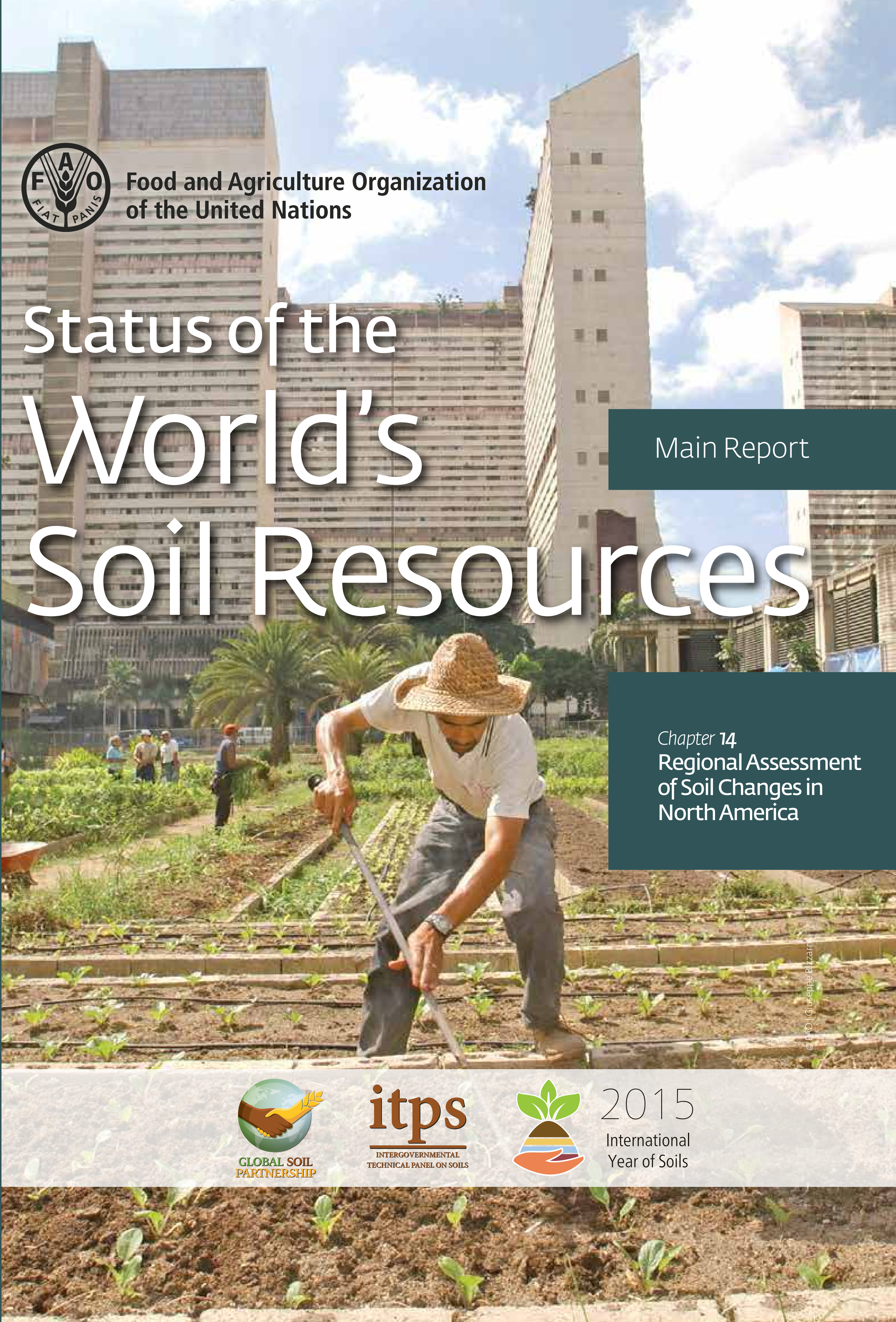
Food and Agriculture Organization
of the United Nations

Status of the World's Soil Resources

Main Report



Chapter 14
Regional Assessment of Soil Changes in North America

GLOBAL SOIL PARTNERSHIP

itps
INTERGOVERNMENTAL TECHNICAL PANEL ON SOILS

2015
International Year of Soils

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Recommended citation:
FAO and ITPS. 2015.
Status of the World's Soil Resources (SWSR) – Main Report.
Food and Agriculture Organization of the United Nations
and Intergovernmental Technical Panel on Soils, Rome, Italy

ISBN 978-92-5-109004-6

14 | Regional Assessment of Soil Changes in North America

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14.1 | Introduction

Although Canada and the United States of America have a long history of collaborative research activity in soil science, there have been no previous attempts at a regional assessment of threats to soil functions. Nor are there any ongoing institutional arrangements that coordinate soil assessment or management across the two countries, unlike trans-border water issues – which are adjudicated by an International Joint Commission – or atmospheric issues, such as when cross-border problems with acidification were the focus of the Air Quality Agreement of 1991. Cross-border coordination is further complicated by the lack of a common soil classification system between the two countries.

In the absence of a regional reporting system for threats to soil functions, this chapter draws on the appropriate national reporting systems and on the expertise of leading soil scientists where national assessments do not exist.

The main data source used for Canada is the Agri-Environmental Indicators report series, which was developed by Agriculture and Agri-Food Canada (AAFC). This series began in 1993 with the intent of producing science-based environmental indicators specific to the agriculture and agri-food sector. The work presented in this chapter is drawn from the forthcoming *4^{th} Agri-Environmental Indicators report* (Clearwater *et al.*, 2015). The series estimates change in the indicators in five-year periods beginning (for most indicators) in 1981. Indicators that assess primary agriculture are calculated using mathematical models or formulas that integrate information on soil, climate and landscape, mainly derived from the Soil Landscapes of Canada (SLC) (*Soil Landscapes of Canada* Working Group, 2007), with information on crops, land use, land management and livestock from the *Census of Agriculture* and other custom data sets from provincial agencies, the private sector, remote sensing, etc. Information on the specific indicators is available in AAFC (2013).

The *4^{th} Agri-Environmental Indicators report* provides information for soil erosion, change in SOC, and nutrient imbalance, and this information is featured in Sections 4.3 and 4.4 of this chapter. Leading Canadian scientists selected by the Canadian Society of Soil Science provided information on the remaining threats.

The major information source used for the United States is the National Resources Inventory (USDA, 2013a). This report provides a range of land use and management statistics and national estimates for sheet and rill erosion and for wind erosion. The report provides data for the period 1982-2010. Data are gathered annually by the National Resources Conservation Agency and major reports are released at five-year intervals. Information on specific threats such as salinization was also provided by the STATSGO2 database (Soil Survey Staff, 2014). Leading United States soil scientists selected by the Soil Science Society of America also provided information for the United States.

14.2 | Regional stratification and soil threats

14.2.1 | Regional stratification and land cover

The spatial framework used in this chapter is the multi-level Ecological Regions of North America developed by the Commission for Environmental Cooperation (Commission for Environmental Cooperation, 1997). The Level II ecoregions are used as a consistent geographical reference (Figure 14.1).

The contiguous 48 United States, Hawaii, Puerto Rico, and the United States Virgin Islands cover almost 88 Bha of land and water. About 71 percent of this area is non-Federal rural land – nearly 57 billion ha (USDA, 2013a). The non-Federal rural lands of the United States are predominantly rangeland (165 million ha), forest land (166 million ha), and cropland (146 million ha) with smaller areas composed of developed land, pastureland and water.

Rangeland is dominant in the western half of the United States in the Cold Deserts, Warm Deserts, Great Plains, South Central Semi-Arid Prairies and Western Cordillera ecoregions. Forest is the dominant land cover in the northwest, north central and eastern one-third of the country, in the Western Cordillera, Mixed Wood Plains, Ozark, Ouachita-Appalachian Forests ecoregions.

Cropland is the dominant land cover in the Central United States Plains, South Eastern United States Plains, the Mississippi Alluvial and Southeast United States coastal plains, Temperate Prairies, West Central Semi-Arid Prairies, South Central Semi-Arid Prairies and Mediterranean California ecoregions.

Cropland in the United States increased by about 1 million ha from 2007 to 2010, following a steady decline in area in the previous 25 years. These gains can be attributed to land withdrawn from the Conservation Reserve Program as grain prices reached near-record levels. This led to an increased threat to the soil resource from erosion and loss of terrestrial C. The National Resources Inventory tracks the cropland area for specific conservation measures such as terracing. However, according to the Conservation Technology Information Center there has not been a national survey of crop residue management practices since 2004; at that time 45.6 million ha was in conservation tillage out of a total of 112 million ha of cropland (Conservation Technology Information Center, 2014).

Total farmland in Canada increased from 1981 (65.9 million ha) to 2006 (67.6 million ha) (all values from AAFC, 2013). The largest agricultural region (54.7 million ha) occurs in the Temperate Prairies and West-Central Semi-Arid Prairies ecoregions in southern Alberta, Saskatchewan, and Manitoba. In 2006 approximately 29 million ha of farmland in this region was cropped, primarily to cereal grains, oilseeds and pulse crops, and 18 million ha was in pasture. Approximately 1.4 million ha was in tillage summer fallow, where land is fallowed during the growing season with weed suppression by one or more tillage operations. The area under tillage summer fallow has declined greatly from 5.3 million ha in 1991 and this decline has reduced soil degradation in this region.

Farmland in Ontario and Quebec (8.9 million ha) is concentrated in the Mixed Wood Plains ecozone. In 2006 5.6 million ha of this was cropped, primarily to forages, maize, cereal grains, and oilseeds (soybeans). The area of pastures in this region has declined from 1.7 million ha in 1991 to 1.1 million ha in 2006. Tillage practices in this region have also undergone a major shift, with the percentage of cropland under conventional tillage decreasing from 80 percent in 1991 to 50 percent in 2006, and conservation tillage and no-tillage increasing from 16 percent to 26 percent and from 4 percent to 24 percent respectively over the same period.

Farmland in British Columbia (2.8 million ha in 2006) is dominated by forage production and pasture dispersed through the Western Cordillera and Cold Desert ecoregions. Finally the Atlantic Highlands and Mixed Wood Plains ecoregions in Atlantic Canada have 1.1 million ha of farmland, dominantly in forages but with significant areas of potato production in New Brunswick and Prince Edward Island.

Overall the greatest shift in Canadian agriculture has been the adoption of no-till and reduced tillage systems. The 2011 Census of Agriculture (Statistics Canada, 2015) reports that of 29.6 million ha seeded in 2011, 16.7 million ha were in no-till and a further 7.2 million ha were in tillage systems that left most residue on the soil surface; only 5.6 million ha were in conventional tillage e.g. with most residue turned into the soil.

Wetlands are extensive in both Canada and the United States and are subject to considerable alteration by human activity. Bridgham *et al.* (2006) estimate that the historical area of wetlands in Canada of 150 million ha has been reduced to 130 million ha by land-use conversion. In the contiguous United States, the same study estimated a reduction from 90 million ha historically to current levels of 43 million ha.

The area of forested land in Canada is estimated at 348 million ha (Natural Resources Canada, 2012). Forest is the dominant land cover in the Northern Forests, Boreal Plain, Boreal Cordillera, Western Cordillera and Marine West Coast Forest ecoregions. Forest harvest activity has decreased in the period from 2004, and approximately 0.7 million ha were harvested in 2010 (Natural Resources Canada, 2012). Canada's National Forest Inventory shows that gross deforestation rates were typically in the order of 64 400 ha yr^{-1} circa 1990, and decreased to 44 800 ha yr^{-1} by 2010, corresponding to about 0.02 percent of Canada's forest area (Natural Resources Canada, 2012). Deforestation minus afforestation (according to UNFCCC definitions) amounts to a net loss of 35 000 ha yr^{-1}. Overall, there is a definite decrease in total deforestation rate from the 1990s to present, which is expected to continue in coming years, but at a lower rate of decrease (Masek *et al.*, 2011). The expansion of agriculture is the largest source of forest conversion, accounting for two thirds of gross deforestation. Urban and industrial development is the next largest driver at approximately 17 percent, followed by forestry at half that rate. The Boreal Plains ecozone spanning central Alberta, Saskatchewan, and Manitoba (generally termed the Prairie provinces) was the dominant location of deforestation over the 1990–2008 time period, contributing just under half the nation's deforestation for most years, largely due to agricultural conversion (Masek *et al.*, 2011).

The Tundra (233 million ha), Taiga (200 million ha) and Arctic Cordillera (21.7 million ha) ecoregions are vulnerable to effects of climate change. Permafrost soils in these regions are estimated to contain 39 percent of all organic C in Canada (Tarnocai and Bockheim 2011) and hence the interaction of soils and climate in these regions is a major concern.

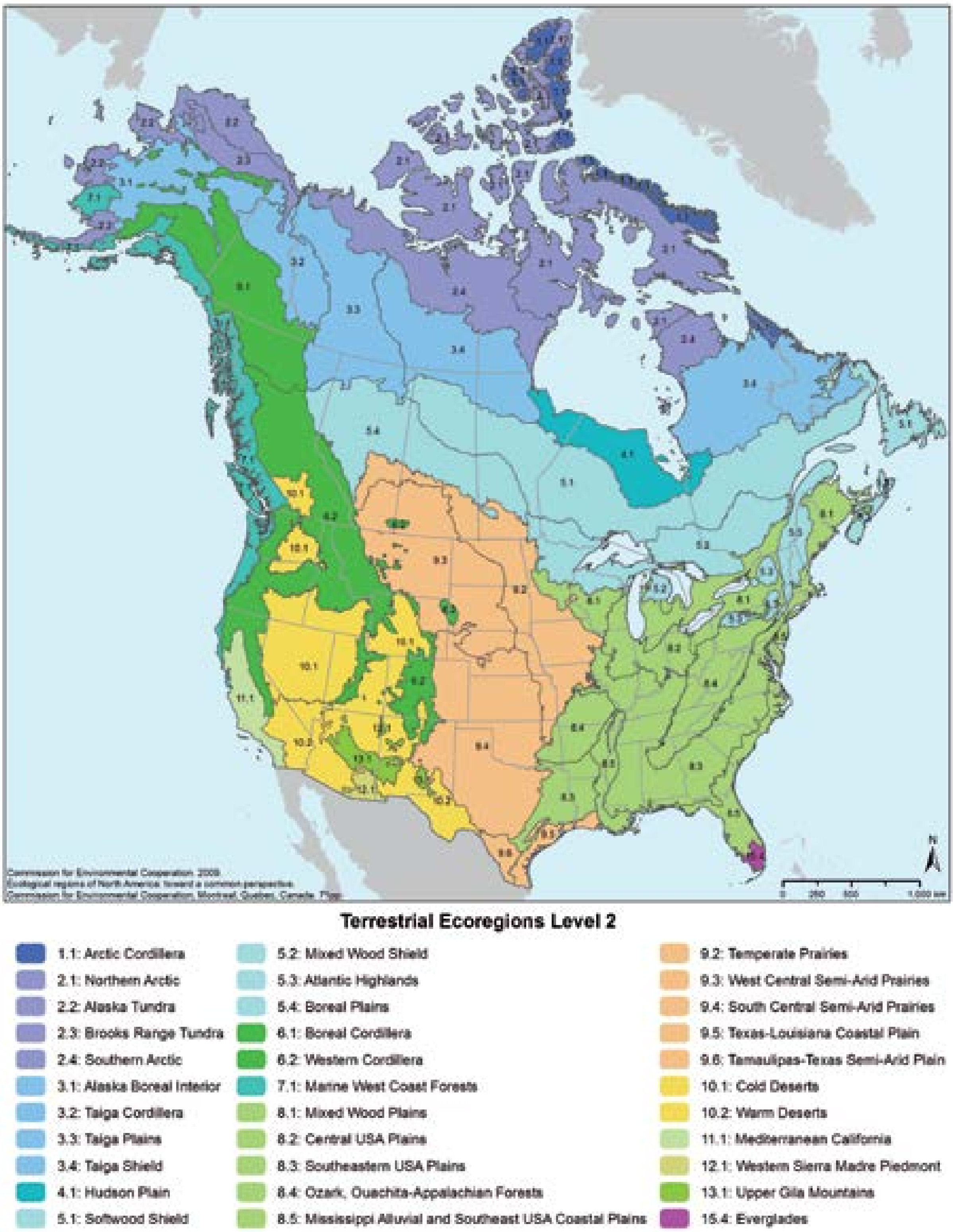

Figure 14.1 | Level II Ecological regions of North America.
Source: Commission for Environmental Cooperation, 1997.

14.3 | Soil threats

This section focuses on the status and trends for six threats to soil functioning: acidification, contamination, salinization, sealing/capping, compaction, and waterlogging. Four threats that are judged to be the most serious (erosion, nutrient imbalance, carbon change, and soil biodiversity) are discussed in greater detail in the following section.

14.3.1 | Soil acidification

While many native forest communities are well-adapted to strongly acidic (pH < 5.5) soil conditions, most managed agricultural and horticultural plants suffer from enhanced metal phytotoxicity (Al, Fe, Mn, etc.), reduced N and P availability, and decreased microbiological activity because soils have become acidified below their optimum range. Excessive soil acidification also poses environmental risks of enhanced surface water acidification, sediment losses due to loss of vegetation, and increased loadings of soluble metals into groundwater. Soil acidification is enhanced by a range of anthropogenic effects, including excessive inputs of acidic atmospheric deposition, intensive removal of aboveground biomass, and exposure of sulfidic materials by mining, construction, dredging, and other disturbances.

Acidic deposition from rain that has low pH and significant amounts of sulphate and nitrate contributes to base cation depletion and soil acidification in industrialized regions of the world (Meinz and Seip, 2004). These effects, however, have been documented only rarely in the United States. Coarse-textured soils in high-altitude forests that were originally low in pH and base saturation are particularly susceptible to degradation and loss of function. Finer-textured and more highly buffered soils are much more resistant to the negative effects of acidic deposition. The Clean Air Act Amendments of 1990 resulted in significant declines in sulphate emissions (http://nadp.sws.uiuc.edu/ntn/), although emissions of nitrogen oxides have remained elevated due to transportation and agricultural sources. Some lakes in the Adirondacks have shown significant improvement in water quality as a result of the Clean Air Act Amendments. Research by Driscoll *et al.* (2001) has shown, however, that tighter controls on atmospheric emissions will be needed if soil and stream chemistry in this region is to return to pre-industrial levels in a reasonable time range. Alternatively, aerial application of calcium sources such as wollastonite ($CaSiO_3$) to acidifed catchments can accelerate the return of base saturation to pre-industrial levels (Johnson *et al.*, 2014). However, the widespread applicability of this reclamation approach is limited. Localized, highly acidic deposition from heavy metal smelter and other industrial facilities also impacted large areas of land such as the Copper Basin in Tennessee, where many square miles of land were denuded by open air smelting of metal sulphide ores. Current concerns centre on the effects on soil fertility and acidification from the interaction between intensive biomass harvesting and acidic deposition on forest soils (Adams *et al.*, 2000).

Sulfidic materials (as defined by *Soil Taxonomy* (Soil Survey Staff, 1999)) are routinely exposed by mining, construction, and dredging activities. This exposure can rapidly lower the pH of local soils and water to < 4.0 via sulfuricization processes (Kittrick, Fanning and Hossner, 1982). While most active mining operations now isolate sulfidic materials from contact with groundwater and surface water via the application of appropriate acid-base accounting procedures (Skousen *et al.*, 2002), construction-related impacts have become increasingly common since the 1970s due to larger scale excavations and the construction industry's lack of recognition of risk (Fanning *et al.*, 2004; Orndorff and Daniels, 2004). Once exposed, sulfidic materials require large inputs of liming agents (e.g. ~ 31 Mg of agricultural lime per 1000 Mg material for 1 percent pyritic-S) to become properly neutralized and stabilized.

In Canada, the major risks associated with soil acidification occur in forested areas. As in the United States, areas most at risk from acidification are in regions dominated by coarse-textured soils that have low base cation weathering rates and that receive high levels of acid deposition (Ouimet at al., 2006). These areas of coarse-textured soils include much of the Softwood Shield and Mixed Wood Shield ecoregions and the southern, coastal parts of British Columbia (Aherne and Posch, 2013) in regions where glacial parent materials were derived from igneous rocks. Both the loss of essential base cations and the mobilization of metals such as Al and Mn can have adverse impacts on forest vegetation. It has been proposed that the ratio of base cations or Ca to Al (e.g. base cations (BC/Al or Ca/Al) in soil solution is a useful indicator of the potential risk to trees from soil acidification (Cronan and Grigal, 1995; Sverdrup and Warfvinge, 1993). Critical loads are also increasingly used to estimate the risk of soil acidification (Whitfield *et al.*, 2010).

Aherne and Posch (2013) estimated critical loads for acid deposition for upland forest soils in Canada (~2 600 000 km^2). They reported that in 2006, because of acid deposition levels, 4.5 percent of the mapped area (~100 000 km^2) was at risk based on a BC/Al ratio of 1.0; and 20.3 percent (~500 000 km^2) of the area was at risk based on a BC/Al ratio of 10.0. Exceedance of the critical load was primarily driven by elevated anthropogenic emissions from large point sources, such as the activities in the Athabasca Oil Sands region and in ore smelting near Sudbury, Ontario. In addition, exceedance in central and eastern Canada was associated with long-range (transboundary) air pollution and emissions from shipping along the St. Lawrence River.

In Canada, national emissions of SO_2 and NO_x decreased by 21 percent and 3 percent, respectively, between 2008 and 2010 (Canadian Council of Ministers of the Environment (CCME), 2103). This decrease reduces the risk of soil acidification in Canada. Emission reductions, however, vary by province. The bulk of the reduction in SO_2 and NO_x emissions has been in Ontario in central Canada. Minimal decreases or even increases in emissions, associated primarily with the oil and gas industry (CCME, 2013), have occurred in British Columbia and Alberta in western Canada. Currently, the risk of soil acidification caused by acid deposition is generally decreasing over much of eastern Canada but is unchanged or increasing in parts of western provinces, such as Alberta and British Columbia.

14.3.2 | Soil contamination

Soils can be compromised via industrial, mining, municipal, residential and agricultural activities. In North America, metals (Pb, Cd, Cr and As), salts (Na and K), pesticides (herbicides and insecticides), pathogens and nutrients (N and P) contaminate soils to varying degrees and with great spatial variation. There are also chemicals of emerging concern, including engineered nanoparticles, pharmaceuticals and personal care products. Perfluorinated compounds are also of concern: they occur in small concentrations but, because of their high reactivity or potential to be endocrine disrupting, they may pose significant risks to human health and the environment.

In the United States, there are thousands of organic- and metal-contaminated sites of varied scope and significance. To address, monitor and remediate the myriad of sites, the United States Environmental Protection Agency oversees the Superfund programme, which is charged with the clean-up of the nation's hazardous waste sites. This effort follows the National Priorities List (NPL), which defines the known releases or threatened releases of contaminants in the United States and its territories (EPA, 2014a). As of 29 September 2014, there are 1 322 final sites on the NPL with 1 163 having completed measures to address the contamination threat and an additional 49 proposed sites (Figure 14.2). In addition, there are vast areas of low-level soil contamination across the United States which are not monitored by the EPA.

Figure 14.2 | Map of Superfund sites in the contiguous United States Yellow indicates final EPA National Priorities List sites and red indicates proposed sites.
Source: EPA, 2014a.

In Canada, because it has a huge expanse of soil and a relatively small population, soil contamination in a spatial context is a relatively minor issue. However, the most agriculturally productive soils and greatest density of population and industry occur concomitantly along the narrow region close to the southern border. This is also the region where there is the greatest potential for soil contamination. In addition, the hinterland has widely dispersed petroleum and mineral resource industries that form hot spots of soil contamination (Doyle *et al.*, 2003).

More insidious is non- point- source, dispersed contamination (Chan *et al.*, 1986). For example, field crop soils surveyed throughout the Mixed Wood Plains ecoregions of southern Ontario in Canada showed elevated levels of Ba, Cd, Mo, Pb, Sb, Se, Nb, U and Zn, which were speculatively attributed to non- specific urban sources such as road dust (Sheppard *et al.*, 2009). Watmough and Hutchinson (2004) came to a similar conclusion about Pb in forest soils of Southern Ontario. Toxicity in soil from such sources, however, is a relatively remote possibility.

There is concern about soil contamination by agricultural activities, especially as farms increase in size and effectively become industrial point sources. For example, soils in areas of livestock facilities have been found to have metal levels that exceed Canadian soil quality guidelines (Sheppard and Sanipelli, 2012). Some of these metals came from livestock pharmaceuticals (e.g. Bi in teat dips). The contribution of livestock manures containing antibiotic residues to the development of antibiotic-resistant genes in the environment is a growing public concern. In a few cases, the naturally occurring, trace element bioavailability of some Canadian soils has resulted in food crops with amount of elements that exceed guideline concentrations. The most notable are spatially isolated cases of Cd in durum wheat and sunflowers (Grant *et al.*, 1998).

As industrialization and urbanization increase, concomitant with increased agricultural activities in decreasing land areas, the potential for soil contamination remains an important issue. Although soil contaminants in the United States and Canada are ubiquitous in areas close to human populations, the specific threats posed by these contaminants to human health and environmental quality are not well defined. There is a need for improvements in assessments of soil contamination to better protect human health and environmental quality and ensure food safety and security.

14.3.3 | Soil salinization

Soil salinization is a serious threat to the ecosystem services provided by the soil resource with regard to food and fibre production in many parts of North America. The movement and accumulation of salts that cause saline conditions in the soil are affected by the soil water balance. Processes such as climate shifts, improper irrigation and drainage, farming and management practices affect this balance. Soil salinity is a dynamic soil condition and can spread or become more severe in areas that are already saline, especially if the land is not managed properly.

These concerns are especially prevalent in the western portions of the United States (Figure 14.3) (Soil Survey Staff, 2014). Similar threats to food and fibre production are also associated with sodic conditions in the soil. In the United States, saline soils occupy approximately 2.2 million ha of cropland and another 31 million ha are at risk of becoming saline (USDA, 2011).

In Canada, a Risk of Soil Salinization (RSS) Indicator has been developed as part of the Agri-Environmental Indicators programme to assess the ***state*** and ***trend*** of the risk of dryland soil salinization on the Canadian Prairies as a result of changing land use and management practices. Two of the primary conditions required for dryland salinization - water deficits and an inherent salt content in the soil and/or groundwater - occur to a significant extent only in the Prairie region of Canada. The risk of salinization on other agricultural lands in Canada is negligible. The risk of soil sodicity is not assessed as part of this index and is not believed to be a major risk in western Canada. The RSS is derived by calculating a unit-less Salinity Risk Index (SRI) which considers a combination of factors that control or influence the salinization process (Wiebe, Eilers and Brierley, 2010).

In terms of the state of soil salinity in Canada, approximately 1 million ha of surface soils on the Prairies are affected by moderate to severe soil salinity (Wiebe, Eilers and Brierley, 2006). In 2011, 85 percent of the land area in the agricultural region of the Canadian Prairies was rated as having a very low risk of salinization (Figure 14.4).

From 1981 to 2011, the trend has been a 19 percent increase in the land area in the Very Low and Low risk classes. Over the same 30-year period, the land area in the Moderate, High and Very High risk classes decreased from 15 percent to 8 percent. These improvements were largely attributed to the reduction in tillage summer fallow, mentioned above, and to a 4.8 million ha increase of permanent cover (a 14 percent increase from 1981 to 2011). A reduction in risk has been observed in all Prairie provinces. The greatest decline was recorded in Saskatchewan, where the area of summer fallow decreased by more than 5 million ha and the area of permanent cover increased by more than 3 million ha. Changes in land use and management practices have reduced the risk of salinization and indicate a trend towards improved soil health and agri-environmental sustainability.

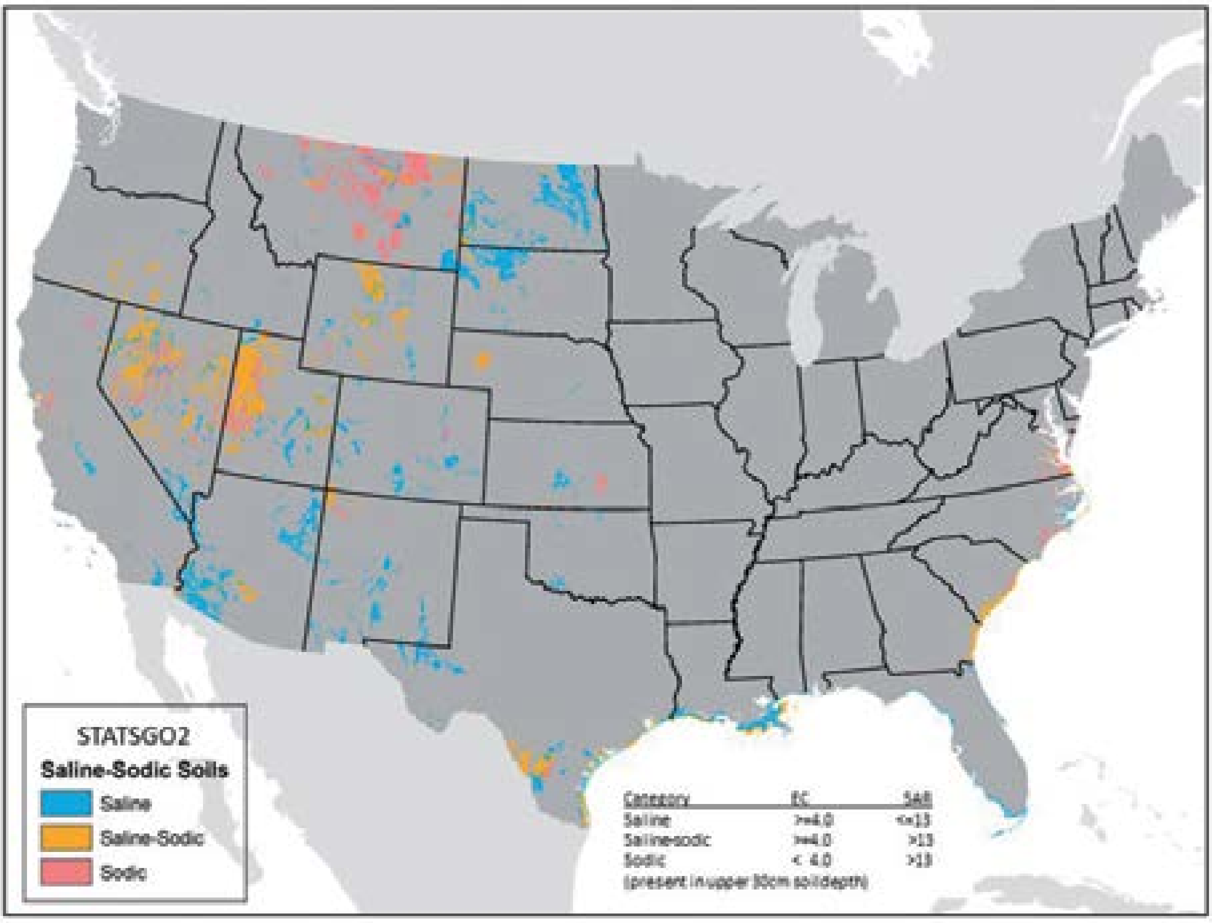

Figure 14.3 | Areas in United States threatened by salinization and sodification.
Source: NRCS[1]

1 http://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/

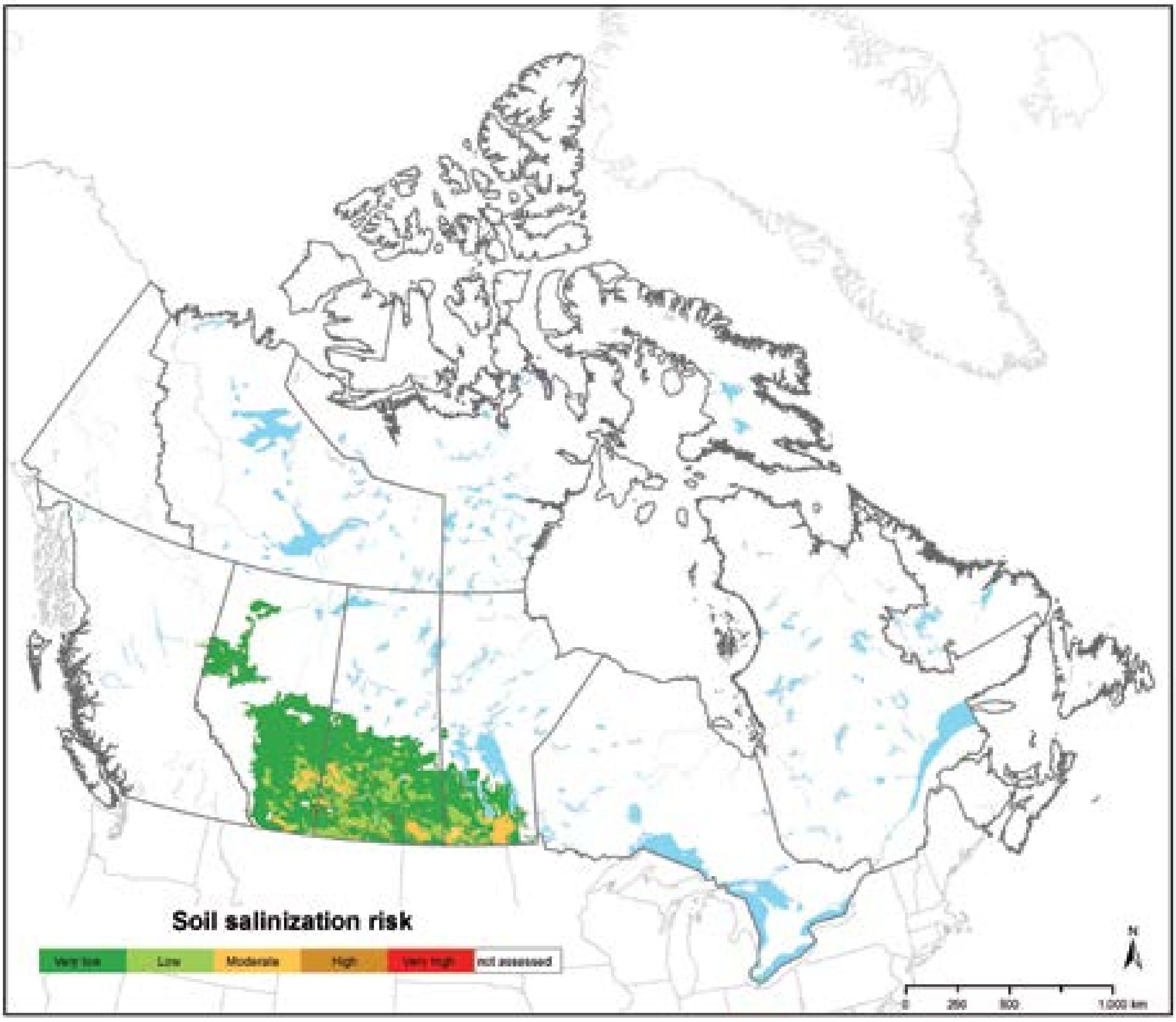

Figure 14.4 | Risk of soil salinization in Canada 2011.
Source: Clearwater et al., 2015.

14.3.4 | Soil sealing/capping

The population of North America is approximately 5 percent of the world population (340 million) and it has been growing at a rate of 0.9 percent a year, during the last decade. In the United States, the threat of loss of soil due to soil sealing and capping consequent on expansion of settlements and infrastructure is significant and has been steadily increasing since 1982, as documented by the USDA Natural Resources Conservation Service's National Resources Inventory Program (NRI) (USDA, 2013a). Between 1982 and 2007, it is estimated that 16.5 million ha of land were developed for urban or transportation uses. By 2007, the United States had an estimated total of 45 million ha developed into urban uses. Of the newly developed land, 41 percent was previously forest land, 27 percent was cropland, 17 percent was pasture, and 13 percent was rangeland. In regard to land categories, 35 percent of the land in the United States that was developed into urban uses during the period of 1982 to 2007 was classified as prime farmland. Prime farmland is land that has the best combination of soil physical and chemical characteristics for producing food, feed, forage, fibre and oilseed crops and has the soil quality, growing season, and moisture supply needed to economically produce sustained high yields of crops when treated and managed at high levels. Prime farmland is also the most economically viable land to develop as it typically has the lowest degree of limitations for conversion into urban development. This increases the pressure on land with the best soil. Using the 2007 NRI information as a base, the trajectory of prime farmland (cropland portion) conversion and the loss of potential food production is immense over the next 25 years. With this rate of loss, the United States will lose the equivalent of 10M metric tonnes of corn in 2022 due to sealing/capping activities.

The drivers for soil sealing in Canada are very similar to those in the United States. The growth of metropolitan centers has been particularly rapid since the 1990s in areas surrounding Toronto, Kitchener-Waterloo, Ottawa, and Vancouver and, most recently, in areas surrounding urban centers in Saskatchewan and Alberta. Between 1996 and 2006, urban land increased by more than 10 percent nationally. It now totals nearly 0.13 million ha (Statistics Canada, 2009), or 0.25 percent of the total land area in Canada. Given land-cover data extrapolated from a suburban United States city (specifically, San Jose with 59 percent impervious surface by area (Xiao *et al.*, 2013) and the fact that suburbs now make up the majority of Canada's metropolitan population (Gordon and Janzen, 2013), it is estimated that more than 1 300 km^2 of soil was capped through urban expansion between the 1990s and 2000s. It is noteworthy that this expansion has occurred largely on highly productive soils (Francis *et al.*, 2012; Hofmann, Filoso and Schofield, 2005). Major interregional highway construction and expansion (e.g. highway twinning) have also been ongoing, particularly in Ontario, British Columbia, and Alberta. Total road length (in two lane equivalents) in Canada increased by more than 17 percent between 1990 and 2009 (Transport Canada, 2012; United States Department of Transportation, 2014), and, assuming a conservative average road width of 10 m, roads now cover more than 10 000 km^2. However, it is important to note that a portion of this impervious area is also included in the estimated urban area described above.

In the past few decades, areas used for agriculture and forest harvest have decreased (Natural Resources Canada, 2014; Francis *et al.*, 2012; Hofmann *et al.*, 2005). Thus, it is assumed that sealing as a result of new construction for agriculture service and forest industrial roads is relatively minor. The overall existing extent of unpaved roads in Canada that serve the needs of these industries is substantial.

14.3.5 | Soil compaction

Soil compaction is an acknowledged threat to the ability of the soil resource to provide a wide range of essential ecosystem services, including food and fibre production and maintenance of good water quality. Compaction decreases the water infiltration capacity of the soil, increases runoff and erosion, reduces plant growth, and reduces the penetration, size, and distribution of roots. It restricts water and air movement in the soil. It also causes nutrient stresses and slow seedling emergence. Soils in North America that are most susceptible to the threat of compaction are located in managed agricultural and forested regions.

The most common cause of soil compaction (or the formation of hardpans) is agricultural traffic, including tractors, harvesting equipment and implement wheels on moist soils where soil moisture is at or above field capacity. Wheeled traffic compacts soil aggregates, in some cases destroying the aggregates completely, which results in a dense soil with few large pores and limited aeration. Compaction can reduce yields up to 50 percent in some areas, depending upon the depth of compaction and its severity (Wolkowski and Lowery, 2008).

The type and condition of a soil have an effect on the potential of compaction to occur. Soils low in organic matter tend to be more susceptible to compaction because their ability to form strong aggregates is decreased. Soils high in clay content compact more easily because clay particles adhere to water, which makes it easier for them to move against each other. In the United States, Ultisols in the Coastal Southeast United States Coastal Plains ecozone are especially susceptible to compaction due to their highly weathered state and low organic carbon levels (Simoes *et al.*, 2009).

In Canada, there has not been a national-scale assessment of compaction since McBride, Joosse and Wall, (2000). Generally, fine-textured soils in the Mixed Wood Plains ecozone under cropping systems with a high potential for soil structure degradation and compaction (e.g. those for the production of maize, soybeans, vegetable and root crops) were judged to have the highest risk of compaction. In the period from 1981 to 1996, the area of fine-textured soils under high-risk cropping practices grew substantially (e.g. by as much as 61 percent in Ontario). This area expansion of potentially compaction-inducing cropping practices has continued to the present day. Agricultural soils in western Canada and the United States are generally believed to have a lower risk for soil compaction. The exception is irrigated soil in this region, where the wetter soil conditions can contribute to higher compaction levels. In addition, adoption of conservation tillage, which limits compaction, has also been lower on irrigated land.

Soil compaction also occurs in forestry operations throughout Canada and the United States, especially where roads and landings have been constructed. Generally, finer-textured soils are at the greatest risk, but the amount of organic matter in coarser textured soils can form a strong negative relationship with the potential for compaction (Krzic *et al.*, 2004). Compaction has been shown to reduce regeneration of species such as aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* [Moench] Voss) (Kabzems, 2012), but little is known about its general impact on soil functions.

14.3.6 | Waterlogging and wetlands

The threat of waterlogging to the sustainable use of soil resources is difficult to assess because waterlogging is not considered a threat in all cases. Wetland areas that are nearly or permanently waterlogged provide many positive benefits to the environment. Wetlands are some of the most biologically diverse habitats on earth and are of great benefit to many species of wildlife. They also act as a filter, trap sediments, improve water quality, are a carbon sink, and reduce peaks of floodwater runoff. Until 2014, the Wetland Reserve Program in the United States was a voluntary programme offered to landowners to protect, restore, and enhance wetlands on their property. Nearly 1 million ha has been enrolled in this programme (USDA, 2014).

Much of the drainage of wetlands in North America has been concentrated on freshwater mineral wetlands (Bridgham *et al.*, 2006), which are wetlands dominated by Gleysolic soils rather than organic soils. Bridgham *et al.* (2006) estimate that both the United States and Canada have experienced over 50 percent conversion of this class of wetlands (e.g. a reduction from 36 million ha to 16 million ha in Canada and from 76 million ha to 31 million ha in the United States).

In North America, the primary driver of large-scale waterlogging on non-wetland soils is flooding due to dam construction for hydroelectric power, to flood control measures and to mining activities (Maynard *et al.*, 2014). This includes both upstream flooding associated with dam construction and high spring water levels and downstream flooding associated with controlled releases during high-water periods and for hydroelectric power generation during the winter.

Another indirect driver is deforestation, which can reduce infiltration and/or evapotranspiration. It has been proposed that reduced evapotranspiration in northern Alberta contributes to a significant rise in the water table when deforestation is coupled with wet climatic periods (Carrera-Hernandez *et al.*, 2011).

Concern about waterlogging has been growing due to the substantial increase in the frequency and severity of extreme precipitation events in recent years in some regions (Brimelow *et al.*, 2014), even though this may not indicate an overall increase in mean annual precipitation for most regions. Waterlogging related to all of the above causes is exacerbated by increased precipitation.

14.4 | Major soil threats

Four threats to soil functions were selected as major threats and are covered in more detail in this section. The main criterion for their selection was the area of land affected by these threats – all four of these threats operate in most agricultural (and many non-agricultural) landscapes, whereas the threats covered in Section 14.3 tend to be more locally focused. Data on these four threats for Canada are covered in more detail in the case study in the following section (14.5). The present section focuses on North American-scale drivers and specific results for the United States of America.

14.4.1 | Soil erosion

Soil erosion in the United States and Canada accelerated after the arrival of European settlers, who cleared extensive areas for agriculture and subsequently ploughed and overgrazed the land (Montgomery, 2008). Soils rapidly degraded and erosion increased as settlement spread from east to west. In the United States, erosion was greatest on the east coast in the early 1800s, in the mid-south during the early 1900s, and in the Great Plains during the 'Dust Bowl' era in the 1930s. Some badly degraded lands were abandoned and then reverted to secondary growth forests, a process that slowed erosion rates. Wind erosion was very significant in Prairie Canada during the 1930s. Soils that were badly degraded due to wind erosion were subsequently stabilized and converted to permanent pasture.

Agricultural mechanization, commercial nitrogen availability, and federal policies encouraging maximum crop production led to cash-crop intensification throughout the middle of the 20th century in both the United States and Canada. Forage-based rotations were shortened or eliminated, field sizes were increased by the removal of hedgerows and fences, and tillage intensity remained high. As a result, the potential for soil erosion increased during this period. In the late 20th and early 21st centuries higher yielding varieties and improved herbicide technology supporting the adoption of conservation tillage helped reduce the potential for water and wind erosion. Federal farm programmes in the late 20th and early 21st centuries had both favourable and unfavourable impacts on soil erosion rates. In Canada, the most significant cropping change was the major reduction in summer fallow (e.g. the practice of leaving land fallow for one growing season and suppressing weed growth by one or more tillage events) in the two Prairie ecoregions in Canada. This change substantially reduced the risk of wind erosion.

In the United States, the National Resources Inventory (NRI) has reported statistically robust estimates of water (sheet and rill) erosion and wind erosion on privately owned cropland, since 1982 at five year intervals (USDA, 2013a), based on a wide monitoring network and an assumed historic average climate for each location. The estimated decrease in sheet and rill erosion between 1982 and 2002 was 39 percent, and that between 1982 and 2010 was 41 percent. In the same periods, wind erosion decreased by 41 percent and 46 percent, respectively.

In 2010, the most intense sheet and rill erosion was in the Temperate Prairie and Mixed Wood Plains ecoregions of the Midwest United States, in the adjacent area of the South-eastern United States Plains ecoregion and in the Palouse (Cold Desert ecoregions in the state of Washington). These areas and the West-Central Semi-Arid Prairies ecoregion also had the highest wind erosion rates.

If 2010 NRI estimates of sheet and rill erosion plus wind erosion are averaged across all United States cropland, the average annual rate is about 10 Mg ha^{-1}, and 57 percent of this is due to sheet and rill erosion (USDA, 2013a). Tolerable annual soil erosion rates ('T') used in the United States typically range from 2 to 11 Mg ha^{-1}, depending upon the soil type. The criteria used to calculate T have been widely criticized (Johnson, 1987) and the overall average soil loss rate is one order of magnitude greater than estimated soil renewal rates, which are less than 1 Mg ha^{-1} per year (Alexander, 1988; Montgomery, 2007). In addition, erosion varies spatially and may greatly exceed T at any specific NRI point, due to the soil, slope, management and climate at that location.

The state of soil erosion in Canada and the drivers of change are covered in more detail in Section 14.5 of this chapter. Soil erosion on undisturbed forested land in Canada is generally believed to be low (Maynard *et al.*, 2014) and no national estimates exist for rates of erosion on disturbed forest land.

Not all forms of erosion are considered in the national estimates and this leads to considerable overall uncertainty in estimates. In the United States, the NRI erosion assessment does not include ephemeral gully or tillage erosion. Tillage erosion is within-field soil redistribution by tillage implements, which has been extensively documented in both the United States and Canada. Both of these processes may result in degradation rates comparable to those from wind and water erosion. The best estimate of soil erosion rates must include estimates of these processes. When these two processes are included, average United States cropland soil erosion rates exceed published soil development rates by more than one order of magnitude. In the future, an increased frequency of extreme rainfall events due to climate change will likely increase the water soil erosion threat in many parts of the United States and Canada.

In Canada, the national Agri-Environmental Indicators programme does include an assessment of tillage erosion, which is known to be of equal or greater significance than wind and water erosion on some landscapes. Gully erosion is not included in the Canadian monitoring system, but its incidence in Canada is believed to be limited. Although accelerated erosion associated with forest harvest is a concern, there are no recent national-level surveys of its incidence in Canada.

14.4.2 | Nutrient imbalance

Many regions of North America have experienced and continue to experience nutrient applications in excess of plant requirements. These surpluses lead to elevated levels of N and P in soils, which cause a range of environmental problems and are a source of considerable societal concern throughout North America.

The greatest issue with nutrient imbalance in North America is the impact of elevated N and P levels in soil from past and present agricultural activities on water quality. The linkage of elevated soil N and P levels to water quality problems ranges from algal blooms due to eutrophication in Lake Winnipeg in Manitoba (Schindler, Hecky and McCullough, 2012), at the northern edge of the agricultural zone, to the seasonal hypoxia in the shallow coastal waters of the Louisiana shelf in the northern Gulf of Mexico, at the southern end of the agricultural zone (Alexander *et al.*, 2008).

Estimates on excess nutrient levels presented by Foley *et al*. (2010, Supplementary Information Maps S6e and S6f) show that excess application of N continues in many regions of North America whereas little excess application of P occurs. Excess N application of between 60 to 100 kg ha^{-1} occurs in much of the Temperate Prairie and Mixed Wood Plains ecoregions in both the United States and Canada, throughout the Mississippi River valley, and in pockets in the Southeast United States Coastal Plains ecoregion. Hence over-application of N is an on-going issue whereas elevated P levels may be largely due to historical over-application.

The linkage between agricultural practices and N and P loads in waterways has been shown by many studies. For example, recent studies on the Missouri River (Brown, Sprague and Dupree 2011) and the entire Mississippi River basin (Alexander *et al.*, 2008) using the Spatially Referenced Regressions On Watershed Attributes (SPARROW) model by United States Geological Survey (2014) researchers found that the majority of both total N and total P in these waterways is from agricultural land. Specifically, 52 percent of total N reaching the Gulf of Mexico was from maize-and soybean-producing land with a further 14 percent from all other crops in the basin. Some 37 percent of total P was from rangeland/pasture land with a further 25 percent from maize- and soybean-producing land. Considerable regional variations occur. For example, in the western sections of the Missouri River basin where cattle grazing is the dominant land use, as much as 34 percent of total N was from manure whereas in the Mississippi River basin as a whole, only 5 percent of total N was from rangeland and pasture land.

The relationship between soil properties, management, and particular N and P fractions is complex (Sharpley and Wang, 2014; Harmel *et al.*, 2006). Harmel *et al.* (2006) examined the relationship between soil and site attributes and N and P fractions in nutrient loads from watersheds in 15 United States states and two provinces of Canada. Particulate N and P loss contributed, on average, three times as much as dissolved forms to loads, indicating the overriding effect of soil erosion and transport on N and P loads. Median particulate N loads were greater in areas of conventional tillage (which experience higher erosion rates on average) and lower in areas of conservation tillage and no-till land, although no differences were observed for particulate P. There was a weak relationship between soil test P and all forms of P load, again indicating the importance of existing or legacy soil P content. Dissolved N and P loads were highest in areas of no-till land. The build-up of P at the soil surface in no-till systems was also implicated in the increase since 1995 of dissolved P load in the Maumee River system (which drains into Lake Erie), although the response of this system to management changes was very complex (Sharpley and Wang, 2014).

Excess soil nitrogen can also leach from the soil as nitrate. This threat is most severe in situations where shallow aquifers are used as potable water sources in humid or sub-humid climates with coarse-textured soils utilized for intensive agricultural production. Examples in Canada include Prince Edward Island, the Abbotsford aquifer, BC and Kings County, Nova Scotia. The indicator of risk of water contamination by nitrogen (IROWC-N) in the Canadian Agri-Environmental Indicators doubled from ~5 mg N L^{-1} in 1981 to a value approaching the Canadian drinking water guideline for nitrate (10 mg N L^{-1}) in 2006 in the Atlantic Highlands and in the Canadian portions of the Mixed Wood Highlands (AAFC, 2013).

Country-specific information for nutrient imbalance in Canada is given in Section 14.5 of this report.

N levels in excess of plant requirements in soils are also linked to other environmental issues, especially the enhanced release of the potent greenhouse gas, N_2O, from soils. In both Canada and the United States, agriculture accounts for 6 to 7 percent of total GHG emissions (EPA, 2014b; Environment Canada, 2013b). Emissions of N_2O from agricultural soils account for 75 percent of the agricultural total in the United States and 65 percent in Canada. The highest N_2O emissions occur under anaerobic conditions and hence are intimately linked to changes in waterlogging in agricultural landscapes. Health concerns are also linked to forms of N in groundwater and fertilizer application, although the direct link to human health can be difficult to ascertain (Manassaram, Backer and Moll, 2006).

14.4.3 | Soil organic carbon change

Assessment of soil organic carbon (SOC) in the United States and Canada currently includes a number of approaches aimed at either directly measuring or modelling SOC change over time. Both countries utilize national-scale modelling of SOC change for GHG emissions inventories and reporting.

Models of SOC changes currently show increases in the United States. These increases in SOC are primarily due to less intensive agriculture (McLauchlan, Hobbie and Post, 2006) and reduced tillage intensity (West *et al.*, 2008). Models generally predict that converting areas from native vegetation (e.g. prairies and native forest) to cropland and forest plantations results in decreased SOM; however, in some cases, high-productivity crops and SOC-conserving management may enhance SOC. For instance, Ogle *et al.* (2010) estimated that SOC in United States croplands increased by 14.6 and 17.5 Tg yr^{-1} during 1990-1995 and 1995-2000, respectively, primarily due to reductions in tillage intensity.

For agricultural soils in Canada, national-level modelling indicates that improvements in farm management have resulted in a dramatic shift from stable SOC levels (e.g. additions are equal to losses) during the mid-1980s, to a situation where the majority of cropland had increasing SOC levels in the mid-1990s through to 2011 (discussed in more detail in Section 14.5 of this chapter).

There is currently high uncertainty associated with SOC models (Ogle *et al.*, 2010) such as CENTURY (National Resource Ecology Laboratory, 2007), the SOC model most commonly used in the United States and Canada to predict SOC change. Improving model parameterization and adding additional SOC measurements over time could help reduce uncertainty. This information could be used to better calibrate, estimate and potentially reduce model uncertainty as well as to directly track SOC change (Jandl *et al.*, 2014). National-level modelling is also limited by the lack of data on SOC stocks and change deeper in the soil profile. Models and researchers generally consider subsurface SOC as a relatively stable pool. Little direct evidence has been provided, however, that SOC stabilized under previous conditions will remain stable with changing conditions, such as with climate change. Some studies have shown that previously stable SOC may be rapidly converted to CO_2 (Fontaine *et al.*, 2007; Fang *et al.*, 2005).

There are currently two major United States-wide efforts that sample soil over time, the Forest Inventory and Analysis (FIA) by Gillespie, 1999, covering United States forests, and the Rapid C assessment (USDA, 2013b), which includes all vegetated areas. The FIA samples soil to a maximum depth of 20 cm, so its utility in monitoring whole-profile SOC over time is limited (Waltman *et al.*, 2010; Jandl *et al.*, 2014). The Rapid C assessment (USDA, 2013b) samples soil profiles to 100 cm depth. It is currently uncertain what depth is required to truly understand SOC and potential changes in SOC (Harrison, Footen and Strahm, 2011). Some studies have shown that results of monitoring SOC change vs. land management depend more on maximum soil sampling depth than on treatments (Liebig *et al.*, 2005; Khan *et al.*, 2007; Harrison, Footen and Strahm, 2011).

Field data on losses of SOC in Canadian soils after conversion from native land to cropland, and for different tillage, crop rotation and fertilizer management practices were compiled from a total of 62 studies by VandenBygaart *et al.* (2003). They demonstrated that 24 ± 6 percent of the SOC was lost after native land was converted to agricultural land. In the past two decades, no-till (NT) increased the storage of SOC in Mollisols (Chernozems) of the two Prairie ecoregions by 2.9 ± 1.3 Mg ha–1; however, in the moister soils of central and eastern Canada, conversion to NT did not increase SOC. More recent studies using meta-analyses (Congreves *et al.*, 2014) of long-term agricultural management effects on SOC in Ontario indicate trends towards higher SOC with NT than under conventional tillage practises. Crop rotation was found to lead to higher SOC than when continuous maize was grown, and the application of N fertilizer led to an increase in SOC compared to when no N fertilizer was applied.

Carbon change in managed forests (232 million ha) in Canada is assessed as part of the National Inventory, primarily using the CBM-CFS model (Kurz *et al.*, 2009). Carbon emissions from the dead organic matter and soil pools are lumped together. Results showed a small increase in emissions from 2000-2007 due to the short-term effect of past disturbances, especially insect infestation. However, the values decreased from 2008 until 2012 and have returned to long-term levels. Freshwater mineral wetland soils in the Prairie ecoregions are also important carbon reservoirs, and approximately 70 percent of these were impacted by agricultural activities in 2005 (Bartzen *et al.*, 2010); however there is no regional estimate of associated carbon change.

Permafrost soils are classified as Cryosols in Canada and cover 2.5 million km^2; they are estimated to contain 39 percent of all organic carbon in Canadian soils (Tarnocai and Bockheim, 2011). The greatest driver of change in these soils is climate change. The IPCC 5^{th} Assessment Report (Clais *et al.*, 2013) states that there is high confidence that reductions in permafrost due to warming will cause thawing of some currently frozen carbon, but there is low confidence on the magnitude of CO_2 and CH_4 emissions to the atmosphere due to the complexity of the biogeochemical processes involved.

14.4.4 | Soil biodiversity

Soil biodiversity refers to the myriad of organisms living in the soil, ranging from the smallest microorganisms (e.g. bacteria, archaea and fungi) to soil invertebrates. Up until the advent of molecular biology and its use in soil science in the 1990s, the assessment of soil biodiversity was done using morphological methods. Methods to study soil biodiversity are improving constantly with the application of sequencing technologies, complementing the morphological assessments.

As a result of our paucity of knowledge, assessing threats to soil biodiversity is very difficult. There is no reference baseline data for these organisms, nor do scientists have the ability to estimate the true numbers of soil organisms, particularly microorganisms. Many organisms have not been described and overall we need a better understanding of the biogeography of soil organisms in North America (Nunez and Dickie, 2014). Advances, however, have been made. For example, Taylor *et al.* (2014) completed a comprehensive survey of fungi in black spruce (*Picea mariana*) sites in Alaska and recorded 1 002 taxa in this system. They reported a fungus: plant ratio of 17:1.

However, as soil organisms are so intricately tied to aboveground plant species, threats to plant species such as habitat loss are also liable to affect soil organisms (Wardle *et al.*, 2004). Evidence of this exists. For example, it has been shown that removal of logging residues from harvested forest sites is one of the major threats to forest fungi and insects (Berch, Morris and Malcolm, 2011). Similarly, invasive plant species and their mutualistic microbes pose a threat to native mutualist communities (Nunez and Dickie, 2014). Invasive alien species are entering North America with increasing frequency due to the growing volume of trade, the broadening of trading partners, and the increases in travel and tourism that accompany globalization (Environment Canada, 2013a).

Regional or national-level programmes that monitor soil biodiversity are lacking in North America. In Europe, Gardi *et al.* (2013) used modelling of data from 20 experts to demonstrate that the main pressures on soil biodiversity were intensive land exploitation (such as agriculture intensification using tillage, crop rotations, and additions of pesticides and herbicides) and changes in land use (such as the reduction in forests that have the highest soil biodiversity and the increase in soil sealing) combined with decreasing amounts of soil organic matter and increasing numbers of invasive species.

These modelling results are increasingly being supported by field studies using emerging identification and community analysis techniques. Crowther *et al.* (2014) assessed deforestation effects on soil biodiversity at eleven sites in the United States and found that forest removal was generally associated with reductions in fungal and bacterial microbial biomass and increases in diversity of taxa. The magnitude of differences due to deforestation varied drastically between sites and was best explained by differences in soil texture: the effects were greatest in coarse-textured soils and least in fine-textured soils. Crowther *et al.* (2014) suggest that the relationship between soil biodiversity and soil texture offers the potential for mapping regional and national patterns of the susceptibility of total (fungal, bacterial, and archaeal) soil biomass to changes in vegetation (see Figure 4 in Crowther *et al.*, 2014). Studies based on a meta-analysis of crop rotation found that adding one or more crops in rotation increased microbial biomass carbon by 20.7 percent and microbial biomass nitrogen by 26.1 percent, indicating the sensitivity of soil microbes to the quantity and biochemistry of crop inputs (McDaniel, Tiemann and Grandy, 2014). Other studies, such as those by Wagg *et al.* (2014), are explicitly examining the relationship between decreasing biodiversity in the soil community and changes in ecosystem functions, such as carbon sequestration and nitrogen and phosphorus leaching.

In addition, climate change is considered a threat to soil biodiversity. Unfortunately, there is a scarcity of data on this issue. To determine this threat we need to predict soil biodiversity patterns, which is not possible with our current knowledge. However, there are indications that soil biodiversity will be reduced by climate change. Studies in the Canadian Arctic show that extreme ecosystems contain many unique organisms that may become extinct with permafrost melting (Vincent *et al.*, 2009). Wildfire events, which are another threat to soil biodiversity, are also predicted to increase because of climate change (Krawchuk *et al.*, 2009).

At present, no national or regional assessment on loss of biodiversity can be made for North America, but there are signs that such an assessment may be possible in the future. The Global Soil Biodiversity Initiative (GSBI) was launched in 2011 and provides a welcome platform for the coordination of research in this area (GSBI, 2014).

14.5 | Case study: Canada

As discussed in the Introduction (14.1), there are no existing regional maps for threats to soil functions for North America. In this section the maps produced under the Canadian Agri-Environmental Indicators programme (Clearwater *et al.*, 2015) for wind and water erosion, SOC change and nutrient imbalance (residual soil N and P-source risk classes) are presented so that the linkage between drivers and threats to soil functions can be illustrated. The maps focus on agricultural impacts on soil functions. No comparable products exist for other soil threats.

The major changes to drivers in Canada have been discussed in detail in Section 14.3 above. There are distinct differences across the main ecoregions of Canada that experience concentrated human impact. The main drivers can be summarized as:

- Intensification of agriculture e.g. reduced pasture area, increased area of maize and soybean production, higher fertilizer inputs in the Mixed Wood Plains ecoregion in southern Ontario and Quebec and in the agricultural areas of eastern Canada e.g. in New Brunswick, Nova Scotia, and Prince Edward Island.
- Significant reductions in the area of tillage summerfallow in the Temperate Plains and West-Central Semi-Arid ecoregions.
- Widespread adoption of conservation tillage practices in most cropping systems in Canada.

14.5.1 | Water and wind erosion

In Canada, the Soil Erosion Risk Indicator was used as part of the Agri-Environmental Indicators programme to assess the risk of soil erosion from the combined effects of wind, water and tillage on cultivated agricultural lands (Figure 14.5). This indicator and its component indicators for wind, water and tillage erosion reflect the characteristics of the climate, soil and topography and correspond to changes in farming practices over the 30-year period from 1981 to 2011. Wind and water erosion are the primary focus of this summary. For details on calculation of the indicators, see Li *et al.* (2008), McConkey, Li and Black, (2008), and Huang and Lobb (2013).

The erosion indicator calculation estimates the rate of soil loss. These values are reported in five classes. Areas in the very low risk class are considered capable of sustaining long-term crop production and maintaining agri-environmental health under current conditions. The other four classes represent the degrees of risk of unsustainable conditions that call for soil conservation practices to support crop production over the long term and to reduce risk to soil quality.

The risk of soil erosion on Canadian cropland has steadily declined between 1981 and 2011. The majority of this change occurred between 1991 and 2006. In 2011, 61 percent of cropland area was in the very low risk class overall, a considerable improvement over 1981 when only 29 percent was in this risk class. This decrease in water and wind erosion risk was most pronounced in the Temperate Prairie and West-Central Semi-Arid ecoregions in Alberta and Saskatchewan (Figure 14.5 and 14.6). Much of the improvement in erosion risk is from reductions due to the reduction in tillage summer fallow. A second driver is the increased adoption of direct seeding and conservation tillage, which is largely responsible for the decrease in tillage intensity and soil erosion.

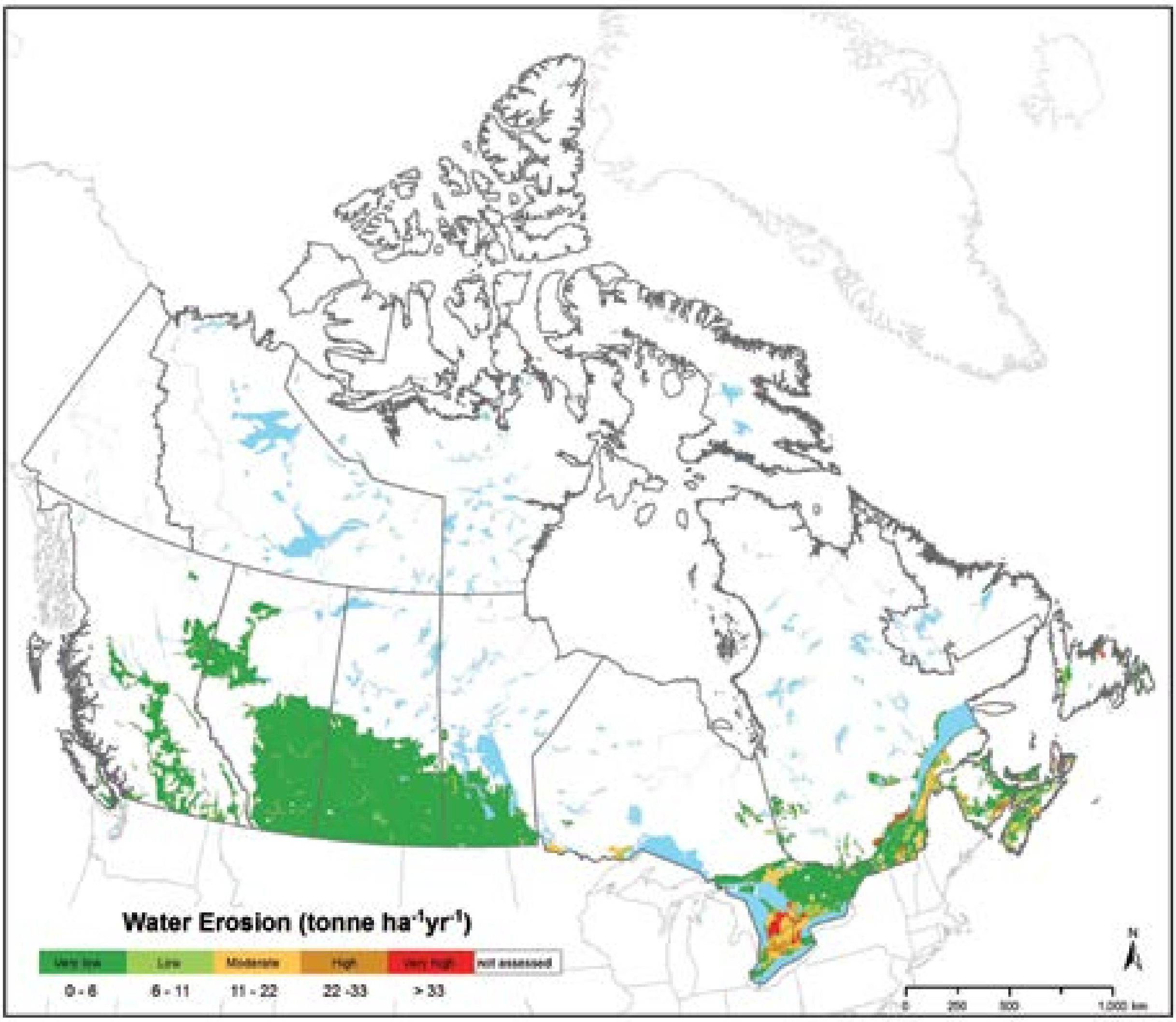

Figure 14.5 | Risk of water erosion in Canada 2011.
Source:Clearwater et al., 2015.

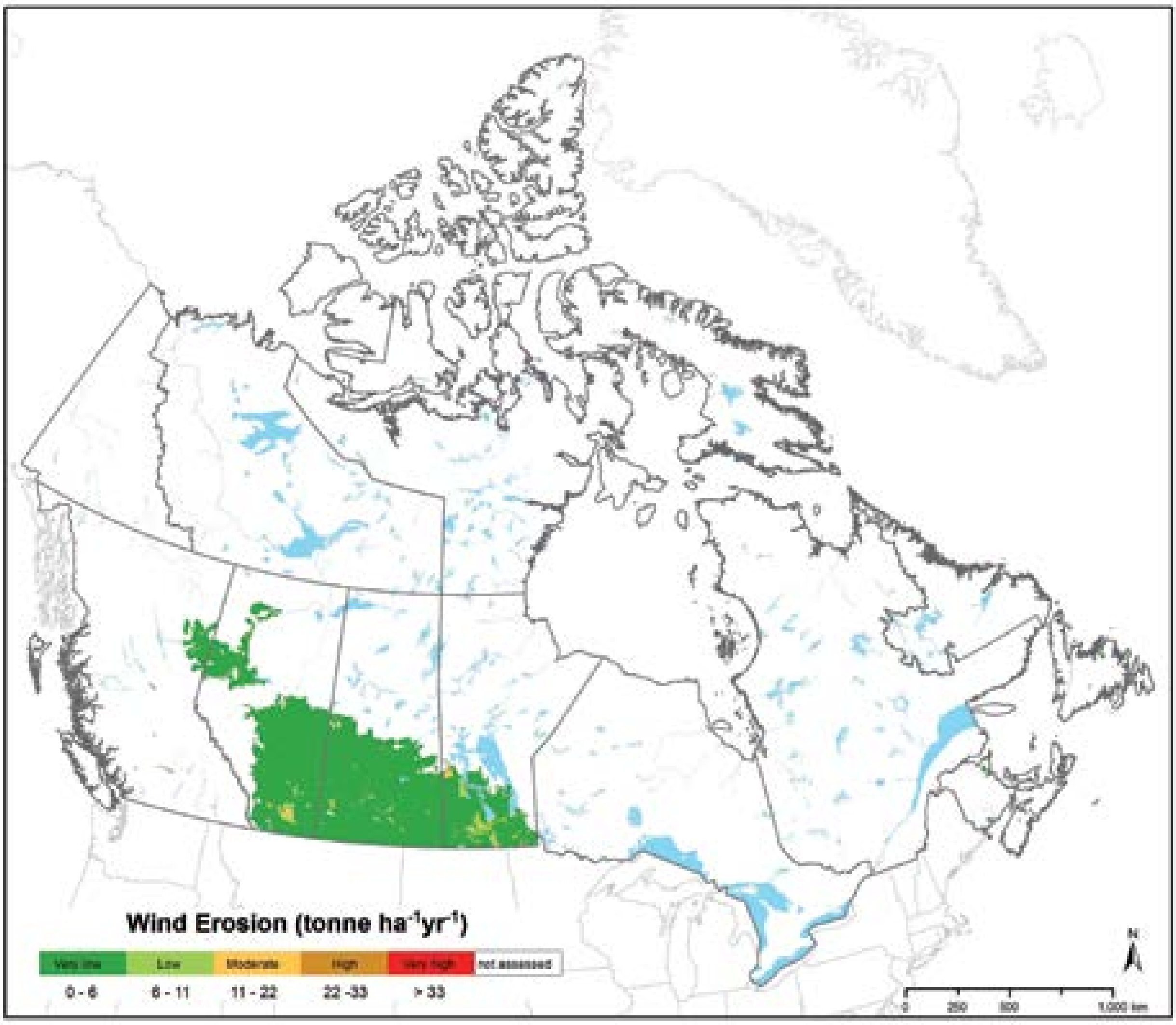

Figure 14.6 | Risk of wind erosion in Canada 2011.
Source: Clearwater et al., 2015.

Of the cropping systems across Canada, the risk of soil erosion by water is greatest under potato production in central and eastern Canada. In these areas there is intensive tillage and little opportunity to reduce the intensity through conservation tillage practices (Figure 14.5). The cropping system with the next greatest risk of erosion is the production of maize and soybeans under conventional tillage; however, there is a significant opportunity to reduce this erosion risk with conservation tillage. Of all soil landscapes across Canada, the risk of soil erosion by water is greatest in areas with maximum slopes of 10 percent or more, especially those located in central and eastern Canada where the risk of water erosion is inherently high due to climate (Figure 14.5).

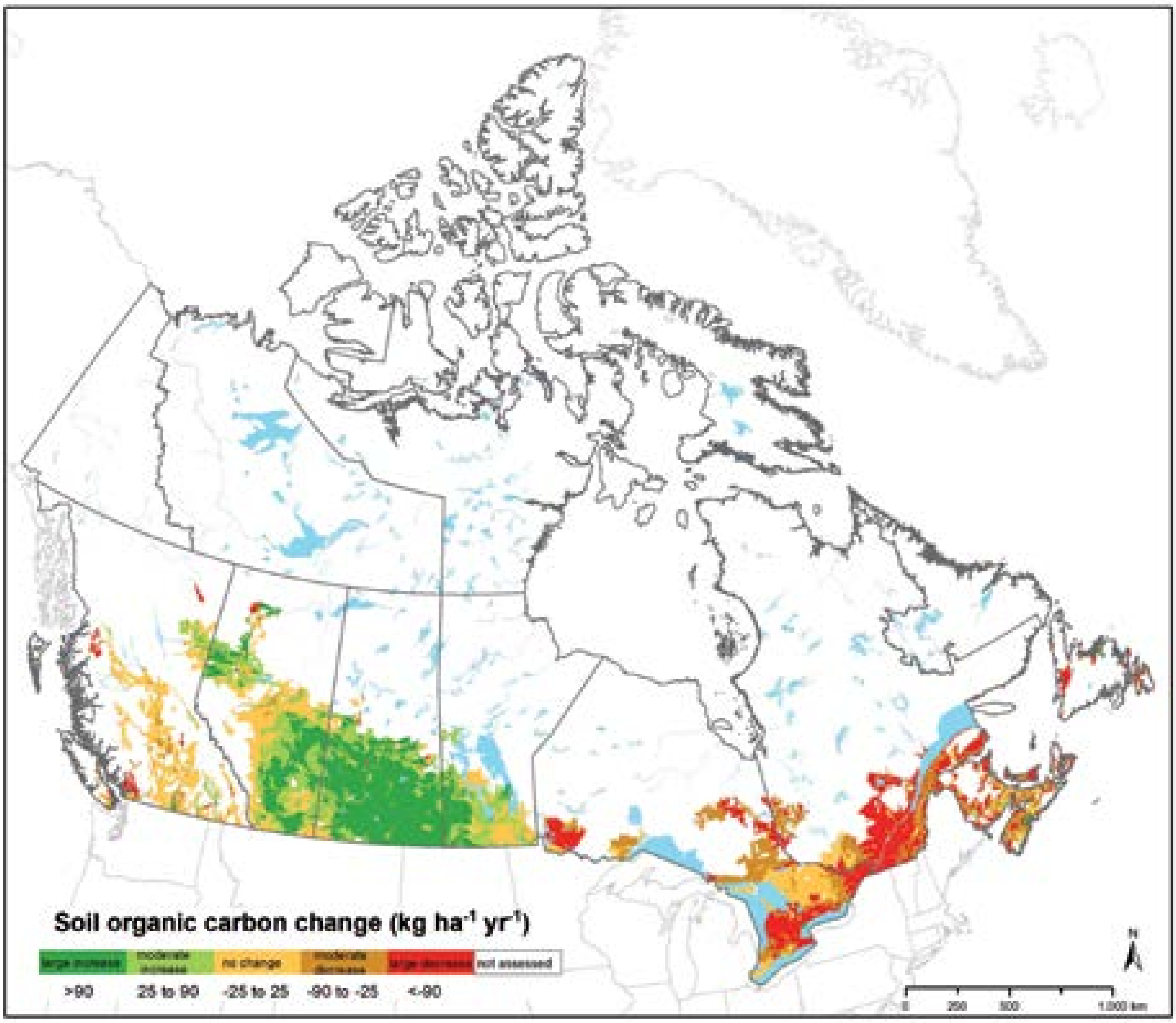

Figure 14.7 | Soil organic carbon change in Canada 201.
Source: Clearwater et al., 2015.

14.5.2 | Soil organic carbon change

The soil organic carbon (SOC) change indicator used in the national Agri-Environmental Indicators programme assesses how organic C levels are changing over time in Canadian agricultural soils. The indicator is based on the method used for the Canadian National Inventory Report (Environment Canada, 2014). The indicator uses the Century model (NREL, 2007) to predict the rate of change of organic C content in Canada's agricultural soils due to the effects of land management change since 1951. These include changes in tillage and summer fallow frequency, and change between annual crops and perennial hay or pasture. It includes land use changes such as clearing forests for agriculture or breaking native grass for cropland, but does not include the loss of C from the above-ground forest biomass.

No changes in SOC were assumed if there were no indicated changes in land use or land management. The SOC change indicator does not consider soil erosion.

The SOC change indicator results are presented (Figure 14.7) as the percentage of total cropland that falls into each of five SOC change classes expressed in kilograms per ha per year (kg ha^{-1} yr^{-1}). Negative values represent a loss of SOC from the soil and positive values represent a gain of SOC.

For the Boreal Plains ecoregions from Ontario eastward, there was an overall loss of SOC from 1981 to 2011 due to the reduction in the area of hayland and pasture and the corresponding increase in the area of annual crops (Figure 14.7). This shift in land use reflects a reduction in the demand for feed associated with the declining cattle populations in those provinces. The losses in Ontario and Quebec have been offset to a limited degree as a result of the adoption of conservation tillage. However, conservation tillage has not been implemented to the same extent in provinces in eastern Canada due to their cooler and wetter climatic conditions.

The two agricultural ecoregions in the Prairie provinces have seen major increases in SOC over time due to reductions in tillage intensity and in summer fallow. These changes are responsible for the overall net gain in SOC in Canada (see Section 14.4.3 above).

14.5.4 | Nutrient imbalance

The assessment of nutrient imbalance in the Agri-Environmental Indicators programme focuses on N and P, and assesses both the N and P status of soils and the risk to water quality associated with the soil stores. The risk to water quality involves coupling hydrological and climate data with the land surface information for each region. This section focuses on the N and P status of soils.

The residual soil nitrogen (RSN) indicator used in the National Agri-Environmental Indicators program provides an estimate of the amount of inorganic N that is left in the soil at the end of the growing season which may be susceptible to loss (Drury *et al.*, 2007, 2010). The RSN indicator is estimated as the yearly difference between the total N input to agricultural soils and the output in harvested crops and gaseous losses including ammonia, nitrous oxide and dinitrogen. The major categories of N inputs into soil include fertilizer addition, manure application, biological nitrogen fixation by leguminous crops and free-living bacteria, and atmospheric wet and dry deposition. Nitrogen outputs include N removal in the harvested crop and gaseous N emissions via ammonia volatilization (NH_3), nitrification (N_2O) and denitrification (N_2O, N_2).

The RSN on Canadian agricultural land has steadily increased from a low of 9.4 kg N ha^{-1} in 1981 to a maximum of 25.3 kg N ha^{-1} in 2001 (a year where many regions experienced drought conditions and were unable to use the applied N). The latest figure is 23.6 kg N ha^{-1} in 2011, the most recent census year. On a national basis, N inputs have almost doubled over the 30 years from 44.4 kg N ha^{-1} to 80.8 kg N ha^{-1} whereas N outputs have only increased by 63 percent from 35 kg N ha^{-1} in 1981 to 57.2 kg N ha^{-1} in 2011.

The RSN map (Figure 14.8) for Canadian farmland in 2011 generally shows that there are high or very high residual N contents in farmland in many areas across Canada. Considerable change has occurred since 1981; for example, the Temperate Prairies in Manitoba were primarily in the very low and low risk classes in 1981 whereas the great majority of the province is now in a very high risk class in 2011 (Figure 4.4). The Mixed Wood Plains in central and eastern Canada are also currently predominantly in the very high risk group, which again a considerable increase since 1981.

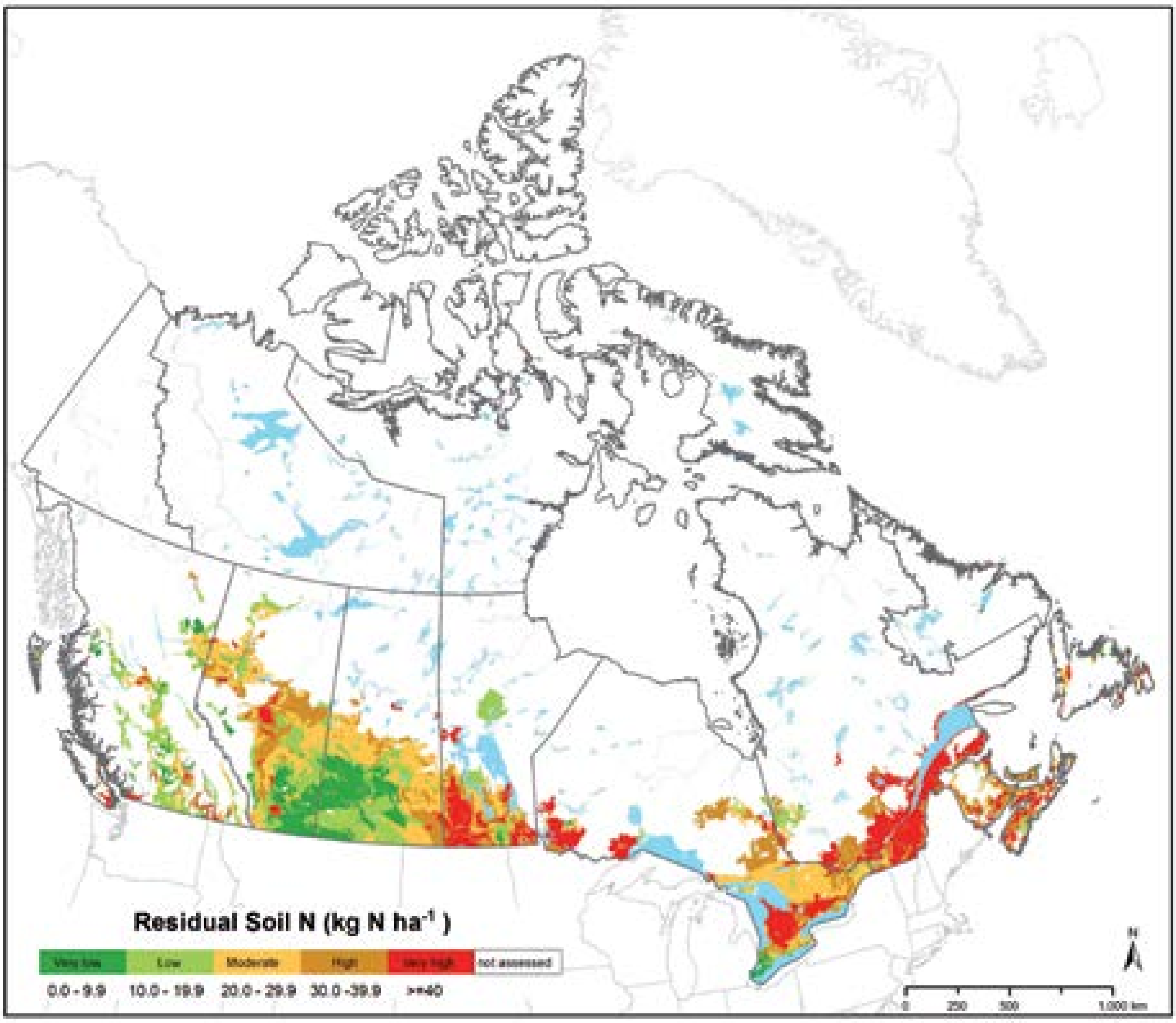

Figure 14.8 | Residual soil N in Canada 2011.
Source: Clearwater et al., 2015.

Changes to management practices are required especially in the more humid regions in the Canada (notably Ontario, Quebec and eastern Canada) to reduce N losses from soils, to increase fertilizer use efficiency and to better synchronize N application with crop N demand. Further, the use of cover crops, especially in years with reduced yields, may help to reduce N losses from soil.

The IROWC-P Indicator was developed to assess the status and trends over time for the risk of surface water contamination by P from Canadian agricultural land and is reported for agricultural watersheds (van Bochove *et al.*, 2010). The initial stage in calculating IROWC-P involves the estimation of the annual amount of dissolved P that may potentially be released from agricultural soils (P source). P source is estimated as a function of cumulative P additions and removals (P-balance) over a 35-year period up to 2011 and the resulting degree of soil P saturation.

There has generally been an increasing trend in the P-source levels in the surface of agricultural soils in Canada since 1976 as intensified agricultural practices have resulted in the application of P in excess of crop uptake (also called positive annual P balance) and have therefore increased soil P saturation. In 2011, very high concentrations of P (more than 4 mg of P per kg, or >4 mg P kg^{-1}) at risk for release by storm events were located in regions where the agricultural production has been historically intensive and where soils have reached high P saturation values. High risk of water- contamination by P occurs around Abbotsford, British Columbia in the Marine West Coast Forest ecoregions, in the Temperate Prairies around Lethbridge in Alberta, and in portions of southern Saskatchewan and Manitoba (Figure 14.9). Intensive livestock operations near Abbotsford and

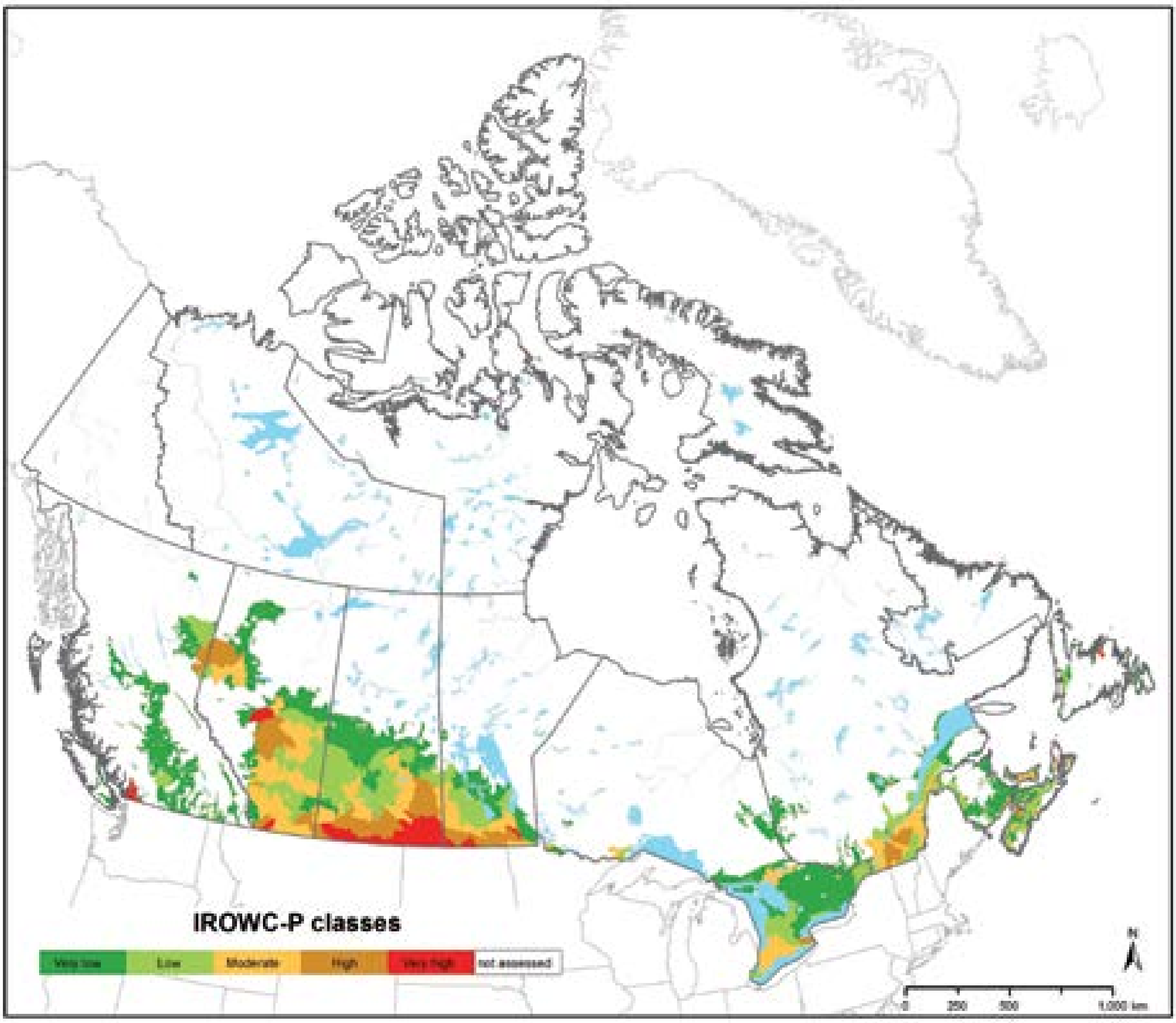

Figure 14.9 | Indicator of risk of water contamination by phosphorus (IROWC-P) in Canada in 2011.
Source: Clearwater et al., 2015.

Lethbridge are major local sources of high P loadings. The Mixed Wood Shield ecoregion of central Ontario and the Mixed Wood Plains ecoregion in Quebec, New Brunswick and Prince Edward Island are also dominated by very high or high P source risk.

Implications of soil threats for soil functions

Clearly the national assessment of the threats to soil functions shows a distinct separation between the agricultural systems of the Prairie provinces and those of Ontario, Quebec, and Atlantic Canada. Both the state and the trend of soil change in the Prairie provinces are generally positive, especially in soil erosion (notably wind erosion) and carbon change. The greatest risk in this region lies in the high residual nutrient levels in areas like Manitoba and in the possible contribution of these high residual levels to eutrophication in lakes in this region (Schindler, Hecky and McCullough, 2012).

The level of the threats in the Mixed Wood Plains of central and eastern Canada is very different. There are generally high or very high levels of threat for soil organic carbon change, erosion by water, and nutrient imbalance. The well-integrated drainage system and higher precipitation levels than in the Prairie provinces lead to significant sediment and nutrient delivery to waterways. There is thus a risk of serious impact of agricultural land management on water quality (Clearwater *et al.*, 2015). The combined effects of soil organic carbon loss and water erosion presumably also reduce services and products delivered by the soil, but these have been poorly documented in this region.

14.6 | Conclusions and recommendations

Overall there has been significant progress made in reducing threats to soil functions in North America. Threats from acidification and contamination have been reduced due to the imposition of a stronger regulatory framework. The greatest change in cropping practices - reduced tillage - has largely come about through adoption by individual producers supported by government and private sector extension agents.

However, major areas of concern remain. Erosion rates are still above what are believed to be tolerable levels in the Temperate Prairies ecoregion of the United States and throughout the Mixed Wood Plains ecoregion of Canada and the United States. Transport of soil-derived N and P to waterways is a major problem, and excess application of N continues throughout much of the cropland in the United States and in central and eastern Canada.

Although a wide variety of best management practices for optimum nutrient application and erosion control have been developed and promoted, the problems of erosion and nutrient imbalance persist.

Salinization, contamination, and acidification affect smaller areas in North America, and in the case of the latter two threats the current regulatory framework limits the expansion of the affected area. Waterlogging is little studied in North America, and we recommend that future reports include assessments of loss of wetlands as an important metric for sustainable management in this and other regions.

The loss of agricultural land to soil sealing is not perceived as a major issue in North America. However, the paucity of data on this threat needs to be addressed for a more informed assessment to be made.

Changes in carbon stocks in North America have been extensively modeled as part of national reporting programs on greenhouse gas emissions, but only in a few landscapes are the models adequately supported by field observations of SOC change. The greatest uncertainty surrounding SOC change lies in the response of carbon in permafrost soils to climate change in northern Canada and Alaska and improved monitoring of this response is essential.

Like the SOC models, the agri-environmental indicators approach used in the Canadian case study allows estimation of the change in threats to soil function over time. However, several criticisms can be made of the approach. First, there is a lack of ongoing monitoring of important soil physical, chemical and biological properties at relevant scales through time and hence it is difficult to assess the performance of the models that underlie the indicators. Second, the interaction between indicators (for example, between erosion and carbon) is not considered, and this can bias the assessment of soil change. Third, it is difficult to assess the variability associated with modelled results and therefore to evaluate overall the confidence that can be placed in the results. Overall there is a need to revise the models in light of new scientific advances and to develop and refine scientifically credible programs to assess model performance.

The greatest uncertainty overall in our knowledge about the threats to soil functions lies in our limited understanding of the changes in soil biodiversity in the past and present and the implications of these changes for sustainable soil management.

Based on the above finding, a provisional assessment is made of the status and trend of the 10 soil threats in order of importance for the region. At the same time an indication is given of the reliability of these estimates (Table 14.1)

Stable = | Variable ↗↙ | Improving ↗ | Deteriorating ↙ | Evidence and consensus is **low** | Evidence and consensus are **limited** | **Adequate** high-quality evidence and **high level** of consensus

Table 14.1 | Summary of soil threats status, trends and uncertainties in North America

Threat to soil function	Summary	Condition and Trend					Confidence	
		Very poor	Poor	Fair	Good	Very good	In condition	In trend
Soil erosion	Reduced tillage and improved residue management have lowered erosion rates in regions such as the Great Plains in Canada but water erosion rates continue to be too high in the northern Mid-West of the U.S. and agricultural areas of central and Atlantic Canada.			↗			Adequate high-quality evidence and high level of consensus	Adequate high-quality evidence and high level of consensus
Nutrient imbalance	Excess application of fertilizers in many regions causes significant degradation of surface water quality and increased emissions of nitrous oxide to the atmosphere. Contamination of surface water is strongly linked to high erosion rates, and occurs in the same regions (northern mid- west U.S., Mississippi River Basin, and agricultural regions of central Canada).		↙				Evidence and consensus are limited	Evidence and consensus are limited
Organic carbon change	The majority of cropland in the U.S. and Canada has shown improvements in SOC stores due to the wide-spread adoption of conservation agriculture (i.e., reduced tillage and improved reside management). There is a lack of field validation sites to support the national-level modelling results. Loss of SOC from northern and Arctic soils due to climate change is a major concern.			↗			Evidence and consensus are limited	Evidence and consensus are limited

Loss of soil biodiversity	The extent of loss of soil biodiversity due to human impact is largely unknown in North America. The effects of increasing agricultural chemical use, especially pesticides, use on biodiversity is a major public concern. Known level of carbon loss suggests similar loss in biodiversity.			↗↙				
Compaction	Compaction continues to be a low-level issue, especially in regions with texture-contrast (Luvisol, Alfisol, Ultsol) soils. The regional-scale impact of compaction on plant growth is largely unknown.			=				
Sealing and land take	Substantial expansion of housing and infrastructure in areas of high quality farmland continues in both countries but is (incorrectly) not perceived as a concern. Neither country has reliable data on sealing and land take.			↙				
Salinization and sodification	Salinization is believed to be increasing in parts of the northern Great Plains in the U.S.A. but the risk of salinization is decreasing in western Canada.			↗↙				
Contamination	Although many legacy contamination sites exist, improved regulatory systems in both countries has limited the creation of new areas of contamination. Large-scale land disturbance due to resource extraction activities continues to be a significant issue.				↗			
Soil acidification	Trans-national environmental legislation has significantly reduced soil acidification in forested areas of eastern and central North America. Localized areas of acidification in agricultural land managed through lime application.				↗			
Waterlogging	Waterlogging is not believed to be a significant threat in North America. Localized flooding has occurred due to a wider amplitude of precipitation events in the past decade. Loss of wetlands is a more significant threat in North America.				=			

Acknowledgements

Jenny Sutherland of NRCS in Lincoln, Nebraska very capably edited the material on the soil threats. Tim Martin of Agriculture and Agri-Food Canada provided access to the updated Canadian agri-environmental indicators material used in this chapter. The chapter was reviewed by D. Burton, F. Walley, C. Rice, E. Gregorich, C. van Kessel, T. Moore, and F. Larney and their suggestions for revisions are gratefully acknowledged.

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