CHAPTER

On the horizon

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From the outset of this book project, we wanted to address three simple questions: how are forest soils faring in our rapidly changing world? Then, how are we progressing as stewards of global soils? Finally, how can we improve our stewardship to meet the challenges of a changing world? We challenged our subject experts to provide insights into the condition of Earth's forest soils, their current management, future needs, and proposed actions where current practice falls short. From Asmeret Berhe (Chapter 3) comes the related concern that sustainable forest management needs to be rooted in the latest advances in our scientific understanding of the soil system, as well as appreciating and applying local knowledge of soil resources, to maintain soil health and associated ecosystem services. In this regard, Dan Binkley (Chapter 2) emphasized that our ability to detect, monitor, understand, and predict change will be a key focus for forest soil science and soil management over the ensuing decades. Still, roadblocks exist. As an example, DeLuca et al. (Chapter 16) discuss the critical importance of soil biota to the health and function of forest ecosystems, yet confess that "there continues to be limited capacity to transform soil biotic data into a useful form for land managers." They do, however, provide a roadmap into the rapidly evolving techniques and methods (and hope) of modern genetic analyses for solving the mystery of soil biota, arguably the 'final soil frontier'.

Multiple stressors are in play in the Anthropocene and are having effects, both direct and indirect, on soil properties in a "cumulative" fashion, which, in turn, are eliciting system-level responses. We have summarized the interplay between human activities, environmental stressors, and global forest soils, as highlighted throughout the book, in a "pathways" diagram of adaptive management (Fig. 20.1). Beyond the traditional industrial sectors (i.e., forestry, mining) the diagram highlights that other human pursuits also need to be considered for the added pressures they place on the Earth's natural resources, such as recreation and subsistence, the latter being of particular importance to indigenous peoples and rural communities that not only rely heavily on the natural resources that surround their communities but view stewardship as a sacred responsibility as with a family member. As Berhe also highlights (Chapter 3, section 3), changes in socio-economic conditions (e.g., market demands, land tenure, demography, among others) invoke indirect effects on the suite of stressors of forest ecosystem and soil change. Our chapter authors have assembled a comprehensive list of anthropogenic

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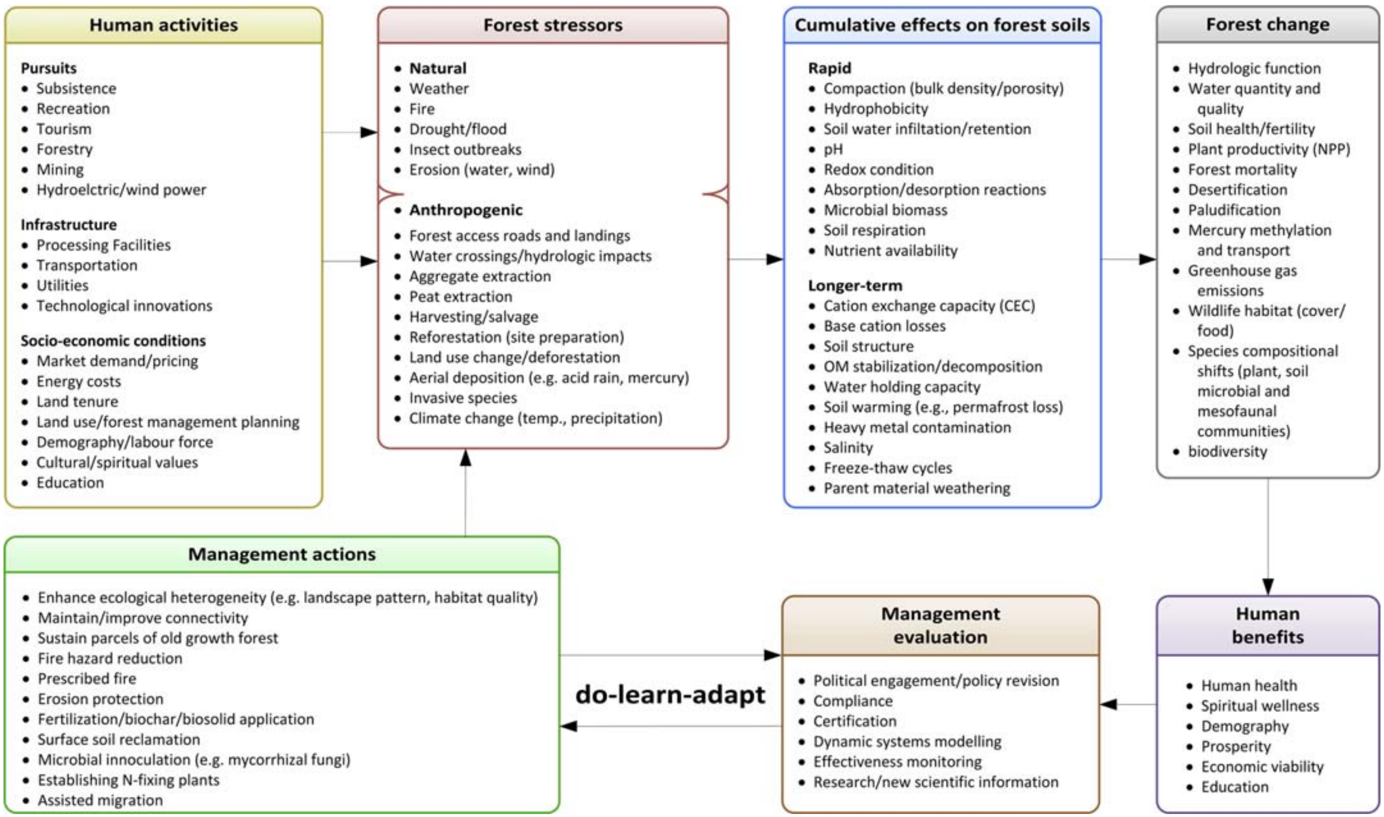

FIG. 20.1

Pathways diagram illustrating the stressors acting on global forest soils, their cumulative effects, forest-level changes, management options and the evaluation of their effectiveness. Adaptive Management in action!

and natural stressors, listed in Fig. 20.1, which interactively operate over axes of frequency, severity, duration and extent to impose wide ranging effects on soil properties and processes. Collectively, these interacting effects will cause the full complement of short term, long lasting or even permanent ecosystem-level changes to soil microbial community structure, hydrologic and biogeochemical function, and pedogenesis, to name a few. In a feedback fashion, these changes can in turn drive societal responses intended to sustain human health, economic prosperity and spiritual wellbeing — the very socio-economic conditions that when uninformed with robust knowledge has so often driven unintended change in the first place.

Visualizing this long list of interacting factors makes the task of land stewardship seem overwhelming, but at the level of a single biome type, problems can seem less daunting and solutions more tractable. Critically, we learn from our authors that these key stressors and potential effects can vary strongly across forest biomes. Safford and Vallejo nicely highlight this reality for soils of Boreal (Fig. 12.4) and Mediterranean (Fig. 12.9) biome types. Concerns in the boreal, particularly its more northern extent, are centered around the impacts of atmospheric warming, resulting soil warming, and impacts on permafrost loss, the effects of increased freeze-thaw activity on soil structure, elevated soil moisture and accelerated soil organic matter decomposition. In strong contrast, warming is manifested in Mediterranean soils as decreases in already moisture limited soils with consequences of a completely different nature, including altered fire regimes, reduced plant growth and over longer periods, changes to the composition, structure, function and dynamics of the ecosystem. Science has provided us with an abundance of single factor experiments, and for a subset of stressors, multi factor stressors. With rare exception, all are very short lived when viewed through the lens of soil formation — with the longest experiments running for mere decades, As a result, we currently have a very poor understanding of how interactions among stressors play out for soils of the Earth. As can be imagined, resulting predictions of system-level responses to multiple interacting stressors are quite uncertain — as these often rely on modeling exercises based on first principles assumptions. These uncertain predictions then feed adaptive management planning seeking to formulate appropriate mitigating measures. In the future, we will need to lean heavily on analytical techniques like structural equation modeling approaches to statistically tease out the strongest individual and interacting effects, and use, as examples, platforms such as A Landscape Cumulative Effects System (ALCES: https://www.alces.ca) or the Spatial Discrete Event Simulation (SpaDES: https://spades.predictiveecology.org/), which use the best available science and forecast analyses to simulate future conditions, identify thresholds and tipping points, and offer management alternatives for soil stewards while providing tools to inform policy makers.

In the Introduction, Fig. 1.2 provides a projection of global increases in air temperature out to 2050, highlighting that predicted increases will be greatest in the northern reaches of the boreal biome (3 — 6 °C). For tropical soils, the smaller increases being forecasted may well be of minor comfort given that smaller changes are required to move systems into new climatic territory as envelopes for equatorial regions are much narrower. Retrospective studies clearly show that the world's soil resource is already experiencing the pressures of global change, and forecasted future increases in these pressures are part of a century old ramping up of natural and anthropogenic stressors. These changes are written in pedons of our managed landscapes, as seen in Fig. 20.2, which captures one facet of accelerating change for a warming "hot spot" in northwestern Canada (A), including what is essentially permanent change to the depicted soil from permafrost melting (B). The resulting rise in the water table in low. Relief areas drive wide spread changes in growing conditions for trees, with extensive tree mortality due to water logging an unanticipated consequence of warming, itself having feedback consequences

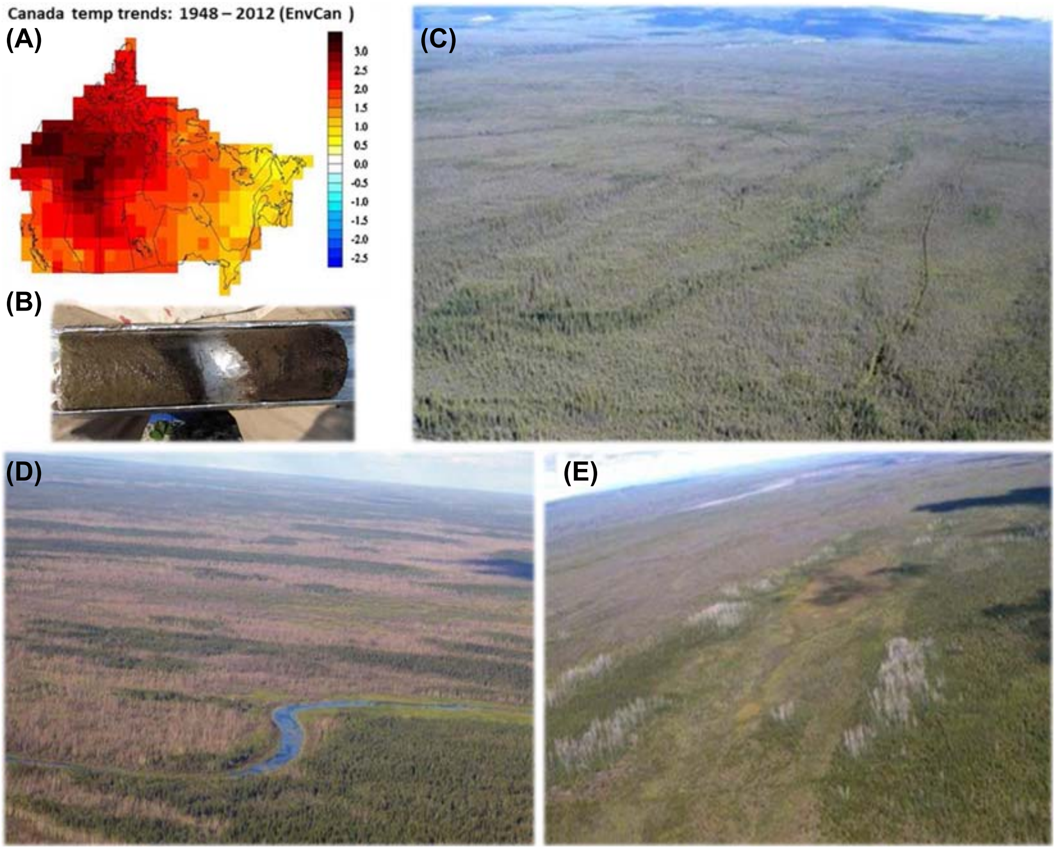

FIG. 20.2

Impacts of melting permafrost in northern reaches of North America's boreal forest that highlights the north-western hot spot for temperature change (A), and a melting permafrost core (B), large expanses of browning/dying black spruce (suspected cause due to permafrost melting/water table rise in low relief areas) (C), large areas of flood-related mortality (D), and aspen "islands" dying (E).

Photo credits: Roger Brett — NRCan, Canadian Forest Service (A, C-E), Jim McLaughlin — MNRF, Ontario Forest Research Institute(B).

for landscape level state changes (C-E). Other biomes experience their own dominant stressors, unanticipated consequences and positive feedbacks. For example, beyond land use change and deforestation, Jaramillo and Murray-Tortarolo (Chapter 7) highlight changes in precipitation patterns (i.e., amount, seasonality, and variability) that are having consequences for key soil processes controlling soil respiration in the Tropical Dry Forest Biome. Similar soil moisture concerns were identified for Mediterranean Forests, and the potential for desertification — a dramatic state change with consequences for soils and humanity (Safford and Vallejo — Chapter 12). The changes in precipitation patterns are, however, highly regionalized with some areas experiencing droughts of unprecedented duration and severity, while others are experiencing an increased frequency of extreme weather events (e.g., hurricanes or typhoons) leading to flooding and soil erosion. Due to their proximity to large human populations and centers of industrial activity, temperate forests are affected by an additional set stressors — pollution including acid deposition and elevated ozone, and invasive species (Adams et al. — Chapter 6), with peak effects in the urban forest (Pouyat and Trammell — Chapter 10). With the rapid growth in the number of people living in planet Earth's urban areas, and the quickly expanding geographic foot print of our cities, the science of urban soil stewardship must be mainstreamed — especially as society seeks to enhance the sustainability and livability of the urban ecosphere. Across all forested biomes, management practices modify soil physical, chemical, and biological properties including notables such as soil disturbance (i.e., soil compaction, and rutting that alter hydrologic function) and nutrient removals associated with high utilization "biomass-for-energy" harvests.

Not surprisingly, natural disturbance regimes are also changing, with changes driven in part by a quickly changing climate but also invasive species, for example a global scale invasion by fire prone grasses. Changes in management, for example a century of large scale fire suppression in North America and the growth in the area impacted by native pest outbreaks are causing dramatic and very large scale changes in our forests, for example the ongoing Mountain Pine Beetle outbreak in western North America, which together is resulting in accumulation of unprecedented fuel loads that combined with a warming and drying climate are leading to wildfires of increasing intensity and spatial extent. These mega fires are fundamentally altering soils of entire regions. On the more humid end of the soil spectrum, increases in the frequency and severity of major ice events, hurricanes and floods are moving soils into new ground — with hard to predict or even imagine changes to the soil resource.

All is not lost! Chapter authors have offered up a broad range of management actions, largely geared to increase soil resiliency or restore soil function in damaged systems (Fig. 20.1). As just a few examples, Prescott et al. (Chapter 13) provide explicit options for rehabilitating soil following severe disturbance from mining operations that are based on theory supported by experience and extensive research. In addition to rehabilitation, restoring soil physical and hydrologic functions by using amendments such as biochar (Bruckman et al. - Chapter 17), which may also help mitigate climate change by sequestering carbon within the soil profile and enhancing plant growth. And in their comprehensive synthesis on global forest soil carbon, Nave et al. (Chapter 11) discuss the role of soil carbon in a changing world. Relying on FAO's Global Ecological Zones framework, they identify soil carbon management considerations for each of Earths major forest types.

One area that has not been given adequate attention in the past is policy and management evaluation, which closes the adaptive management loop (Fig. 20.1). How well do local, state, federal and international policies protect forest soils and support management that sustains forest soil resources in perpetuity? As highlighted by Kishchuk et al. (Chapter 18) in their Canadian case study, most existing policies, from high level legislative acts to guidelines including Best Management Practices (BMPs), have not been developed for the conservation of forest soils. Are our management strategies, practices and mitigation actions effective in building resiliency and sustaining ecosystem integrity? In other words, if one did what policy directed or managers prescribed, would one get the desired outcome? Further, how "portable" are our successful management actions to other geographic regions? Critically, guidelines and BMPs that are largely built on past or even recent experiences and research may not continue to be effective in a rapidly changing world. Expect the unexpected! And Do → Learn → Adapt! As we move forward, it has become imperative to bridge the gaps between soil scientists, forest practitioners, and the general public through better multi-directional communication, allowing for a better understanding of emerging issues and required research — all designed to provide meaningful management actions under realistic future scenarios. Where positive outcomes emerge from research or management pilots, we need clearly articulated methods to “operationalize” these successes.

We cannot stress enough the value of long-term manipulative experiments (e.g., the North American Long-term Soil Productivity Network - LTSP, Free-Air Carbon Dioxide Enrichment − FACE – studies, Rothamsted’s long-term agronomic experimental trials), and monitoring frameworks (e.g, Long-term Ecological Research, National Ecological Observatory Network - NEON, UK’s Environmental Change Network, USDA Forest Service’s Forest Inventory and Analysis Program, National Forest inventories - NFI, the Montreal Process and their Criteria and Indicators framework used to report on the state of the world’s forests), all providing interdisciplinary opportunities to examine soil change. As Dan Binkley eloquently described in Chapter 2, there is a need for experimental designs that operate at many points along the intensive versus extensive spectrum, from in-depth studies at single sites that describe the mechanisms causing soil change, to broadscale monitoring designs that emphasize capacity to make largescale spatial inferences. There will also be increased value in repeated measurements in one’s “controls”. The term “control” tends to suggest all is static, unchanging. In a world increasingly defined by accelerating change, and in forests and forest soils increasingly impacted by multiple large scale stressors, the stability − even the very idea − of “long-term controls” or “baselines” can no longer be assumed. Moving forward, there is a need for well-designed, long-term experiments, with “controls”, to better understand the effects of any applied treatments when the entire system is itself responding to long-term climate change realities.

If we were to provide a mid-term report card on our soil stewardship efforts, based on the work presented in this book, what would we say about our prospects for excellent final grades? For the most part, we suggest a passing grade, with room for continued improvement. Encouraging to us is the shift in public perceptions, in the decisions made by policy makers, and in the increasingly effective work of land managers, all of whom are able to more successfully translate their perspectives on the need for strong soil stewardship into effective management. No longer can we rely on the inherent resiliency of the world’s soils and their inexhaustible capacity to resist or be resilient to external stressors and maintain soil function. We need active management to apply what we are learning and evaluate the consequences of the actions we take. Chapter authors have presented good evidence that we are moving the science-management yardsticks forward, but these efforts will remain an adaptive, highly iterative challenge. Taking on the challenge is critical to avoid being confronted with the need to “imagine a world without soil”. Let’s not!