Introduction

The ecosystems of the Arctic have evolved over millennia, and until recently have represented stable environments maintaining extraordinarily interesting specialised life forms. In recent times, however, climate change has been endangering Arctic biodiversity by virtue of rising sea levels, coastal erosion, disappearing ice flows, melting permafrost, release of methane and more volatile weather. Moreover, warming of the Arctic is certain to increase human population, exploitation of natural resources and development of international transportation routes, all of which will also degrade north polar biodiversity. As discussed in this contribution, the welfare of the delicate, fragile north polar ecosystems is heavily tied to one dominant family of flowering plants, which accordingly needs to be appreciated and conserved.

Clarification of some vague climate-geographical terms

Geographically, the Arctic Circle (approximately 66° 34′ N) is the latitude above which the sun does not set on the summer solstice, and does not rise on the winter solstice. From an ecological perspective, this is a less than satisfactory line of delimitation because north of it the climate differs considerably, particularly in coastal areas. As pointed out by ACIA (2004), ‘Other boundaries used to define the Arctic include treeline, climatic boundaries and permafrost extent on land.’ The area north of the natural latitudinal tree-line (generally located at 65–70° N), is often referred to as ‘tundra.’ This includes about 7.5 million km² or 2.9 million square miles (ACIA 2005), representing 5% of Earth’s land. ‘Tundra’ is widely understood to represent one of the planet’s major ‘biomes’ (a biome is a large naturally occurring community of flora and fauna occupying and adapted to a geographical area with distinctive climate and other environmental stresses). Nearly three-quarters of the treeless area of Arctic landscapes is covered by wetlands underlain by permafrost – a layer of frozen soil and partly decayed organic material largely derived from dead plants. ‘Tundra’ is often used specifically to indicate permafrost areas, but is also sometimes used more generally for cold-climate treeless regions. The frozen soil maintains water on the surface, producing numerous lakes, streams, bogs and fens (wetlands with peaty soils, usually alkaline, neutral or only slightly acidic) during the summer.

South of the treeless areas of the north, the tundra intergrades with areas where trees grow. In Europe one encounters the term ‘taiga’ to indicate both the relatively barren northernmost areas of tree growth as well as the relatively more southern and luxuriant coniferous forests (the latter usually understood as the ‘boreal forest’ in North America, a phrase sometimes equated with taiga in Europe).

‘Subarctic’ is a vague term referring to the coldest areas (approximately 50–65° N) of the temperate zone which border the Arctic. ‘Polar’ and ‘subpolar’ are also vague terms, respectively more or less equivalent to Arctic and Subarctic. We follow the convention of capitalising ‘Arctic’ when it indicates the geographic region, but employing lowercase when it refers to ecological attributes such as low temperatures.

The distinctions pointed out above are particularly centred on whether permafrost is present. Climate warming, which is perhaps the principal issue altering the welfare and distribution of northern biodiversity, is effectively reducing the most essential sustainer of Arctic species and habitats: prolonged freezing temperatures. The Arctic’s permafrost is the foundation for much of the region’s unique terrestrial ecosystems, and hence deterioration of the permafrost is the most alarming aspect of global warming for most northern land-dwelling animals and
plants. Permafrost in the Arctic extends as deep as 1500 m (almost 5000 feet) in some places (for example in Siberia), which might seem to indicate that it is unlikely to disappear in the foreseeable future, but since plant growth occurs just in the ‘active layer’ (the top unfrozen and/or annually defrosted soil layer) relatively small changes in temperature can have large effects. The southern limit of permafrost is projected to shift northwards several hundred km over the next century (ACIA 2004).

**Arctic plants with special reference to herbivores**

There may be thousands of plant species north of the Arctic Circle, especially in the relatively warm coastal and southern areas. However, the northern treeless tundra (excepting ‘dwarf trees’), especially in the inland areas, is relatively depauperate in biodiversity. In the tundra, a simple trophic (food chain) structure exists, whereby a small number of flowering plant species dominate the rooted terrestrial vegetation. These are consumed particularly by a small number of herbivorous vertebrate animals (just a few dozen), which in turn are prey for an even smaller number of carnivores. Range ecologists and agronomists commonly confuse the term ‘grazing’ to consumption of herbaceous vegetation, and employ ‘browsing’ for consumption of woody plants. As noted in the next paragraph, in the tundra not only rooted herbaceous plants and woody plants are eaten, but also so are lichens, and we employ ‘graze’ to refer to all plant consumption by vertebrates.

The ‘plants’ of the northern treeless tundra that feed grazing animals fall into two basic categories: those without and those with flowers. The plants without flowers most notably include mosses such as *Polytrichum* (Haircap or Hair Mosses) and *Sphagnum* (Sphagnum Mosses); and lichens such as *Cladonia* (cup lichens, particularly *C. rangiferina* – Reindeer or Caribou Moss). (Strictly, the algae and fungi which together make up lichens are no longer considered to be ‘plants.’) The flowering plants that feed grazing animals especially include: grasses such as *Calamagrostis* (Reed Grass); shrubs of the Ericaceae or heath family such as *Arctostaphylos* (Manzanita, Bearberry), *Cassiope* (Cassiope), *Empetrum* (Crowberry), *Ledum* (Labrador Tea; now usually placed in *Rhododendron*) and *Vaccinium* (Blueberries) and several shrub/dwarf trees such as *Betula* (Birch), *Alnus* (Alder) and *Salix* (Willow). In the more southern (taiga, subarctic or boreal) areas with trees, a variety of other flowering plants are also important fodder for grazers. As noted next, sedges (Cyperaceae) are especially important for Arctic grazers. While the Cyperaceae provide considerable food for their survival, in the northern treeless (tundra) areas non-flowering plants (mosses and lichens) are often more plentiful. However, mosses and lichens are slow-growing, and once consumed a patch can require decades to regrow. By contrast, many sedges (as well as several grasses) are very resistant to grazing damage. The majority of their biomass is under ground, providing considerable energy reserves allowing the plants to regrow relatively quickly.

**Arctic sedges with special reference to herbivores**

Of all flowering plants, the sedge family (Cyperaceae) is dominant in the northernmost areas of the world, both in terms of proportion of species in the region and frequency (coverage) of occurrence. The name ‘Sedge’ is often used...
specifically to refer to species of \textit{Carex}, but is also employed to refer to any species of the Cyperaceae. The sedge family is a large group of flowering plants with about 5000 species in approximately 100 genera. It is closely related to the grass family (Poaceae), and many of the species superficially resemble grasses, especially because of the possession of narrow, grass-like leaves and numerous small flowers and fruits developed on well-branched stems. Many sedge stems are distinctly triangular in shape (giving rise to the expression ‘sedges have edges’) and are solid, whereas grass stems never have triangular stems and are often hollow. Sedges are found on every continent except Antarctica, and occur in nearly every habitat from Arctic and alpine tundra to deserts and tropical forests, although they are most abundant in temperate wetlands and forests.

The sedge family is naturally adapted to the very widespread, seasonally wet conditions of the Arctic, created by superficial thawing during the summer. Continuing glacial upheaval of the ground because of the severe climate produces innumerable small and large bodies of water, which are ideal for sedges.

By no means is the Arctic uniform. It includes such specialized substrates as salt marshes, dry and wet rocky, gravelly and sandy habitats, both acidic and basic peatlands, snow beds, mud boils and diversified bedrocks. The climate of the Arctic and sub-Arctic vary from ‘continental’ on the inland areas to ‘oceanic’ over the polar sea. Matching this physical diversity, there are numerous species of Cyperaceae (especially of \textit{Carex}) that characteristically occupy distinctive habitats.

\textbf{\textit{Carex} species}

\textit{Carex} is a huge genus of about 2000 species, ranked by some as the world’s fifth largest genus. It is distributed throughout much of the world. With about 140 species in the Arctic, \textit{Carex} is the most species-rich genus of the Arctic flora. Especially widespread species in the Arctic

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{arctic_sedges.jpg}
\caption{Common \textit{Carex} species of the Arctic. (a) \textit{Carex saxatilis}. (b) \textit{Carex bigelowii}. (c) \textit{Carex aquatilis}. Photos courtesy of Marie-Ève Garon-Labrecque.}
\end{figure}
Tussock Cottongrass (*E. vaginatum*) has a special importance in the ecology of the tundra. It produces densely packed clusters (‘tussocks’) of dead stems and leaves, which are flammable. During dry summers wildfires develop and large areas burn or smoulder for weeks. While other plant species burn, only the outer layers of the tussocks do so. The fires rejuvenate the Cottongrass and release nutrients into the soil to nourish the plants.

Cottongrasses

The genus *Eriophorum* (Cottongrasses, or Cotton Grasses), with about 25 species, is common in the Arctic. Especially widespread species include *E. scheuchzeri* (Scheuchzer’s Cottongrass) and *E. vaginatum* (Tussock Cottongrass). The last-mentioned is so frequent in the Arctic that it has been described as the ‘Dandelion of the North’. The ‘cotton’ of Cottongrass is a mass of fibres attached to the ‘seeds’ (technically fruits), and serving as sails or parachutes, much like dandelion floss acts to carry the seeds away on the wind. (Indeed, cotton fibres similarly are attached to Cotton seeds for wind distribution.)

Figure 3. Scheuchzer’s Cottongrass (*Eriophorum scheuchzeri*). Photo courtesy of Marie-Ève Garon-Labrecque.

Figure 4. Tussock Cottongrass (*Eriophorum vaginatum*). (a) Plants in flower. Photo by Elke Freese (CC BY SA 3.0). (b) Plants in fruit. Required attribution: Rob Bendall.
ornamental, and the fluffy seed heads are sometimes used in arts and crafts, and in floral arrangements. Occasionally in times of famine the stems of Cottongrass have been consumed by Arctic peoples. In past centuries, Cottongrass has been used in northern Europe to treat coughs and colds, although this is now considered inadvisable.

**Sedge meadows**

Sedge meadows are, as the name implies, meadow-like expanses of moist land dominated by members of the Cyperaceae. These wetland ecosystems are even more common in temperate than they are in Arctic regions, and outside of the Arctic they are highly valued as grazing pasture for livestock. In the Arctic, sedge meadows provide critically important forage for the dominant large terrestrial herbivores, particularly Caribou and Muskoxen, as well as smaller herbivores such as Lemmings, Voles and Arctic Hares. Sedge meadows also provide habitat for insects and nesting birds such as waders and geese.

**Arctic grazing animals in relation to Sedges**

‘Sedges play a significant role in supporting food webs by recycling nutrients and using energy for photosynthesis to produce biomass for consumers, such as grazing animals, the animals that feed upon these higher organisms and, ultimately, also decomposers… Sedges are the dominant vegetation associated with highly productive systems such as coastal salt marshes and freshwater sedge marshes… Waterfowl and fur-bearing animals abound in these active and productive wetlands, and wildlife is distinctly concentrated in these areas of the vast boreal and Arctic ecosystems… Sedges provide the dominant source of energy during critical stages in the life cycles of many species of birds and mammals. They provide feeding, breeding, nesting, escape and staging habitat for waterfowl, shore birds, raptors and songbirds. In addition to these roles, sedges also provide habitat structure for production of macroinvertebrates (invertebrates, crustaceans, insect larvae) that many other species of animals are dependent upon. Most wetland sedge species produce a large crop of water-dispersed fruits. These are eaten by a variety of animals, such as insects, water birds, passerines and some mammals. The leaves are often used as nesting material, and some mat-forming species provide shelter and nesting sites… Sedges also play an indirect but critical role in furbearer production, waterfowl and big game hunting, and commercial and sport fishing by providing essential habitat for these species.’

Tande and Lipkin (2003)
Arctic is matched by a relatively small number of animal species. Because they are so common, and also because they are rather nutritious, *Carex* and *Eriophorum* species are especially critical for the welfare of several animals, especially mammals and birds, several of which are economically significant. Grazing wild Arctic herbivores consuming the plants include Caribou, Deer, Elk, Geese, Grizzly Bears, Ground Squirrels, Hares, Lemmings, Ptarmigan and Voles. Of these herbivores, the most significant are Caribou and Lemmings. Grazing domesticated herbivores, such as Cattle, Sheep and Horses, also consume the plants but mostly south of the Arctic region, principally in natural sedge meadows. In some locations, sedge hay is harvested for feeding livestock.

In northern Yukon, Cottongrasses have been observed to comprise over three-quarters of Caribou diets during calving in the spring. Barren-ground Grizzly Bears (Brown Bears) in Alaska have been found to eat Cottongrass flowers, these making up a significant amount of their food. Birds frequently use *Carex* Sedges and Cottongrasses as nesting habitats, and rodents employ the plants as cover. Birds also eat insects which consume the plants.

Because of the low temperatures in the North Polar Region, organic decay by bacterial action is greatly reduced. As a result, the nitrates, phosphates and other nutrients needed by plants are deficient. Where animal dung, urine and other remains accumulate (at sites such as fox dens, owl perches, bird cliffs and lemming burrows), they provide these essential nutrients (especially nitrogen) for Arctic plants. The grazing animals of the Arctic are, accordingly, important in stimulating the growth of...
the plants that they consume. By disturbing the soil (by digging through snow to find forage, or from excavating dens) the animals stimulate the upper levels of soil to thaw and become usable for plant growth.

The late Robert Jeffries and colleagues found that nesting Snow Geese are particularly important in fertilising Arctic plants that serve as forage for their broods. However, these scientists also found that while a few geese were a good thing, too many were not. Increased grain from altered agricultural practices and decreased hunting pressure in their wintering grounds in the American Gulf states led to an explosive increase in Snow Goose populations in the 1980s. When the numerous birds flew to the Arctic, the result was serious overgrazing and damage to Arctic grazing areas. This curious situation demonstrates how susceptible Arctic plants are to changes in the normal balance of biodiversity interactions.

**Adaptations of Arctic plants**

Arctic plants are severely constrained by their very short growing season (despite long periods of sunlight) and environmental stresses (especially cold temperatures and nutrient-deficient soils). They are usually low-growing to avoid desiccation by wind and scouring by wind-borne ice particles. Growing in clumps is a way of stabilising the stems from being blown over by wind. Plants are almost always perennials and tend to spread vegetatively, as seedlings are difficult to establish. An evergreen habit maximises use of foliage for more than one growing season. Curiously, many northern plants have features that reduce water loss, such as tough foliage resistant to wilting (reminiscent of desert plants; indeed, the High Arctic has been described as a true desert). This is because so-called ‘physiological dryness’ characterises plants growing in northern habitats where although water is abundant, it is frozen or so cold that for much of the year it is unavailable.

**Harvesting of biodiversity with special reference to the Arctic**

Vascular plants (Angiosperms or flowering plants as well as conifers and related groups) are the foundation of most of the world’s terrestrial biological production. This is simply because they carry out most of the photosynthesis conducted by land plants. They are the basis of the majority of the planet’s agriculture, horticulture, agroforestry and wild-crafting (harvesting of non-cultivated plant resources), which occur primarily in temperate and tropical regions. However, humans conduct very little cultivation and only limited harvesting of wild plants in Arctic and Subarctic areas because of the short season, harsh climate and stressful habitats.

The predominant way that humans to date have harvested terrestrial northern biodiversity is by hunting, principally by indigenous northern peoples, who learned how to do so sustainably and to this day espouse a philosophy of responsible harvesting that is respectful of the natural world.

Caribou are the only Arctic animal that has been domesticated. Caribou and their domesticated form, Reindeer (both are classified in the species *Rangifer tarandus*), illustrate various degrees of sustainable human management of grazing herd animals. Caribou have been
hunted since time immemorial by northern peoples, and to this day remain a major source of subsistence for Canadian Inuit. In northern Eurasia, Reindeer have been extensively managed by various peoples for millennia, as sources of meat, milk, fur and bone tools, and as beasts of transportation. For the most part, the natural migration of Reindeer herds has been tended by traditional herders, rather than by sedentary farmers in the manner of maintaining cattle, and much of the rangelands employed do not have permafrost.

**The threat to Arctic biodiversity in relation to the welfare of sedges**

Plant growth is very slow in the Arctic, and when plants are grazed or damaged they are especially slow to recover. Accordingly, the Arctic is an extremely fragile and vulnerable environment. Vehicles, oil spillage and damage from pipeline construction are special concerns. In particular, Sedges provide critical habitat for both sedentary and migratory herbivores, and are easily degraded by such anthropogenic disturbances as petroleum development, mining, atmospheric pollution and vehicular traffic. Many crops currently suitable only for warmer parts of the world may become growable as far north as the Arctic Circle, and this represents a threat to natural Arctic biodiversity. Moreover, there has been continuing interest in agricultural exploitation of the Arctic. ‘It has been suggested that the tundra could be developed into an important meat producing area if modern management were introduced, such as regular rotation of pastures, nitrogen fertilisation and sowing of productive grasses’ (Schultz 2005). The Arctic has been one of the last large natural refuges where biodiversity has remained relatively free of the destructive hand of mankind, largely because of its inaccessibility and harsh climate. These protections are now being significantly reduced, and it has become imperative to limit the growing threats to the unique northern habitats. Towards this goal, it is important to understand that the sedge family is critical for the continuing welfare of all other northern terrestrial species.

**Believe it or not**

- The Antarctic continent is a harsher environment for flowering plants than the Arctic area. Antarctica is mostly permanently covered by ice and snow leaving less than 1% available for plant colonisation. By contrast with the Arctic region, which is the native home of hundreds of flowering plants, only two flowering plants are indigenous to Antarctica: Antarctic Hair Grass (*Deschampsia antarctica*) and Antarctic Pearlwort (*Colobanthus quitensis*).
- Numerous animals produce trypsin digestive enzymes. It has been claimed that monogastric animals consuming *Carex bigelowii* induce the plants to produce trypsin inhibitors, which neutralise the digestive enzymes, lowering the nutritional benefit of the plants consumed (note Seldal et al. 1994). It has been suggested that under heavy grazing by lemmings, sedges produce so much of these chemicals that the animals begin to starve because they cannot digest the plants, and engage in huge migrations sometimes ending in disaster such as drowning or falling over a cliff, phenomena commonly interpreted as Lemming mass suicide.
- Arctic plants have been compared to icebergs: much more of the plant is often underground than aboveground. Sedges growing in the Arctic often have extensive fibrous root systems that, although often shallow because of the limited unfrozen soil, may be much larger than the above-ground portion.
- In Arctic *Carex* species, the reproductive organs (flowers, fruits and accompanying bracts) are frequently...
darkly coloured. By contrast, in most temperate-zone Carex species these are paler. This appears to be an adaptation to absorb sunlight in order to promote seed development in the cold climate.

- The fibres attached to the seeds of Cottongrasses are translucent and trap sunlight, producing a miniature greenhouse effect, and the resulting heat is maintained by the insulating effect of the cottony fibres. The resulting warmth speeds up seed maturation in the very cold polar environment. In these respects Cottongrass fluff is reminiscent of Polar Bear fur, which is believed to act as a solar heat collector (http://www.adn.com/article/20,150,811/inside-polar-bear-hair-complex-heat-holding-labyrinth-pores).

- Purple Saxifrage (Saxifraga oppositifolia) is frequently considered to be the northernmost flowering plant, recorded at Lockwood Island, 83° 24′ N, on the north coast of Greenland. The same species is thought to occupy the coldest place on Earth occupied by a flowering plant; an altitude of 4505–4543 m (about 15,000 feet) near the summit of the Dom, the highest mountain in Switzerland near the Matterhorn. The following temperature conditions were recorded in 2008–2009 (Körner 2011): the growing season had only 66 days with a daily mean rooting (2–3 cm below ground) temperature >0 °C; winter minimum: −20.9 °C; mean for growing season: 2.6 °C; all plant parts including roots experienced temperatures <0 °C every night.

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