolution is possible through the analysis of regional historical climate records (Yapo *et al.* 1996; Aronica *et al.* 2005; Jaiswal & van Westen 2009). Hence, analysis of regional climatic variability and prediction for future likelihood using historical data is a precondition to assess their effects on different land uses and land conversions. Particularly, the effects of rainfall on different regional soils are highly relevant for a critical comparison of the hydrological balances before and after land conversion and needs to be investigated. In this study, we analysed historical regional climate data to identify past climatic patterns and likely future climate scenarios. Based on the climate analysis, we performed hydrological modelling within the vadose zone to evaluate the effects of land conversion on the water balance using natural state soil (before) and agricultural converted soil (after). To compare the differences between the two soil conditions, saturation values and the rates of changes in saturation (saturation increasing rates, $\theta_{si}$) were used.

## MATERIAL AND METHODS

### Climatic data analysis

For the regional climatic data analysis, historical records from two nearby weather stations were used, Corner Brook (48°56′00 N, 57°55′00 W) and Deer Lake (49°12′33 N, 57°23′40 W). Both stations are located in western Newfoundland (Humber Valley watershed) in Canada. This region encompasses established agricultural lands, recently converted areas, and areas planned for future agriculture expansion, therefore providing an excellent example for land use conversion of boreal soils. We employed 12 available climatic parameters using the following established definitions (Perry & Hollis 2005):

- MAX (maximal temperature in °C)
- MIN (minimal temperature in °C)
- MEAN (average temperature in °C)
- FFD (frost free days, the yearly period between the last and the first frost day)
- $GDD_5$ (growing degree days = FFD daily MEAN −5 for MEAN >5 °C)
- $GDD_{10}$ (growing degree days = FFD daily MEAN −10 for MEAN >10 °C)

- CDD (consecutive dry days = maximum number of consecutive days with rainfall <0.2 mm)
- CWD (consecutive wet days = maximum number of consecutive days with rainfall >0.2 mm)
- RAIN (rainfall amount in mm)
- Rain days (total days with a rain amount ≥1 mm)
- Rain Intensity (Rainfall intensity = Total rainfall on rain days ≥1 mm/Number of rain days ≥1 mm)
- SNOW (snow amount in mm)

We used 1961–1990 as the reference period, which is the widely accepted baseline (Gao *et al.* 2011; Huang *et al.* 2016; Liu *et al.* 2016), and 1990–2014 as the recent period, to assess the recent climate conditions. Time series analyses as well as 10-year moving averages were performed for all climatic parameters. For assessment of temporal variation of a climatic variable, the slope (rate) and its probability (*p*-values) were calculated by linear regression (Liu & Chen 2000; IPCC 2013). A monthly analysis for MIN, MAX, MEAN and RAIN were further performed for the recent period. To link the study to agricultural activities, the wettest and the driest growing season (May to October; e.g. Sinclair *et al.* 2009) was further defined based on the total rainfall amount. The resolution of available GCMs and RCMs for this region was not sufficient for the intended regional analysis (Finnis 2013). Therefore, the rain events from the observed wettest and driest growing seasons were used as potential future wet and dry scenarios, assuming historical rainfall to represent likely future rainfall (Aronica *et al.* 2005; Lehmann *et al.* 2013). GDD values are recognized as a link between climate and plant physiology. To adjust the GDDs to boreal agricultural activities, the growing degree days of above the thresholds of 5 °C ($GDD_5$) and 10 °C ($GDD_{10}$) were considered, suitable for crop growing in the northern hemisphere (Bennie *et al.* 2010; Brosnan *et al.* 2011). Raw data for temperature, rainfall and snowfall

**Table 1** | Soil properties: field capacity (FC), saturation (θs), $\alpha$ and $n$ of the soil water retention function, and saturated hydraulic conductivity (Ks), (a) for the reference soils from the literature and (b) for the soil samples from ground truthing

| | Soil layer | Depth [cm] | SOM [%] | FC [ − ] | θs [ − ] | Alpha [1/m] | n [–] | $K_s$ [m/day] |
|---|---|---|---|---|---|---|---|---|
| (a) | | | | | | | | |
| Agricultural | 1 Loamy | 0–16 | n.a. | 0.334 | 0.611 | 3.6 | 1.56 | 0.250 |
| | 2 Sandy loam | 17–26 | n.a. | 0.198 | 0.485 | 7.5 | 1.89 | 1.061 |
| | 3 Clay loam | 27–36 | n.a. | 0.365 | 0.514 | 7.5 | 1.89 | 1.061 |
| | 4 Silt loam I | 37–49 | n.a. | 0.348 | 0.567 | 2.0 | 1.41 | 0.108 |
| | 5 Silt loam II | 50–59 | n.a. | 0.316 | 0.467 | 2.0 | 1.41 | 0.108 |
| | 6 Sandy loam | 60–100 | n.a. | 0.189 | 0.469 | 7.5 | 1.89 | 1.061 |
| Boreal | 1 Sandy loam | 0–46 | n.a. | 0.179 | 0.410 | 7.5 | 1.89 | 1.061 |
| | 2 Loamy sand | 47–100 | n.a. | 0.121 | 0.410 | 12.4 | 2.28 | 3.502 |
| (b) | | | | | | | | |
| Outside 4 | 1 Clay loam | 0–12 | 9.8 | 0.368 | 0.554 | 1.9 | 1.31 | 0.062 |
| | 2 Clay loam | 21–27 | 2.8 | 0.365 | 0.496 | 1.9 | 1.31 | 0.062 |
| | 3 Clay loam | 27–36 | 3.8 | 0.372 | 0.507 | 1.9 | 1.31 | 0.062 |
| | 4 Silt loam | 36–54 | 4.5 | 0.339 | 0.533 | 2.0 | 1.41 | 0.108 |
| Inside 2 | 1 Clay loam | 0–14 | 4.8 | 0.298 | 0.416 | 1.9 | 1.31 | 0.062 |
| | 2 Clay loam | 14–29 | 3.7 | 0.334 | 0.506 | 1.9 | 1.31 | 0.062 |
| | 3 Clay loam | 29–49 | 2.0 | 0.368 | 0.497 | 1.9 | 1.31 | 0.062 |
| | 4 Clay loam | 49–129 | 0.9 | 0.316 | 0.435 | 1.9 | 1.31 | 0.062 |
| Inside 3.5 | 1 Loam | 0–17 | 2.0 | 0.305 | 0.456 | 3.6 | 1.56 | 0.250 |
| | 2 Clay loam | 17–38 | 4.8 | 0.355 | 0.517 | 1.9 | 1.31 | 0.062 |
| | 3 Loam | 38–55 | 2.3 | 0.320 | 0.464 | 3.6 | 1.56 | 0.250 |
| | 4 Loam | 55–125 | 1.0 | 0.263 | 0.420 | 3.6 | 1.56 | 0.250 |
| Inside 5 | 1 Clay loam | 0–20 | 2.7 | 0.327 | 0.474 | 1.9 | 1.31 | 0.062 |
| | 2 Clay loam | 20–28 | 2.4 | 0.325 | 0.467 | 1.9 | 1.31 | 0.062 |
| | 3 Loam | 28–98 | 7.4 | 0.328 | 0.565 | 3.6 | 1.56 | 0.250 |

amount were obtained from Environment Canada, Government of Canada (http://climate.weather.gc.ca).

## Hydrological modelling

One of the main changes incurred during the conversion of a forest soil, i.e. a podzol, is the change in the horizonation with the intrinsic changes in the physical and chemical parameters of the respective soil (Karavayeva *et al.* 1991). An undisturbed soil tends to have an eluviated horizon close to the surface (E horizon) commonly overlain only by SOM in various states of degradation. A converted podzol with a history of intensive tillage, cropping and the addition of crop organic residues and organic fertilizers, will develop a tilled Ap horizon (continuously plowed and mixed top layer in agricultural soils) above a diminished E horizon. We used soil information from samples collected from fields and from reference soil mapping. Soil samples were taken in Cormack, western Newfoundland (49°21′30″ N, 58°22′60″ W) from an intensively cultivated agricultural field, converted more than 60 years ago. Four sample locations were selected, representing areas inside and outside a cultivated area, to investigate the differences between agricultural soil and reference soil in its natural state. The samples were taken at 4.0 m outside (*outside 4*), 2.0 m inside (*inside 2*), 3.5 m inside (*inside 3.5*) and 5.0 m inside (*inside 5*) of the cultivated area. At each location, a pit approximately 1.5 m deep was excavated with a backhoe and soil samples were collected at distinct horizons along the vertical soil profile. Soil texture was analysed using the hydrometer method (Bouyoucos 1962) and the soil organic matter (SOM) content was determined by ignition of oven

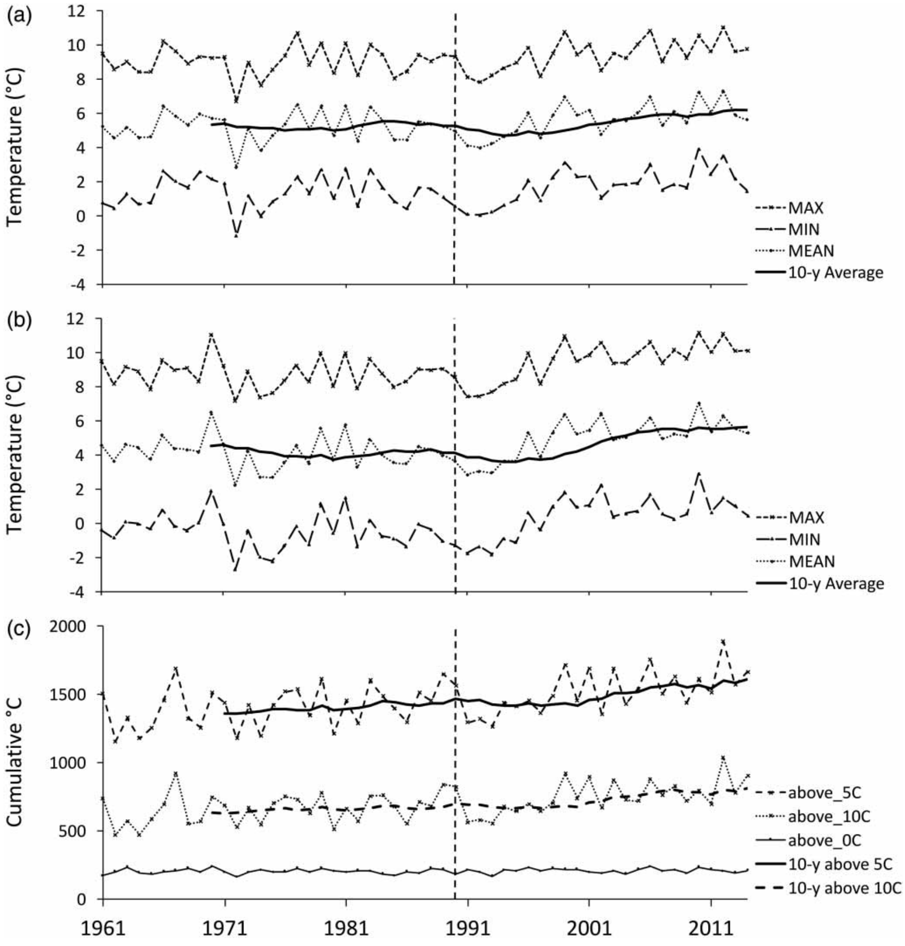


**Figure 1** | Annual average temperature variation at (a) Corner Brook and (b) Deer Lake; (c) the variation of annual growing degree days (GDD) above 5 and 10°C (Corner Brook).

dried samples in a muffle oven at 375 °C for >17 h (e.g. Wang et al. 2012).

The reference soil information for western Newfoundland (Table 1(a)) was obtained from the available literature (Canada Department of Agriculture 1979; Agriculture and Agrifoods Canada 1983). As for the established agricultural reference soil, data for a stony loam at Cape Anguille/Grebs Pond in western Newfoundland (Cape Anguille, 47°54′02″ N 59°24′47″ W) were also taken from the literature; this soil is commonly used for potatoes or other root vegetable production (Canada Department of Agriculture 1979). Further, a Gleyed Humo-Ferric podzol from Cormack/Deadwater Brook (Cormack, 49°23′30″ N 57°23′46″ W) was selected as representing a natural boreal forest soil. The main tree cover at this location is balsam fir, with a minor amount of white birch, and the ground cover consists of feather and plume mosses (Agriculture and Agrifoods Canada 1983). Hydrological water balances for the selected soil columns (1 m depth) were simulated using Hydrus-1D (Šimůnek & Nimmo 2005; Šimůnek et al. 2012, 2016). Hydrus-1D can be employed to simulate the complex vadose-zone hydrological processes (Jacques et al. 2008; Rezaei et al. 2016) and has already been successfully applied for podzol (Nikodem et al. 2010; Schneider et al. 2013). Soil hydrological parameters, field capacity (FC) and saturated soil water content ($\theta_s$) of all soil units were derived from the soil water characteristics program of the SPAW (Soil-Plant-Air-Water) model (Saxton & Willey 2004, 2006) using measured soil texture and organic matter (OM) values. Parameters $\alpha$ and $n$ for soil water retention function and saturated hydraulic conductivity ($K_s$) were taken from Hydrus-1D. Since the simulation was started in May (soon after the snow melt), we assumed that the soils were at FC (Table 1). Hydrus-1D simulations were based on the Van Genuchten-Mualem model with 1.0 cm soil column discretization, free drainage at the lower boundary, and identical initial pressure heads. Each simulation was run for 6 months within the growing season (May to October) with variable upper boundary conditions using real historical climate data as provided by Environment Canada (http://climate.weather.gc.ca). Potential evapotranspiration (PET) was estimated with the Thornthwaite equation (Thornthwaite 1948) using corresponding temperatures and day lengths data for Corner Brook (http://www.timeanddate.com). Given that actual precipitation values are difficult to predict (IPCC 2013; Osborn et al. 2016), we selected the year with the wettest and the driest growing season of the recent period, anticipating examples of wet and dry weather conditions of the future.

To compare the response of the different soil types, the simulated saturation increasing rates ($\theta_{si}$) and the actual saturation ($\theta_s$) were displayed for each centimetre of the soil column and each time step using Surfer 8 (Golden Software, USA). The $\theta_{si}$ values were derived by:

$$\theta_{si} = \frac{\theta_s - (\theta_t - \mathrm{FC})}{\theta_s} * 100 \tag{1}$$

where ($\theta_t$) is the soil water content at each time step (day).

For further analysis, the mean values of several depth integrals were plotted and compared over time. We employed depth integrals of 0–20 cm, 20–50 cm and 50–100 cm to represent the first (A horizon), the second, and the third (bottom) horizon, respectively.

## RESULTS AND DISCUSSION

### Climate results

The variation of annual temperatures is presented in Figure 1(a) and 1(b), and corresponding statistics are displayed in Table 2. The reference period shows relatively stable rates (−0.02° to 0.01°C year$^{-1}$) for all temperatures at both weather stations. None of the temperature trends analysed (i.e. MAX, MIN and MEAN) for the reference period was statistically significant. In contrast, for the recent period, all annual temperatures showed highly significant positive rates (0.07° to 0.11°C year$^{-1}$). The rates for MEAN reached 0.11°C a$^{-1}$ for Corner Brook and 0.08°C a$^{-1}$ for Deer Lake. However, this significant warming process after 1990 was not consistent among seasons. Figure 2(a) and 2(b) display the monthly increasing rates for the recent period and reveals certain differences in the rate of temperature change; corresponding statistics are given in Table 3. Significant positive increasing rates were achieved for almost every month and considered temperature, with the exception of

**Table 2** | Rates for the annual mean climatic parameters: temperature (°C) and precipitation (mm) variation for the reference (1961–1990) and recent period (1990–2014), (a) Corner Brook, (b) Deer Lake, (c) numbers of frost free days (FFD), number of growing degree days (GDD), number of consecutive dry days (CDD) and consecutive wet days (CWD), (d) rainfall values for Corner Brook

| | 1961–1990 rate | 1990–2014 rate |
|---|---|---|
| (a) | | |
| MAX | 0.01 | 0.11*** |
| MIN | −0.02 | 0.11*** |
| MEAN | −0.01 | 0.11*** |
| (b) | | |
| MAX | 0.01 | 0.07** |
| MIN | 0 | 0.09*** |
| MEAN | −0.01 | 0.08*** |
| (c) | | |
| FFD | 0.04 | 0.47 |
| $GDD_5$ | 6.2 | 11.7 |
| $GDD_{10}$ | 4.3 | 8.94** |
| CDD | 0 | 0.02 |
| CWD | 0.20* | 0.02 |
| (d) | | |
| RAIN | 8.68** | −1.78 |
| Rain days | 0.62 | −0.29 |
| Rain intensity | 0.03 | 0.01 |
| SNOW | −0.56 | −0.85 |

Probability values ($p$) are indicated by <0.05*, <0.005**, <0.001***.

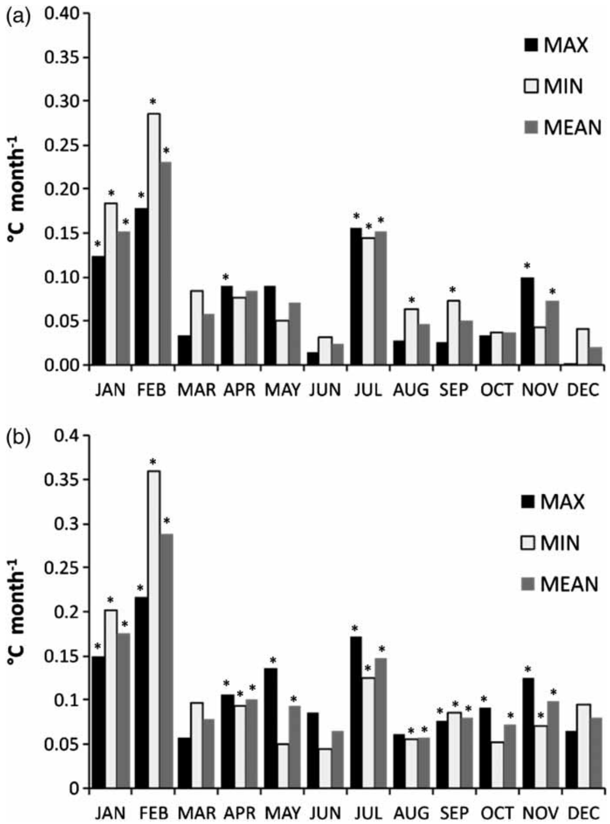


**Figure 2** | Monthly rate of temperature change for the recent period (1990–2014): (a) temperature Corner Brook, (b) temperature Deer Lake (significant values are indicated by *).

March, June and December. The winter temperatures increased particularly fast (January, February), with the highest increase in MIN rates of the entire year (0.29°C $month^{-1}$ $year^{-1}$ for Corner Brook and 0.36°C $month^{-1}$ $year^{-1}$ for Deer Lake) reached in February ($p < 0.001$). These observations, for MIN temperature in particular, matched national and international observations (Jeong et al. 2013; Wang et al. 2013; Kukal & Irmak 2016). The second increase in the temperature rates reached a highly significant peak in July with 0.17°C $month^{-1}$ $year^{-1}$ and 0.15°C $month^{-1}$ $year^{-1}$, respectively, for Corner Brook ($p = 0.006$) and Deer Lake ($p = 0.002$) likewise in accordance with international observed summer trends (IPCC 2013). Spring and fall rates were less prominent, but still positive and mostly significant.

The general warming trend also affected the GDD values (Figure 1(a) and Table 2(c)). An increasing trend was discernible for both periods with higher values and slopes for $GDD_{10}$. These increasing rates were steeper in the recent period, because of particularly low years in the early 1990s followed by high values after 1997. While none of the GDD rates in the reference period was significant, the rates of change in $GDD_{10}$ in the recent period were twice as high as in the reference period (9 $year^{-1}$ versus 4.3 $year^{-1}$, $p = 0.003$). In contrast, the variation of the FFD remained insignificant in both periods, indicating that the increase in GDD resulted from an increase in daily temperatures within the season rather than an extended duration of the growing season.

The annual rainfall variation is displayed in Figure 3(a), and corresponding statistics in Table 2(d). The amount of RAIN increased significantly within the reference period ($p = 0.004$) owing to a shift in the late 1970s, particularly noticeable in the 10-year moving average. No significant

**Table 3** | Rates of change in temperature (°C month$^{-1}$) and precipitation (mm month$^{-1}$) and corresponding probability value (*p*-value) for the recent period (1990–2014), (a) Corner Brook, (b) Deer Lake

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) | | | | | | | | | | | | |
| MAX | 0.12* | 0.18* | 0.03 | 0.09* | 0.09 | 0.01 | 0.15*** | 0.03 | 0.02 | 0.03 | 0.10* | 0.00 |
| MIN | 0.18** | 0.29*** | 0.08 | 0.08 | 0.05 | 0.03 | 0.14*** | 0.06* | 0.07* | 0.04 | 0.04 | 0.04 |
| MEAN | 0.15** | 0.23** | 0.06 | 0.08 | 0.07 | 0.02 | 0.15*** | 0.05 | 0.05 | 0.04 | 0.07* | 0.02 |
| RAIN | 0.06 | −0.68 | −0.51 | 0.36 | −0.82 | −0.19 | −0.79 | 0.62 | 1.37 | −0.54 | 0.72 | −0.48 |
| SNOW | 0.33 | 0.79 | −0.40 | −0.58 | −0.36 | −0.01 | | | | −0.11 | −0.03 | −0.64 |
| (b) | | | | | | | | | | | | |
| MAX | 0.15* | 0.22* | 0.06 | 0.11* | 0.14* | 0.09 | 0.17*** | 0.06 | 0.08* | 0.09* | 0.13*** | 0.06 |
| MIN | 0.20*** | 0.36*** | 0.10 | 0.09* | 0.05 | 0.04 | 0.12*** | 0.06* | 0.09* | 0.05 | 0.07* | 0.10 |
| MEAN | 0.18*** | 0.29*** | 0.08 | 0.10* | 0.09* | 0.07 | 0.15*** | 0.06* | 0.08* | 0.07* | 0.10** | 0.08 |

Probability values (*p*) are indicated by <0.05*, <0.005**, <0009***.

variation of RAIN was observed in the recent period, indicating a constant, relatively high amount (RAIN average = 884 mm year$^{-1}$). The driest growing season was in 1992 (445 mm) while 2009 was the wettest (673 mm) (not displayed). The SNOW variation revealed a decrease, parallel to the increasing rainfall, starting in the late 1970s, likely as a result of warmer surface temperatures. These results agree with global observations, indicating winter-time

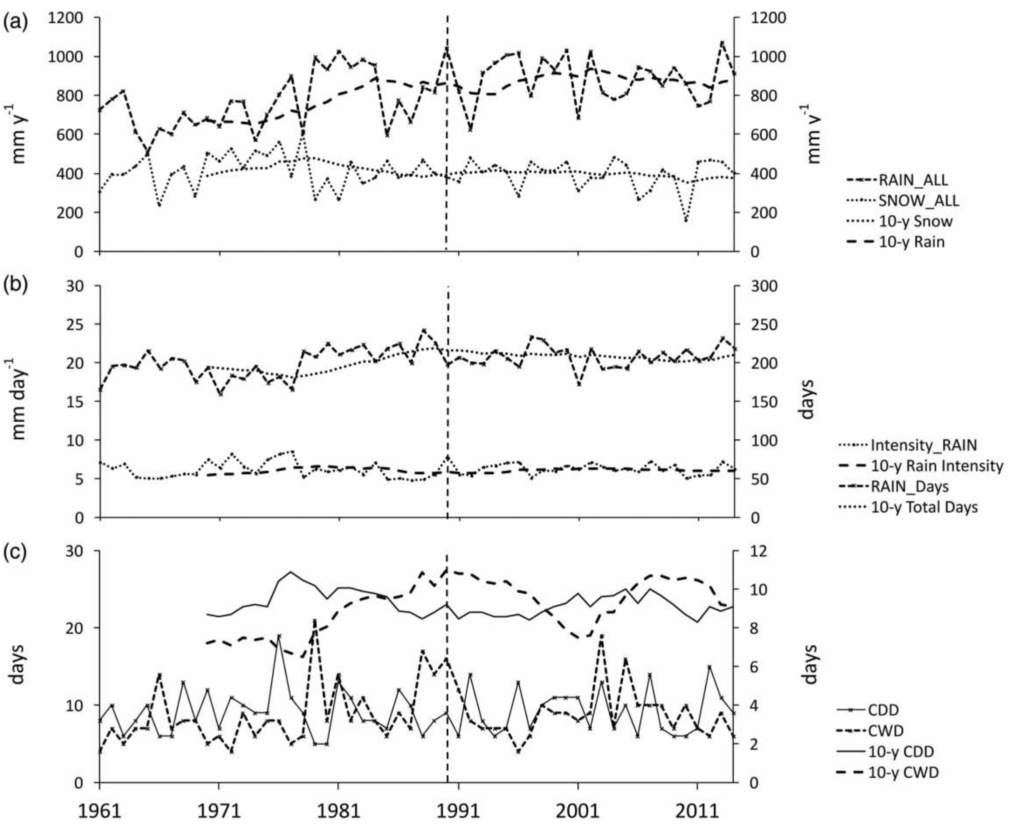


**Figure 3** | (a) Annual rainfall and snow amounts, (b) number of annual rain days and rainfall intensity, (c) variation of annual consecutive wet (CWD) and consecutive dry days (CDD).

precipitation in North America shifting to rainfall rather than snow (IPCC 2013). The increasing of RAIN in the late 1970s is also reflected by a shift in rain days, from 166 days in 1977 to 215 in 1978 (Figure 3(b)). The rainfall intensity curve remained relatively stable after the corresponding drop from 8.5 in 1977 to 5.2 mm day$^{-1}$ in 1978. Figure 3(c)) displays the annual wet and dry periods using CWD and CDD. The CWD increased significantly in the reference period, while no significant variation occurred in the recent period (Table 2(c)) where the 10-year average remained basically >8 days. Similar to the CWD in the recent period, the number of CDD remain stable over both periods with insignificant variation and values around 9 days (Table 2(c)).

## Hydrus-1D results

The historical rainfall and PET of the wettest and driest growing seasons are shown in Figure 4 (upper row). Rainfall frequency and intensity as well as PET in 1992 (dry year) was lower than in 2009 (wet year). Daily rainfall remained mainly under 20 mm during 1992, and only two events of >40 mm were measured in 2009 (Figure 4). Figure 4(a) and 4(b) show the $\theta_s$ values of the agricultural and boreal forest soils, respectively; each horizontal colour bar consists of 282 single columns representing the state of the soil (0–100 cm) for one simulation day. Forest soil has lower actual saturation over the whole soil column, faster response to rainfall events with higher infiltration rates, even to small amounts and thus low runoff, high percolation rates within the whole soil column and hence higher deep drainage. The water balance showed that a rainfall amount of nearly 20 mm day$^{-1}$ is needed to contribute to runoff in forest soil. High percolation rates within the forest soil resulted in low antecedent soil water contents during the dry periods. In comparison, the B horizon of agricultural soil keeps the water longer after rainfall events than the B horizon of forest soil (e.g. September 1992 in Figure 4(a)). While the B horizon of the agricultural soil reached saturation after

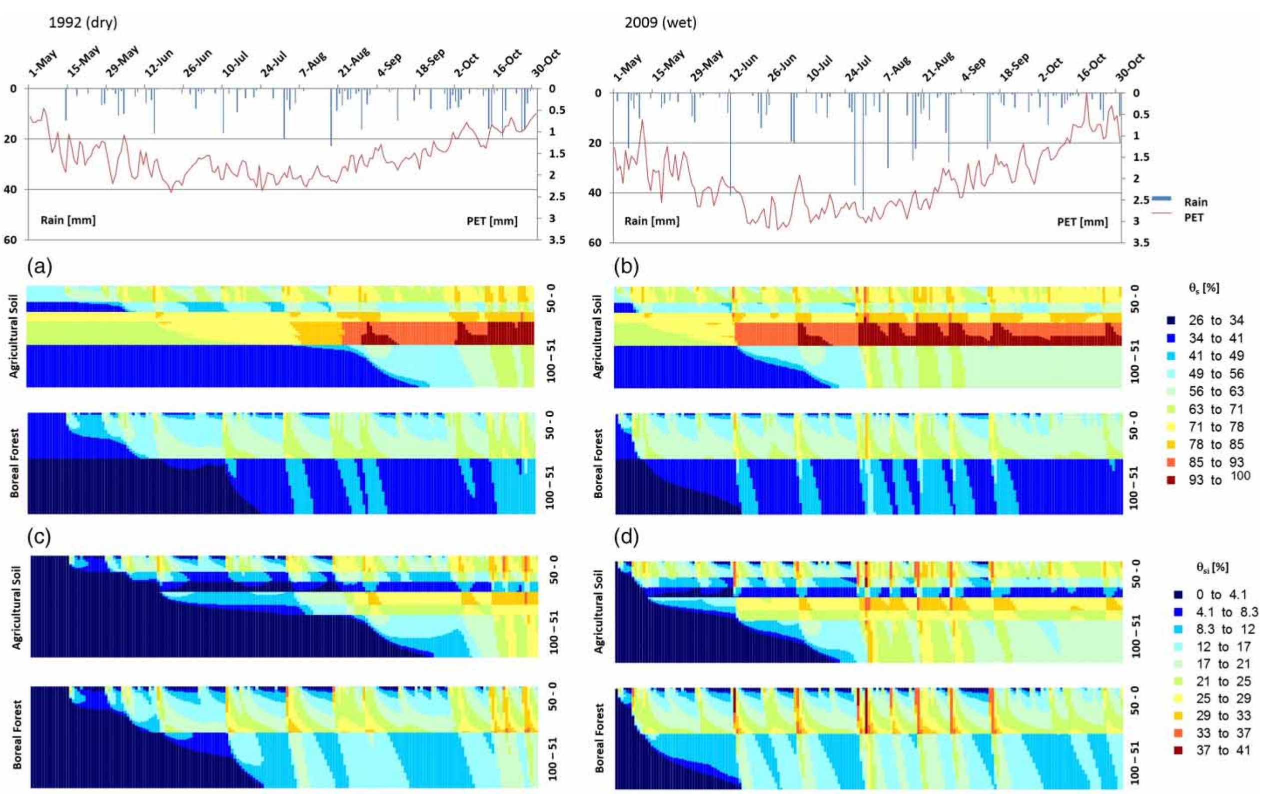


**Figure 4** | Rainfall amount and potential evapotranspiration (PET) of historical rainfall events (upper row) and hydrological water balance for different soils (a) to (d). Each horizontal colour bar consist of 282 single columns representing the state of the soil (0–100 cm) at one simulation day, (a) and (b) show the actual saturation ($\theta_S$), (c) and (d) display the saturation increasing rates ($\theta_{si}$).

several days of continuous rainfall (e.g. after July 24, 2009), the forest soil never reached full saturation. These phenomena can be explained by higher initial saturation of agricultural soil, and low water holding capacity of the second layer, i.e. Ae horizon (17–26 cm; FC = 0.198 in Table 1), while the forest soil has a more uniformly distributed water content over the entire profile and allows for water to drain more rapidly into the B horizon. The differences in response to rainfall events can be highlighted in the display of the $\theta_{si}$ rates (Figure 4(c) and 4(d)). Forest soil has generally higher $\theta_{si}$ (e.g. faster wetting of the bottom of B-horizon) due to the high infiltration and percolation rates while the bottom of the agricultural soil has delayed responses with low $\theta_{si}$ values, which is due to higher water retention ability of the clay loam layer (27–36 cm; FC = 0.365 in Table 1). The highest $\theta_{si}$ values in the upper forest soil were reached during wet conditions; as a direct answer to stronger rainfall events the $\theta_{si}$ values temporarily reached up to 37–41% (after July 24, 2009), but subsequently drained water quickly into the B horizon. In comparison, the $\theta_{si}$ values of the upper agricultural soil in wet periods were lower, but due to slower percolation rates in the deeper horizon the $\theta_{si}$ values remained high for a longer period.

A comparison of the hydrological water balance for models replicating two sample locations in Cormack, *outside 4* and *inside 3.5,* representing the soil conditions in converted and reference soil are shown in Figure 5. The upper horizon (0–20 cm) of *outside 4* reacts faster to rainfall events due to natural soil conditions at the surface, high infiltration and low runoff rates analogous to the forest soil in Figure 4. The saturation increasing rates remain high for a longer period at *outside 4* in comparison to the *inside 3.5* location, which is common for all inside locations (Figure 6). In the middle horizon (21–50 cm), the response reaction reversed (higher saturation rates inside the field) if the soil remains between low to medium wet. For both test years in late August greater rainfall conditions led to higher saturation increasing rates for the outside locations (compare cm resolution in Figure 5). The reversal of the response lines due to rainfall events is particularly obvious in the lower horizon (51–100 cm) where the lines crossed at early September in 1992 and early June in 2009 (compare

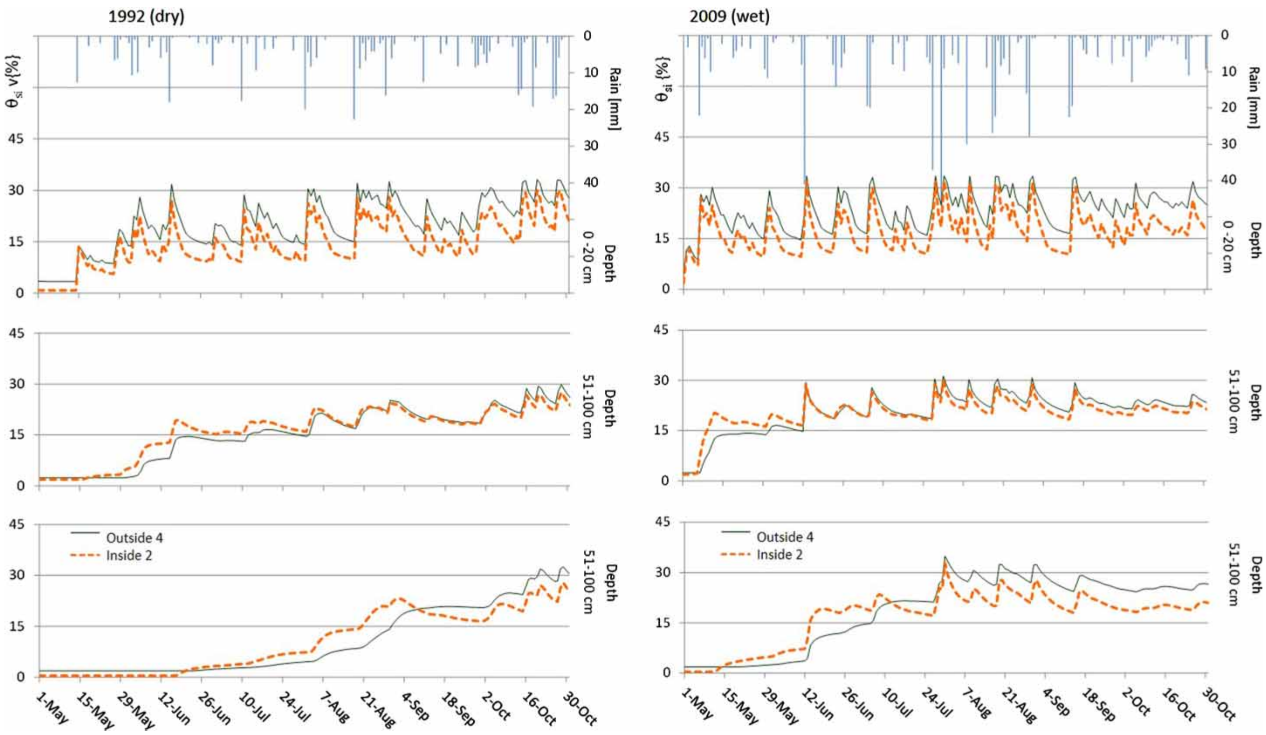


**Figure 5** | Hydrological water balance to historical rainfall events (top) separated into different depth horizons. Lines display the saturation increasing rates ($\theta_{si}$) of the different sample locations: solid line 4 m outside, dashed line 3.5 m inside the agricultural field.

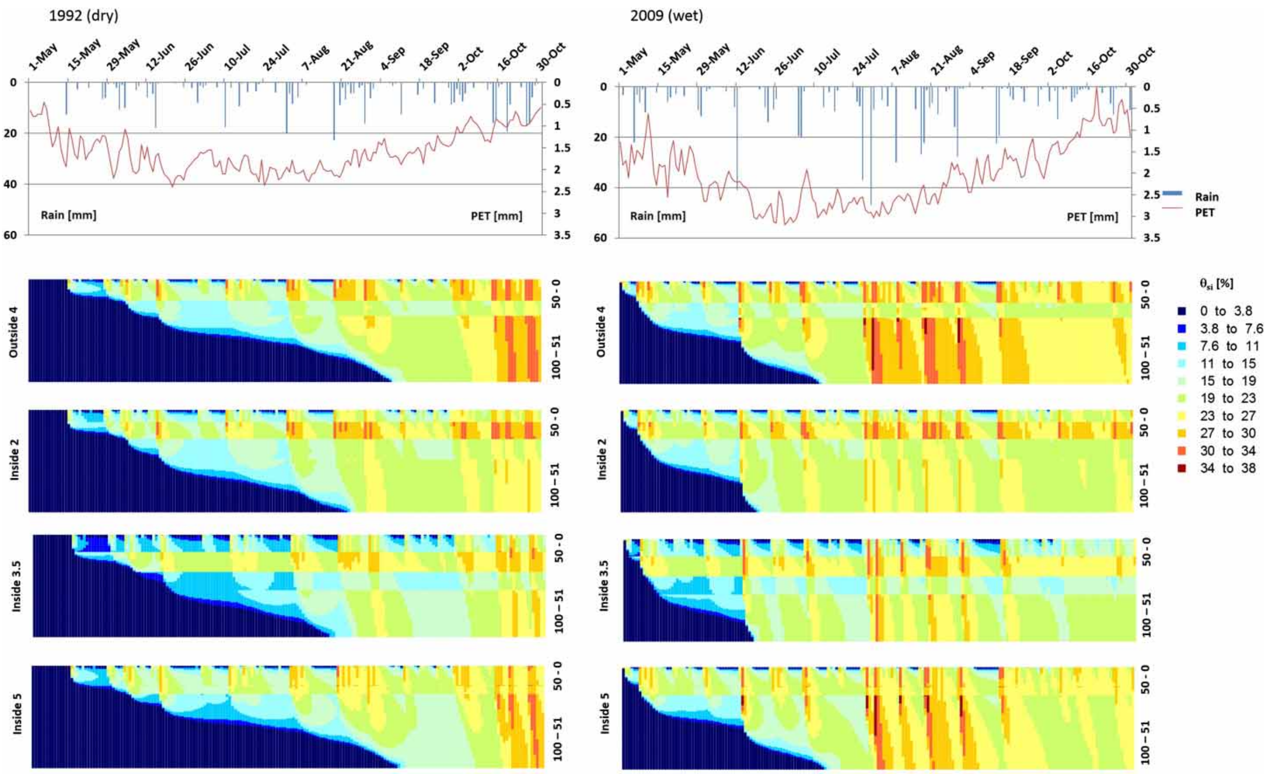


**Figure 6** | Rainfall amount and potential evapotranspiration (PET) of historical rainfall events (upper row) and hydrological water balance from podzols under different management. Each horizontal colour bar consists of 282 single columns representing the saturation increasing rates ($\theta_{si}$) of the soil (0–100 cm) at one simulation day; inside, within agricultural plot; outside, non-managed area surrounding the agricultural plot.

cm resolution in Figure 6). The results showed that soil under natural conditions has higher infiltration rates and thus higher $\theta_{si}$ values in the top horizon. Middle and bottom horizons reacted differently under different weather conditions. During dry periods the $\theta_{si}$ values of the natural soil remain lower in comparison to the converted soil, while the $\theta_{si}$ rates increase after heavy rainfall events (June 10, 2009) or as a result of continuous rainfall (September 6, 1992). Although the differences in $\theta_{si}$ between the locations are not very strong, the outside soil is still characterized by higher infiltration rates, hence higher $\theta_{si}$, basically over the whole soil column (Figure 6). Due to higher infiltration and percolation rates, the outside soil has higher and faster discharge rates into the groundwater, particularly after heavy rains of $>30\,\text{mm day}^{-1}$ (e.g. after July 24, 2009). The situation during drier periods (of both the dry and wet years) is characterized by higher $\theta_{si}$ rates in the upper horizon (0–20 cm) of the outside soil and lower $\theta_{si}$ values in the middle and bottom horizons (e.g. June 1992 and May 2009) (Figures 5 and 6). Results of both examples showed that the boreal forest/natural state soil, in comparison to converted/cropped soil, is characterized by lower saturation values, quicker hydrological responses, and higher infiltration rates, high percolation rates over the whole soil column and thus less surface runoff. For the Cormack soil, the hydrological regime of the lower horizons changed with rainfall amount. The $\theta_{si}$ rates of natural soil were lower under dry and medium wet conditions than for the agricultural soil, while the saturation was higher after heavy rains or because of continuous rainfall events.

Regarding the quality of the natural soil under converted conditions (after clear cut), several short-term consequences need to be considered if an agricultural use is intended, besides the immediate risk of erosion due to the loss of canopy. The concentration of the soil solution can increase after application of soluble substances (e.g. fertilizers and pesticides) to the Ap horizon. Subsequent higher percolation rates and solute fluxes within deeper horizons can lead to accelerated leaching of these solutes. This leads to nutrient losses, and resulting lower nutrient availability to crops while causing pollution problems in connected water bodies (Scanlon et al. 2007; Gomiero et al. 2011; Horel et al. 2015; Stapanian et al. 2016). Solutes loss from the soil profile can reach seasonal peaks during the CWD. This is particularly important since surface soils after clear-cutting will be more exposed to high intensity rainfall events due to the loss of boreal forest canopy, which intercepts 9% to 55% of rainfall (Pomeroy et al. 1999). On the other hand, the likelihood of about 9 CDD year$^{-1}$ and higher temperatures during the growing seasons (e.g. for July up to 0.19°C year$^{-1}$) might cause water stress in plants. The water balance, particularly under the dry scenarios, showed that the water storage period in natural soil is already shortened under the medium temperature conditions (1992). Projected higher surface temperatures and the resulting higher PET will further lower soil moisture (Ge et al. 2013; Mills et al. 2013) resulting in reduced plant water availability, particularly in newly converted soils. In contrast, converted agricultural soils will experience long-term increasing trends in surface runoff while decreasing infiltration and deep percolation, gaining the risk of erosion. These predicted changes in hydrological processes will further gradually reduce groundwater recharge and affect catchment hydrology (e.g. lowered base flow levels, increased direct runoff in streams/rivers). The expected long- and short-term impacts of boreal land use conversion need to be addressed during the decision process.

## CONCLUSION

In this study, we simulated the soil water balance of boreal forest soils before and after conversion into agricultural land, in the context of regional climate variability. The regional climate analysis confirmed global observations: all temperatures increased highly significantly after 1990, particularly in winter and summer months. Greatest warming rates were observed for February (0.36°C year$^{-1}$) and July (0.19°C year$^{-1}$). The hydrological simulations showed that boreal forest soils have lower saturation, quicker hydrological responses, and higher infiltration and percolation rates over the whole soil column. A short-term consequence of agricultural soil conversion is hence increased leaching risks for applied fertilizers and pesticides, enhancing the risk for polluting groundwater and connected water bodies and ecosystems. In contrast, cultivated soils have slower infiltration and retain water for longer, especially in the upper horizons. These effects will gradually increase the risks of erosion and nutrient loss by runoff. Moreover, lower infiltration and percolation rates will diminish groundwater recharge, which affects the sustainability of hydrological processes (dry weather flow) and functions (regulated water flow) at catchment levels. These possible long-term consequences can have an effect on agriculture as well as on domestic water supplies, especially under drought conditions.

Using a representative example of land conversion in western Newfoundland, the study demonstrated that agricultural conversion of boreal soil will fundamentally affect the soil water regime, erosion risk and the quality of the surrounding environment. These effects are further accentuated by the shift in climatic conditions. Conclusively, any proposal for conversion of boreal soils should undergo an assessment of potential short- and long-term consequences. Environmentally sustainable land and water management demands an initial identification of the most suitable areas for conversion to minimize its impacts.

## REFERENCES

Agriculture Canada 1983 *Soils of the Cormack-Deer Lake Area, Newfoundland*. Report No. 5 Newfoundland Soil Survey.

Alaoui, A., Willimann, E., Jasper, K., Felder, G., Herger, F., Magnusson, J. & Weingartner, R. 2014 Modelling the effects of land use and climate changes on hydrology in the Ursern Valley, Switzerland. *Hydrological Processes* **28** (10), 3602–3614.

Aronica, G., Freni, G. & Oliveri, E. 2005 Uncertainty analysis of the influence of rainfall time resolution in the modelling of urban drainage systems. *Hydrological Processes* **19**, 1055–1071.

Augustin, F., Houle, D., Gagnon, C. & Courchesne, F. 2015 Long-term base cation weathering rates in forested catchments of the Canadian Shield. *Geoderma* **247**, 12–23.

Bayley, S. E., Wong, A. S. & Thompson, J. E. 2013 Effects of agricultural encroachment and drought on wetlands and shallow lakes in the boreal transition zone of Canada. *Wetlands* **33** (1), 17–28.

Bennie, J. J., Wiltshire, A. J., Joyce, A. N., Clark, D., Lloyd, A. R., Adamson, J., Parr, T., Baxter, R. & Huntley, B. 2010 Characterising inter-annual variation in the spatial pattern of thermal microclimate in a UK upland using a combined empirical-physical model. *Agricultural and Forest Meteorology* **150** (1), 12–19.

Bouyoucos, G. J. 1962 Hydrometer method improved for making particle size analysis of soils. *Agronomical Journal* **54**, 464–465.

Bradshaw, C. J. A. & Warkentin, I. G. 2015 Global estimates of boreal forest carbon stocks and flux. *Global and Planetary Change* **128**, 24–30.

Brosnan, J. T., Breeden, G. K., Elmore, M. T. & Zidek, J. M. 2011 Application timing affects Bermuda grass suppression with mixtures of fluazifop and triclopyr. *Weed Technology* **25** (4), 591–597.

Canada Department of Agriculture 1979 *Soils of the Codroy Area, Newfoundland.* Atlantic Provinces Soils Institute, Resource Research Institute, Department of Agriculture Canada. http://sis.agr.gc.ca/cansis/publications/surveys/nf/nf2/nf2_report.pdf.

Diodato, N., Bellocchi, G., Romano, N. & Chirico, G. B. 2011 How the aggressiveness of rainfalls in the Mediterranean lands is enhanced by climate change. *Climatic Change* **108** (3), 591–599.

D'Orangeville, L., Houle, D., Cote, B. & Duchesne, L. 2014 Soil response to a 3-year increase in temperature and nitrogen deposition measured in a mature boreal forest using ion-exchange membranes. *Environmental Monitoring and Assessment* **186** (12), 8191–8202.

Finnis, J. 2013 *Projected Impacts of Climate Change for the Province of Newfoundland & Labrador*. Report submitted to the Office of Climate Change, Energy Efficiency & Emissions Trading.

Food and Agriculture Organization of the United Nations (FAO) 2017 *Mineral Soils Conditioned by a (Sub)Humid Temperate Climate.* http://www.fao.org/docrep/003/Y1899E/y1899e12.htm (accessed 7 July 2017).

Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M. D., Smith, P., van der Velde, M., Vicca, S., Babst, F., Beer, C., Buchmann, N., Canadell, J. G., Ciais, P., Cramer, W., Ibrom, A., Miglietta, F., Poulter, B., Rammig, A., Seneviratne, S. I., Walz, A., Wattenbach, M., Zavala, M. A. & Zscheischler, J. 2015 Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. *Global Change Biology* **21**, 2861–2880.

Gao, X. J., Shi, Y. & Giorgi, F. 2011 A high resolution simulation of climate change over China. *Science China-Earth Sciences* **54** (3), 462–472.

Ge, Z.-M., Kellomaki, S., Zhou, X., Wang, K.-Y., Peltola, H., Vaisanen, H. & Strandman, H. 2013 Effects of climate change on evapotranspiration and soil water availability in Norway spruce forests in southern Finland: an ecosystem model based approach. *Ecohydrology* **6** (1), 51–63.

Gomiero, T., Pimentel, D. & Paoletti, M. 2011 Is there a need for a more sustainable agriculture? *Crit. Rev. Plant. Sci.* **30**, 6–23.

Government of Newfoundland and Labrador 2017 *Fostering Growth in Agriculture.* Executive Council, Fisheries, Forestry and Agrifoods, Municipal Affairs. News release. Government of Newfoundland and Labrador, Canada, http://www.releases.gov.nl.ca/releases/2017/exec/0216n01.aspx.

Grünzweig, J. M., Valentine, D. W. & Chapin, F. S. 2015 Successional changes in carbon stocks after logging and deforestation for agriculture in interior Alaska: implications for boreal climate feedbacks. *Ecosystems* **18**, 132–145.

Horel, A., Toth, E., Gelybo, G., Kasa, I., Bakacsi, Z. & Farkas, C. 2015 Effects of land use and management on soil hydraulic properties. *Open Geosciences* **7** (1), 742–754.

Hormann, G., Horn, A. & Fohrer, N. 2005 The evaluation of land-use options in mesoscale catchments: prospects and limitations of eco-hydrological models. *Ecological Modelling* **187** (1), 3–14.

Huang, J. P., Yu, H. P., Guan, X. D., Wang, G. Y. & Guo, R. X. 2016 Accelerated dryland expansion under climate change. *Nature Climate Change* **6** (2), 166.

Intergovernmental Panel on Climate Change (IPCC) 2013 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom & New York.

Jacques, D., Simunek, J., Mallants, D. & van Genuchten, M. T. 2008 Modelling coupled water flow, solute transport and geochemical reactions affecting heavy metal migration in a podzol soil. *Geoderma* **145** (3–4), 449–461.

Jaiswal, P. & van Westen, C. J. 2009 Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. *Geomorphology* **112**, 96–105.

Jeong, D. I., St-Hilaire, A., Ouarda, T. & Gachon, P. 2013 Projection of multi-site daily temperatures over the Montreal area, Canada. *Climate Research* **56** (3), 261–280.

Karavayeva, N. A., Nefedova, T. G. & Targulian, V. O. 1991 Historical land use changes and soil degradation on the Russian Plain. In: *Land Use Changes in Europe, Processes of Change, Environmental Transformations and Future Patterns* (F. M. Brouwer, A. J. Thomas & M. J. Chadwick, eds). Kluwer Academic Publishers, GeoJournal library, pp. 351–377.

Koven, C. D., Riley, W. J. & Stern, A. 2013 Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. *Journal of Climate* **26** (6), 1877–1900.

Kukal, M. & Irmak, S. 2016 Long-term patterns of air temperatures, daily temperature range, precipitation, grass-reference evapotranspiration and aridity index in the USA great plains: Part II. Temporal trends. *Journal of Hydrology* **542**, 978–1001.

Lehmann, E. A., Phatak, A., Soltyk, S., Chia, J., Lau, R. & Palmer, M. 2013 Bayesian hierarchical modelling of rainfall extremes. In: *20th International Congress on Modelling and Simulation (Modsim2013)*, pp. 2806–2812.

Lindroos, A.-J., Derome, J., Derome, K. & Smolander, A. 2011 The effect of Scots pine, Norway spruce and silver birch on the chemical composition of stand throughfall and upper soil percolation water in northern Finland. *Boreal Environment Research* **16** (3), 240–250.

Liu, X. D. & Chen, B. D. 2000 Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology* **20**, 1729–1742.

Liu, Y., Liu, B. C., Yang, X. J. & Bai, W. 2016 Clustering analysis of regional reference evapotranspiration and its components based on climatic variables across northeast China, 1961–2010. *Journal of Water and Climate Change* **7**, 128–141.

Marttila, H., Saarinen, T., Celebi, A. & Klove, B. 2013 Transport of particle-associated elements in two agriculture-dominated boreal river systems. *Science of the Total Environment* **461**, 693–705.

Mills, R. T. E., Dewhirst, N., Sowerby, A., Emmett, B. A. & Jones, D. L. 2013 Interactive effects of depth and temperature on CH4 and N2O flux in a shallow podzol. *Soil Biology & Biochemistry* **62**, 1–4.

Mullan, D. 2013 Catena soil erosion under the impacts of future climate change: assessing the statistical significance of future changes and the potential on site and off site problems. *Catena* **109**, 234–246.

Nelner, T. B. & Hood, G. A. 2011 Effect of agriculture and presence of American beaver *Castor canadensis* on winter biodiversity of mammals. *Wildlife Biology* **17** (3), 326–336.

Nikodem, A., Kodesova, R., Drabek, O., Bubenickova, L., Boruvka, L., Pavlu, L. & Tejnecky, V. 2010 A numerical study of the impact of precipitation redistribution in a beech forest canopy on water and aluminum transport in a podzol. *Vadose Zone Journal* **9** (2), 238–251.

Okkonen, J., Jyrkama, M. & Klove, B. 2010 A conceptual approach for assessing the impact of climate change on groundwater and related surface waters in cold regions (Finland). *Hydrogeology Journal* **18** (2), 429–439.

Osborn, T. J., Wallace, C. J., Harris, I. C. & Melvin, T. M. 2016 Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. *Climatic Change* **134** (3), 353–369.

Pan, Y. D. *et al.* 2011 A large and persistent carbon sink in the world's forests. *Science* **333**, 988–993.

Perry, M. & Hollis, D. 2005 The generation of monthly gridded datasets for a range of climatic variables over the UK. *International Journal of Climatology* **25**, 1041–1054.

Pomeroy, J. W., Davies, T. D., Jones, H. G., Marsh, P., Peters, N. E. & Tranter, M. 1999 Transformations of snow chemistry in the boreal forest: accumulation and volatilization. *Hydrological Processes* **13** (14–15), 2257–2273. doi: 10.1002/(SICI)1099-1085(199910)13:14/15<2257::AID-HYP874>3.0.CO;2-G.

Rae, L. F., Whitaker, D. M. & Warkentin, I. G. 2014 Multiscale impacts of forest degradation through browsing by hyperabundant moose (*Alces alces*) on songbird assemblages. *Diversity and Distributions* **20** (4), 382–395.

Redding, T. & Devito, K. 2011 Aspect and soil textural controls on snowmelt runoff on forested Boreal Plain hillslopes. *Hydrology Research* **42** (4), 250–267.

Rezaei, M., Seuntjens, P., Shahidi, R., Joris, I., Boenne, W., Al-Barri, B. & Cornelis, W. 2016 The relevance of in-situ and laboratory characterization of sandy soil hydraulic properties for soil water simulations. *Journal of Hydrology* **534**, 251–265.

Sanborn, P., Lamontagne, L. & Hendershot, W. 2011 Podzolic soils of Canada: genesis, distribution, and classification. *Canadian Journal of Soil Science* **91** (5), 843–880.

Saxton, K. E. & Willey, P. H. 2004 Agricultural wetland and pond hydrologic analyses using the SPAW model. In: *Conference Proceedings, Self-Sustaining Solutions for Streams, Watersheds and Wetlands*, 12–15 September 2004, ASAE, St Joseph, MI.

Saxton, K. E. & Willey, P. H. 2006 The SPAW model for agricultural field and pond hydrologic simulation. In: *Watershed Models* (V. P. Singh & D. K. Frevert, eds). CRC Press, Boca Raton, FL, pp. 401–435.

Scanlon, B. R., Jolly, I., Sophocleous, M. & Zhang, L. 2007 Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resources Research* **43** (3), W03437. doi: 10.1029/2006WR005486, 2017.

Schaetzl, R. J., Luehmann, M. D. & Rothstein, D. 2015 Pulses of podzolization: the relative importance of spring snowmelt, summer storms, and fall rains on spodosol development. *Soil Science Society of America Journal* **79** (1), 117–131.

Schneider, S., Jacques, D. & Mallants, D. 2013 Inverse modelling with a genetic algorithm to derive hydraulic properties of a multi-layered forest soil. *Soil Research* **51** (5), 372–389.

Šimůnek, J. & Nimmo, J. R. 2005 Estimating soil hydraulic parameters from transient flow experiments in a centrifuge using parameter optimization technique. *Water Resources Research* **41** (4), W04015. doi:10.1029/2004WR003379.

Šimůnek, J., van Genuchten, M. T. & Šejna, M. 2012 HYDRUS: model use, calibration and validation, special issue on standard/engineering procedures for model calibration and validation. *Transactions of the ASABE* **55** (4), 1261–1274.

Šimůnek, J., van Genuchten, M. T. & Sejna, M. 2016 Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal* **15** (7). doi: 10.2136/vzj2016.04.0033.

Sinclair, A., Hebb, D., Jamieson, R., Gordon, R., Benedict, K., Fuller, K., Stratton, G. W. & Madani, A. 2009 Growing season surface water loading of fecal indicator organisms within a rural watershed. *Water Research* **43** (5), 1199–1206.

Stapanian, M. A., Schumacher, W., Gara, B. & Monteith, S. E. 2016 Negative effects of excessive soil phosphorus on floristic quality in Ohio wetlands. *Science of the Total Environment* **551**, 556–562.

Stralberg, D., Bayne, E. M., Cumming, S. G., Solymos, P., Song, S. J. & Schmiegelow, F. K. A. 2015 Conservation of future boreal forest bird communities considering lags in vegetation response to climate change: a modified refugia approach. *Diversity and Distributions* **21**, 1112–1128.

Thornthwaite, C. W. 1948 An approach toward a rational classification of climate. *Geographical Review* **38** (1), 55–94. doi:10.2307/210739.

Wang, S. F., Kang, S. Z., Zhang, L. & Li, F. S. 2008 Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes* **22** (14), 2502–2510.

Wang, X., Wang, J. & Zhang, J. 2012 Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China. *Plos ONE* **7** (8). doi:10.1371/journal.pone.0044334.

Wang, W. G., Shao, Q. X., Yang, T., Peng, S. Z., Yu, Z. B., Taylor, J., Xing, W. Q., Zhao, C. P. & Sun, F. C. 2013 Changes in daily temperature and precipitation extremes in the Yellow River Basin, China. *Stochastic Environmental Research and Risk Assessment* **27** (2), 401–421.

Yapo, P. O., Gupta, H. V. & Sorooshian, S. 1996 Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. *Journal of Hydrology* **181**, 23–48.

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