The Feasibility of Over-Summer Snow Storage at the Craftsbury Outdoor Center, Craftsbury VT

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THE FEASIBILITY OF OVER-SUMMER SNOW STORAGE AT THE CRAFTSBURY OUTDOOR CENTER, CRAFTSBURY VT

A Thesis Presented

by

Hannah Weiss

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The Faculty of the Graduate College

of

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Abstract

Climate change increases the unpredictability of winter weather and threatens the future of nordic skiing. Ski centers at high elevation and high latitude have employed over-summer snow storage, a climate change adaptation strategy, to ensure a consistent start-date to their winter ski season. Over-summer snow storage involves making a large pile of snow during winter and storing the snow beneath protective layers, such as wood chips or foam panels, to impede melt throughout the summer and fall. When ready to open the ski season, the ski center uncovers the pile and spreads the snow to create trails. Though many nordic centers around the world store snow, its implementation has not been widely researched. It has also never been tested in the United States.

This research seeks to evaluate snow storage’s success at the Craftsbury Outdoors Center, a low elevation, mid-latitude ski center in Vermont, U.S.A. To determine success, physical, financial, and environmental analyses were conducted from 2018 to 2019. To test physical feasibility, we collected snow pile volume change data over two summers. In summer 2018, two, 200 m$^3$ piles were created, covered in wood chips, and their volume changes were monitored using laser scanning. Effectiveness of different coverings were also tested through temperature comparisons of snow beneath woodchips, foam panels, and reflective sheets. Mean melt rates were found to be 0.64 % of the initial pile’s volume per day, with maximum loss recorded during mid-summer and minimum loss in the fall. These experiments indicated that wet wood chips covered with a reflective sheet was the most effective cover combination for minimizing volume loss. These results informed the creation of a 9300 m$^3$ pile in 2019. The snow pile was monitored with laser scanning and lost <0.16% of its initial volume per day between April and September. It retained 60% of the initial snow volume by October which was enough snow to open the 2019 season on time. These results render snow storage technically feasible at this location.

To determine financial and environmental feasibility, all steps of the snow storage process were analyzed for cost in dollars and impact in kilograms of CO$_2$ released. Steps included site preparation, snow pile creation and covering, and snow pile uncovering and spreading. The directors of the center confirmed snow storage’s financially viability. When compared to skiers flying to an alternative ski center if the Craftsbury Outdoors Center could not open, snow storage produced less CO$_2$. These data show that snow storage is both financially and environmentally feasible. Overall, snow storage is technically, financially, and environmentally successful at this location and, given current climate predictions for winter, could be implemented at other nordic centers to extend nordic skiing’s lifetime into the twenty-first century.
Citations

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CHAPTER 1: INTRODUCTION

1.1 Climate Change Impact on Skiing

Climate change will continue to impact human and natural communities across the globe, which damages our economy (Martinich & Crimmins, 2019; Tol, 2018; Wuebbles et. al., 2017). Estimates of the global financial cost of climate change range from several hundred billion to several trillion dollars by the end of the twenty-first century (Kahn et. al., 2019; USEPA, 2017). In response to these financial repercussions, many businesses are adapting. A recent report found that over 6,000 major businesses worldwide (equivalent to half of the global economy) have made commitments to address energy use, transportation, and land use as a direct response to climate change (Hsu et. al., 2017). Studies now recommend a wide range of strategies for businesses looking to adapt to climate change, such as developing a more relational business model (Canevari-Luzardo, 2020), empowering female workers, and basing decisions on the most recent climate science (Cameron, 2019). These studies analyze many sectors’ adaptations to climate change across the globe, such as transportation (Quinn et. al., 2018), agriculture, (McLinden Nuijen, 2019), the energy/water sector (Bremer & Linnenluecke, 2016; Gasbarro et. al., 2014), and outdoor tourism (Hewer & Gough, 2018).

Outdoor tourism, a sector of the global economy, is especially at risk because it relies on specific weather conditions (Steiger et. al., 2019; Craig & Feng, 2018). Winter outdoor tourism, including alpine and nordic skiing, relies on consistently cold temperatures to produce enough snow that centers or resorts can open. Due to climate change, these conditions are becoming more unpredictable (Finlayson, 2019). This unpredictability can cause centers or resorts to become financially inviable which
represents a huge economic loss; in the United States (U.S.) alone, winter tourism, majority of which is skiing, attracts over 20 million guests per year and the most recent study shows it contributed $20 billion to the economy (Hagenstad et. al., 2018). Additional vulnerability is revealed through examining alpine compared with nordic ski centers, and high elevation compared with low elevation ski centers. Alpine centers are typically larger and more expensive to operate but possess more financial resources. In contrast, nordic centers are often smaller and less expensive to operate, but possess fewer financial resources, indicating that nordic centers are less resilient. While high elevation ski centers (often alpine centers), are predicted to experience an increase in snow within the next two decades (Hoogenboom et. al, 2014) lower elevation ski centers (often nordic centers) will not experience this same increase (Dawson & Scott, 2007). Due to their size and location, nordic centers are at high risk for closure due to financial instability from climate change (Pidwirny & Clark, 2019).

1.2 Historical and Cultural Significance of Skiing

Skiing is not only important economically; it has deep historical roots as well. Skiing began as a form of transportation; evidence shows hunter-gatherers 6000 years ago skied in present-day Norway and Russia (Huntford, 2009). Records from the 16th century show that the Saami, indigenous peoples to Scandinavia, also used skis as transportation (Pedersen, 2013). Skiing entered the military arena in the 17th century and transitioned into a recreational activity in the mid-1800s; a newspaper referenced the first known cross-country ski “race” in Tromso, Norway in 1843 (Huntford, 2009). Skiing came to the United States when Norwegians, pursuing the California Gold Rush in the 1850s,
landed in San Francisco. Since then, skiing has expanded to include cross country (nordic), jumping, downhill (alpine), biathlon, all as recreational activities and as competitive sports (Lund & Masia, 2003).

Skiing has also become embedded in modern-day culture. In his article, historian E. John B. Allen explores the modernization of skiing, from a physical necessity to a recreational activity through skiers’ connections, or “private meanings…imputed to…[the sport]” (Allen, 1985). Through numerous interviews with skiers across ages and socioeconomic statuses, he found that skiing created a bond between and identity for those who participated. A 2004 novel delves into the cultural history of skiing in the United States and bolsters Allen’s claim that skiing is not just a sport, but an activity with profound cultural heritage (Coleman, 2004). This level of history and personal connection could serve as non-monetary motivators for supporting skiing in a sustainable way; non-monetary benefits have been shown to drive behavior, sometimes more effectively or equally as effective as monetary benefits (Rajapaksa et. al., 2019; Cassar & Meier, 2018).

Due to its economic, historic, and cultural significance, many expect that technological advances will sustain the ski industry through climate change. Innovation is tied to the success of the ski industry; in 1934, skiers, tired of walking up hills to ski down demanded an easier way of reaching summits and one ski resort responded by creating the first rope-tow (Harrison, 2003). Many alpine and some nordic centers have begun to consider modern-day adaptations to tackle climate change (Rivera & Clement, 2019).
1.3 Climate Change Adaptations

One such adaptation, snowmaking, allows for a ski center to make their own snow instead of relying on natural snowfall. Snowmaking requires cold temperatures, water, and energy (Hartl et. al., 2018). Records show that snowmaking began in the 1940s when ski mountains in the U.S. wanted to open their season without complete reliance on natural snow (Leich, 2001). Snowmaking then gained popularity throughout the end of the 20th century; in the United States, almost every alpine resort and some nordic centers make their own snow. Snowmaking requires temperatures to be -2°C or lower to make acceptable snow (Hartl et. al., 2018). Until recently those temperature thresholds were attainable around opening day (usually, late November or early December). However, climate change creates unpredictability around cold temperatures and snowmaking itself is in jeopardy (Spandre et. al., 2019; Demiroglu et. al., 2016).

Over-summer snow storage (here, called snow storage) is one response to address snowmaking’s temperature-consistency problem. This strategy involves using snow guns during a cold month (when weather conditions are ideal for snowmaking) to make a pile of snow between 1,000 and 10,000 m³. That snow is then covered in protective layers, such as wood chips, sawdust, foam panels, or geotextile fabrics to impede melt, and left over the spring, summer, and fall. When the ski center is ready to open, the pile is uncovered, transported to the trails, and spread. This strategy allows for the ski center to consistently open their season on time, regardless of the weather. It can allow a ski center to maintain a stable reputation for opening on time and can attract recreational skiers who like planning their vacations ahead of time, or competitive skiers who need a consistent location to train. This strategy has been applied at ski centers across the globe,
concentrated in areas of high elevation and/or high latitude in Europe. Snow storage had not been tested in the United States, however. One ski center interested in snow storage’s potential is the Craftsbury Outdoors Center (COC). The COC is a nordic ski training facility in the town of Craftsbury, Vermont, a northeastern state in the United States with a robust ski industry.

Vermont was introduced to skiing in the early 1900s – Norwegians living near town of Stowe used skis as winter transportation and its effectiveness caused an increase in interest (Davis, 2010). Nordic skiing began in Vermont through the Von Trapp Family, who immigrated to Stowe in the 1940s, after persecution in their native Austria (trappfamily.com). They opened the Trapp Family Lodge in 1968, a nordic ski center still in operation today (Krukar, 2015). Nordic centers are one branch of Vermont winter tourism; they employ approximately 10,000 people and contribute $595 million to the state’s economy (Hagenstad et. al., 2018).

Climate change has already impacted Vermont’s nordic ski industry and caused several nordic centers to close, such as the Morse Farm Ski Touring Center in East Montpelier (WCAX, 2018). Climate change is likely to continue this trend as it impacts multiple aspects of nordic ski center operations and decreases its financial viability (Guilbert et al., 2014). It is predicted that skier visits will drop by 9.5% in years with low snow, removing $40-51 million from the state’s economy (Burakowski, 2012).

The COC in Vermont invested in snowmaking early in the 2000s, however, during the 2015/2016 winter season, the late November temperatures were still too warm to efficiently make snow. The directors expressed discomfort with the small quantity of snow they were able to make and began seeking sustainable alternatives. They opted to
explore over-summer snow storage through seeing this strategy employed at other nordic ski centers in Europe and Canada.

The only published study at the time focused on two locations: Martell, Italy and Davos, Switzerland (Grünewald et. al., 2018). Two large piles of snow were made in late winter, covered in sawdust, and then measured for volume during April and then the following November to compare size. This first important study laid the groundwork for other snow storage studies in different locations, with different insulative layers. For the COC, it was not known whether snow storage was physically feasible at their location as they were lower elevation and mid-latitude, compared with other nordic ski centers. The financial and environmental costs associated with the project were also not known and not extensively explored in previous research.

1.4 Project Description

This research collaborated with the Craftsbury Outdoors Center to explore the technical feasibility, financial cost, and environmental impacts of snow storage at a low-elevation, mid-latitude nordic ski center in Vermont, U.S.A. Chapter two details the physical feasibility of snow storage. During the 2018 summer, we made two 200 m$^3$ piles in two potential snow storage locations. We then analyzed their size every 10 days from May to September. We conducted experiments to determine which insulation combinations are most effective. We made recommendations for future snow storage efforts based on technical feasibility. These recommendations guided the creation and preservation of a full-size snow pile (9,000 m$^3$) in 2019 at the COC.

Chapter three calculates the financial cost and environmental impact of snow storage. We conducted interviews with COC staff to gather both cost and fuel usage
information regarding each step of snow storage. Financial cost was calculated through summing all costs necessary to prepare the snow storage site, create the insulation-covered pile, and spread the snow. Environmental costs were calculated similarly using CO₂ emissions as the units. In conclusion, we found snow storage to be technically feasible, financially viable, and more environmentally friendly than the likely alternative of flying to an open ski center if the COC could not open. Future research should explore snow storage at other locations, using different materials, to better assess snow storage as a global possibility for extending the lifetime of the nordic ski industry.

1.5 References


CHAPTER 2: OPTIMIZATION OF OVER-SUMMER SNOW STORAGE AT MID-LATITUDE AND LOW ELEVATION

2.1 Abstract

Climate change, including warmer winter temperatures, a shortened snowfall season, and more rain-on-snow events, threatens nordic skiing as a sport. In response, over-summer snow storage, attempted primarily using woodchips as a cover material, has been successfully employed as a climate change adaptation strategy by high-elevation and/or high-latitude ski centers in Europe and Canada. Such storage has never been attempted at a site that is both low elevation and midlatitude, and few studies have quantified storage losses repeatedly through the summer. Such data, along with tests of different cover strategies, are prerequisites to optimizing snow storage strategies.

Here, we assess the rate at which the volume of two woodchip-covered snow piles (each 200 m³), emplaced during spring 2018 in Craftsbury, Vermont (45° N and 360 m a.s.l.), changed. We used these data to develop an optimized snow storage strategy. In 2019, we tested that strategy on a much larger, 9300 m³ pile. In 2018, we continually logged air-to-snow temperature gradients under different cover layers including rigid foam, open-cell foam, and woodchips both with and without an underlying insulating blanket and an overlying reflective cover. We also measured ground temperatures to a meter depth adjacent to the snow piles and used a snow tube to measure snow density. During both years, we monitored volume change over the melt season using terrestrial laser scanning every 10–14 days from spring to fall. In 2018, snow volume loss ranged from 0.29 to 2.81 m³ day⁻¹, with the highest rates in midsummer and lowest rates in the fall; mean rates of volumetric change were 1.24 and 1.50 m³ day⁻¹, 0.55 % to 0.72 % of
initial pile volume per day. Snow density did increase over time but most volume loss was the result of melting. Wet wood-chips underlain by an insulating blanket and covered with a reflective sheet were the most effective cover combination for minimizing melt, likely because the aluminized surface reflected incoming short-wave radiation while the wet wood-chips provided significant thermal mass, allowing much of the energy absorbed during the day to be lost by longwave emission at night. The importance of the pile surface-area-to-volume ratio is demonstrated by 4-fold lower rates of volumetric change for the 9300 m³ pile emplaced in 2019; it lost < 0.16 % of its initial volume per day between April and October, retaining 60% of the initial snow volume over summer. Together, these data demonstrate the feasibility of over-summer snow storage at midlatitudes and low elevations and suggest efficient cover strategies.

2.2 Introduction

Earth’s climate is warming (Steffen et al., 2018). This warming is expressed not only in warmer nights and days but also in the number of winter rain and thaw events that degrade snowpacks (Climate Central, 2016). The duration, extent, and thickness of both lake ice and snow have decreased over the past several decades in response to increasing temperatures, especially at high latitudes (Hewitt et al., 2018; Sanders-DeMott et al., 2018). Winter recreation is particularly vulnerable to such warming. The ski industry has responded by increasing snowmaking as well as attempting to reduce melt by covering snow using various materials (Scott & McBoyle, 2007; Pickering & Buckley, 2010; Steiger et al., 2017). Over the past several decades, ski centers have improved snowmaking strategies and facility operations both to maintain financial stability and to decrease their output of greenhouse gases (Koenig & Abegg, 1997; Moen
& Fredman, 2007; Tervo, 2008; Kaján & Saarinen, 2013). Recent research focuses on analyzing and optimizing stages in the snow production cycle to assist industry efforts (Hanzer et al., 2014; Spandre et al., 2016; Grünewald & Wolfsperger, 2019).

Many sites organizing major winter sports events, such as cross-country or alpine world cup races, have adopted over-summer snow storage in response to the unpredictability of snowmaking weather conditions. In areas of high humidity and warm average fall temperatures, summer snow storage is more reliable than expecting weather conditions to be sufficiently cold and dry for making snow at the start of the winter ski season. For example, the 2014 Olympic Games at Sochi relied on 750 000 m$^3$ of stored snow (Pestereva, 2014).

Over-summer storage of snow and ice is not a new idea; for example, ice houses stored large blocks of lake ice beneath sawdust over the summer (Nagnengast, 1999; Rees, 2013). Today, the ski industry uses stored snow to support the early winter ski season. Modern over-summer snow storage (sometimes referred to as “snow farming”) begins with the creation of snow piles during winter months. Piles are covered (often with sawdust or woodchips and sometimes geotextiles) before the snow is stored over the summer (Skogsberg & Lundberg, 2005). In the fall, the pile is uncovered and snow spread onto trails. Nordic ski centers require less snow-covered area to open than downhill ski centers, and so snow storage on the scale of thousands of cubic meters is practical and cost-effective, allowing the center to open on time instead of losing business, which occurs if centers are unable to make snow and thus must open later. Snow storage has been employed predominately at high-elevation and/or high-latitude ski
centers (Fig. 2.1), many of which benefit from cool, dry summers that minimize energy transfer to the snow, increase evaporative cooling, and thus slow snowmelt.

Here, we examine the feasibility of snow storage in the northern United States at a midlatitude, low elevation (45°N and 360 m a.s.l.) site with a humid, temperate climate, including warm summer temperatures and high relative humidity which limits evaporative cooling (Fig. 2.1). Out of the 28 known snow storage locations, our study location has the highest average June–July–August temperature (24 °C) and highest solar-radiation levels (Worldclim – Global Climate Data, http://worldclim.org/version2, last access: 14 September 2019). In this paper, we report data on the rate of volumetric change of snow stored over the summer and consider those data in the context of both ground temperature and meteorological data that together help define the energy flux, which is responsible for melt into and out of the snow piles. The goals of this research are to (1) determine the rate of volumetric change of small experimental snow piles, (2) suggest an optimized snow storage strategy based on those data, and (3) test the optimized strategy on a larger snow pile sufficient for ski area opening. Our data fill a research gap in measurements of volumetric change during snow storage and provide a novel case study for snow storage at low-elevation and midlatitude sites.

2.3 Background

Although the physics of snowmelt has been considered extensively (Dunne & Leopold, 1978; Horne & Kavaas, 1997; Jin et al., 1999), there has been limited application of physical and energy transfer knowledge to the problem of over-summer snow storage (Grünewald et al., 2018). Snowmelt occurs when the snowpack absorbs
enough energy to raise snow temperature to the melting point (0 °C) and then absorbs additional energy to enable the phase change from solid to liquid water (0.334 MJ kg\(^{-1}\)).

The snowpack gains energy from incoming short- and long-wave radiation, sensible and latent heat transfer from condensation of atmospheric water vapor and cooling and refreezing of rainwater, conduction from the underlying ground, and advective heat transfer from wind (Dunne & Leopold, 1978). Loss of energy from the snowpack occurs through convective and conductive heat transfer to the air, evaporative cooling, and long-wave emission to the atmosphere.

Both regional and local climatic factors influence the energy balance of snow. Short-wave radiational gain is related to latitude (highest near the Equator and least near the poles), elevation, time of year (greatest in summer and least in winter), snow pile surface albedo, slope and aspect, and cloud and tree canopy cover. Long-wave radiation balance depends on atmospheric emissivity, cloudiness, vegetation cover, and temperature of the snow pile surface. Rain falling on the snowpack transfers heat. Conductive heat transfer from the ground depends on soil thermal conductivity and temperature (Kane et al., 2000; Abu-Hamdeh, 2003). Snowmelt typically varies on a diurnal cycle, with melt increasing after sunrise, peaking in the afternoon, and decreasing after sunset (Granger & Male, 1978). Once surface melt occurs, water either refreezes if it percolates into a sub-freezing snowpack, flows through an isothermal (0 °C) snowpack and then infiltrates into the ground below, or flows along the ground surface below the pile, depending on the soil infiltration rate (Schneebeli, 1995; Ashcraft & Long, 2005).

Recent research at nordic ski centers in Davos, Switzerland, and Martell, Italy (Grünewald et al., 2018), has applied snowmelt physics to optimize over-summer snow
storage at high-elevation (1600 m) and midlatitude (46° N) sites. The Davos location has an average summer relative humidity of 79%. Each nordic center built piles of machine-made snow and covered them with 40 cm of wet sawdust and woodchips; researchers then used utilized terrestrial laser scanning to measure the initial (spring) and final (fall) volumes of the two piles. These snow piles retained 74% and 63% of their volume over the summer. Using a physically based model, Grünewald et al. (2018) suggested that the most effective cover, in relation to work and cost, was a 40 cm thick layer of mixed wet sawdust and woodchips, which reduced energy input into the pile by a factor of 12 (1504 MJ m⁻² without woodchips as opposed to 128 MJ m⁻² with woodchips). Deeper cover layers can save more snow, but costs are higher. During the day, solar radiation caused evaporation from surface woodchips while capillary flow continually supplied moisture from the melting snow to the surface. The wet woodchips and sawdust also provided thermal mass, slowing the transfer of energy from the surface to the snow beneath.

Lintzén and Knutsson (2018) reviewed current knowledge of snow storage and experience from areas in Scandinavia and reported new results from an experiment in northern Sweden, analyzing melt loss of stored snow. They report that the most common snow storage method employs a breathable surface layer over an insulating material. From field observations at multiple nordic ski centers, they have found that the choice and age of covering affects the melt rate; older woodchips were less effective at reducing melt than fresh chips. Lintzén and Knutsson also determined that woodchips were a more effective cover than bark. They measured snow volumes three times over the summer and found that higher relative humidity increased the melt rate. They also investigated the geometry of snow piles and determined that shaping piles, in a way that maximized the
ratio of volume to surface area, minimized melt loss; however, steeper snow pile sides caused sliding and failure of cover materials (Lintzén & Knutsson, 2018).

Data related to snow storage for the purpose of summer cooling to improve energy efficiency and comfort supplements those gathered from ski centers. In central Sweden, the Sundsvall Hospital conserves snow over the summer for air conditioning with a 140 m X 60 m storage area (holding 60,000 m$^3$ snow) underlain by watertight asphalt (Nordell and Skogsberg, 2000). After covering with 20 cm of wood-chips, the majority of natural snowmelt resulted from heat transfer from air (83%), while heat transfer from groundwater drove 13% of melt and heat from rain accounted for 4% of melt. Similar work was done by Kumar et al. (2016) and Morofsky (1982) in Canada and by Hamada et al. (2010) in Japan.

2.4 Setting

We conducted our experiment at the Craftsbury Outdoor Center (COC), a sustainability-focused, full-year recreation venue located in northeastern Vermont at 360 m a.s.l. (Fig. 2.1), an area with warm, humid summers and cold, dry winters. The COC maintains 105 km of groomed nordic ski trails and hosts national and international races several times each winter. Average maximum monthly air temperature at St. Johnsbury, Vermont (closest National Oceanic and Atmospheric Administration – NOAA – station to the COC about 30 km southeast; at 215 m a.s.l.), between 1895 and 2018 ranges between 3.6 °C (January) and 29 °C (July), mean temperature ranges from 8.3 °C (January) to 20.7 °C (July), and minimum air temperature ranges between 34 °C (December) and 15 °C (July, Climate Summary for Saint Johnsbury, VT,

2.5 Methods

2.5.1 Initial snow pile experiments

On 30 March 2018, two snow piles were emplaced at the COC using PistenBully snow groomers at two separate sites (Fig. 2.2). Site 1 is adjacent to the COC’s main campus buildings in direct sunlight, with minimal wind protection. Site 2 is 1 km north of Site 1, within a cleared depression in the forest which also is in direct sunlight but more protected from wind than Site 1. At the time of emplacement, the snow was transformed and had a density of > 500 kg m\(^{-3}\). At Site 1, 225 m\(^3\) of machine-made snow was banked against a north-facing slope. At Site 2, 210 m\(^3\) of natural snow was shaped into a symmetrical, rounded pile. The two piles were draped with thin sheets of clear plastic. The plastic sheets, about 0.15 mm thick, were impermeable and emplaced to prevent woodchips from mixing with the snow. The piles were then covered with an irregular layer of woodchips averaging 20 ±10 cm (1 SD) on 21 April 2018; chip thickness ranged from a minimum of 6 cm to a maximum of 40 cm (Fig. 3). In early July, about 50 m\(^3\) of snow
were removed from the pile at Site 1 by COC personnel, the plastic was removed, and the remaining snow was covered again with woodchips and left for continued monitoring.

2.5.2 Weather stations

Weather stations adjacent to each pile and 3–4 m above the ground surface (Davis Vantage Pro2) collected air temperature, humidity, precipitation, solar-radiation, wind speed and direction, and barometric-pressure data. The weather stations record data at 15 minutes intervals and transfer them to the Web, where they are publicly accessible (https://wunderground.com/personal-weather-station/dashboard?ID=KVTCRAFT2#history, last access: 23 October 2019). Local soil temperature was measured with temperature sensors installed at four depths within the soil (5, 20, 50, and 100 or 105 cm below the surface) adjacent to each snow pile. Two HOBO Onset data loggers recorded temperatures at four depths at 20 min intervals between June 2017 and October 2018.

2.5.3 Terrestrial-laser-scanning field methods and processing

During spring and summer, the shape and volume of the piles were measured every 10–14 days using a terrestrial laser scanner (RIEGL VZ-1000). Terrestrial laser scanning (TLS) is an accurate method for obtaining digital surface models (DSMs) of various terrain types, including snow surfaces (Prokop et al., 2008; Molina et al., 2014). Six to ten permanent tie points around each pile were established during the initial survey by fastening reflective 5 cm disks to stable surfaces such as large trees and buildings. The first survey was done prior to snow pile placement in order to establish ground surface topography. Tie-point locations were determined and fixed relative to the scanner GPS position during the initial scan. Each survey consisted of three or four scans per site.
(depending on available vantage points), which were combined in the RiSCAN Pro software version 2.6.2 (RIEGL Laser Measurement Systems GmbH: RiScan Pro, 2011). Scan registration was done in RiSCAN using a combination of tie-point registration (finding corresponding points) and the multi-station adjustment routine using plane patches and tie objects. Similar studies of monitoring bare and covered snow surfaces with TLS have applied this technique (Prokop et al., 2008; Grünewald et al., 2018; Grünewald and Wolfsperger, 2019). Scans were collected at a horizontal and vertical angular resolution of 0.08°. Scans were collected from distances less than 100 m, resulting in average point spacing over the pile <1 cm.

To calculate snow pile volumes and volumetric change over time (between scans), point clouds of each pile were processed into DSMs. Processing the workflow involved cropping the point cloud to the area of interest in RiSCAN Pro and exporting cropped point clouds into LAS format, projected into Vermont State Plane NAD83 coordinates. Point clouds were converted to a 10 cm resolution DSM using the min-Z filter and QT Modeler software (version 8.0.7.2) and adaptive triangulation to fill in small data gaps. Volume calculations and differences in volume between sequential surveys were calculated in QT Modeler using these DSMs.

2.5.4 Density

Snow density was measured using a Rickly Federal Snow Sampling Tube. The snow tube was weighed, pushed into the snow, removed, and weighed again. The weight of the tube was subtracted from the combined weight of the snow and tube, and density was calculated by dividing the mass of snow by its volume (length of snow within the tube multiplied by the area of the opening; 13 cm²). Density was collected three times (in
March, May, and July) at the top surface of pile 1 during 2018. In 2019, density was collected once at the top of the pile in February.

### 2.5.5 Cover experiments

Cover experiments were performed at both sites in June and July 2018. At Site 1, two 5 cm thick, impermeable, rigid foam boards ($R = 3.9$ per 2.5 cm; value expressing resistance to conductive heat flow) were stacked and compared to a 20 cm uniform, porous layer of woodchips ($R = 1.4$ per 2.5 cm) both with and without a reflective cover (aluminized space blanket) (snow’s $R$ value is 1 per 2.5 cm). At Site 2, we covered snow with a double-layered, 2.5 cm thick insulating concrete curing blanket ($R = 3.3$ per 2.5 cm) and overlaid the blanket with either open-cell, permeable foam ($R = 3.5$ per 2.5 cm) or a uniform, porous layer of woodchips (20 cm thickness), both with a reflective cover. For both foam experiments, woodchips and plastic sheeting were removed from the test area. For woodchip experiments, plastic sheeting was removed from the test area. Individual cover experiments were conducted in areas of 1 m$^2$ each, with thermosensors placed in the center of each quadrat at varying depths between layers (Table 2.2; Fig. 2.4).

### 2.5.6 Power spectral density function

We computed the power spectral density (PSD) function to determine relative effectiveness of the different covers. The temperature signal is first decomposed in a series of waves of well-defined frequencies:

$$T(t) = \frac{1}{N} \sum_{k=0}^{N-1} \hat{I}_k \exp(i2\pi f_k t) ,$$
where $T^*_k$ is the Fourier mode at frequency $f_k \frac{k}{2\Delta T}$, $1/\Delta T$ is the sampling frequency of temperature acquisition, and $N$ is the number of samples in the time series. The Fourier mode contains both amplitude and phase information for each wave. The PSD is the power of the signal:

$$\text{PSD}(T) = \frac{\Delta t}{N} \sum_{k=0}^{N-1} |\hat{T}_k|^2,$$

The power of the signal is the sum of the contributions of each wave to the power (or variance) of the signal. Typically plotted on a log–log plot, the norm of the Fourier modes as a function of frequencies is a powerful tool for detecting dominant frequencies (Welch, 1967). In the summer, the dominant oscillation in temperature is diurnal; thus, using PSD, we can judge the effectiveness of cover materials by their ability to damp the diurnal temperature signal and relevant harmonics. We computed the PSD for all temperature records in selected cover experiments (Fig. 2.4b, e, f).

### 2.5.7 Validating cover method, summer 2019

Based on data collected during summer 2018, the COC chose Site 2 (Fig. 2.2) as their snow storage site for 2019. Cost and ease of installation mandated a two-layer cover system – a 30 cm thick layer of woodchips capped with a reflective, permeable covering. No plastic was placed between the woodchips and the underlying snow. The 2019 snow pile filled a drained, oblong pond basin and was gently sloped. During February, machine-made snow was blown into the pile using fanless snowmaking wands. Snow density at and just after emplacement was high, ranging between 500 and 600 kg m$^{-3}$ then compacted with PistenBully groomers and excavators; at that time, TLS showed that the pile had a volume of about 9300 m$^3$ without woodchips. During the next 6 weeks, the
snow pile was allowed to compact and grow denser. In late April, most of the pile was covered in woodchips. By the end of May, additional woodchips were obtained and snow pile covering was completed (total woodchip volume 650 m³). Using the exposed surface area of the pile without woodchips (2300 m²) and the volume of woodchips, we calculate that the average woodchip thickness was 28 cm. By the end of June, the snow pile was covered in a white, 75 % reflective, breathable Beltech 2911 geofabric, secured by ropes and rocks to prevent wind disruption. Between March and October, the pile was repeatedly scanned using TLS; data were processed using methods described below.

2.6 Results

2.6.1 Meteorological Data/Ground Temperature Data

Climate at the COC is strongly seasonal – such seasonality is clear in the meteorological data collected between June 2017 and October 2018 (Fig. 2.5). Between June 2017 and October 2018, air temperature varied between 28.2 and 33 °C (mean annual temperature of 9 °C). Precipitation fell at a maximum rate of 22 mm d⁻¹ (mean of 0.01 mm d⁻¹), and relative humidity ranged between 14 % and 93 % (mean 78 % ± 15%). Solar radiation had a 24 h average of 109 W m⁻² and maximum of 1144 W m⁻² (Table 2.1). Air temperature and solar radiation followed similar trends over the 16 months, decreasing during winter months and increasing during summer months. Precipitation did not follow any significant pattern, and relative humidity remained high (NOAA classifies above 65% as high, and relative humidity remained above this level for the summer), varying more during summer than winter months. Average summer temperature in 2018 (June, July, and August 2018; 22.4 °C) was ranked by NOAA as
“Much above the average of 20.7 °C”; in 2019, average summer temperature ranked “above average” (21 °C). Both years had near-average precipitation (National Oceanic and Atmospheric Administration Forecast Office, Burlington VT, 2018; Craftsbury Outdoor Center KVTCRAFT2, https://www.wunderground.com/personal-weather-station/dashboard?ID=KVTCRAFT2#history, last access: 12 December 2018).

Ground temperature from all four depths at both locations followed similar trends. The shallowest sensor (5 cm below the surface) recorded the greatest variance over time (SD = 7.4 °C for Site 1). Ground temperature variations decreased in amplitude as soil depth increased; at 1 m in depth, the atmospheric temperature signal was damped (SD 3.9 °C for Site 1). Ground temperatures for all depths showed consistent warming from installation (11 June 2017) through late August 2017 and then decreased through February 2018. The shallowest sensor revealed slight warming after February, while the deeper sensors remained stable until May 2018. During May, warming increased more noticeably for all four sensors. Ground temperature depth trends inverted during both May and November. During the winter, the coldest temperatures were at the surface; during summer, the coldest temperatures were at depth. Figure 2.5 displays data from sensors adjacent to pile 1; data were collected at both sites but are missing from Site 2 between 12 December 2017 and 21 April 2018.

2.6.2 Snow volume and density

Snow in both 2018 piles lasted until mid-September; however, snow volume decreased consistently throughout the summer (Figs. 2.6 and 2.7). Comparing the laser-scan survey completed just after woodchip emplacement with the initial bare snow survey showed that the layer of chips ranged in depth from 6 to 40 cm, with an average
of 19±11 cm for pile 1 and 21±11 cm (1 SD) for pile 2 (Fig. 2.3). After the addition of
woodchips, snow volume in both piles decreased following similar trends (Fig. 2.7);
initial decreases in volume were partly related to compaction and increases in snow
density, as snow density was 500 kg m$^{-3}$ at emplacement, 600 kg m$^{-3}$ in May, and 700 kg m$^{-3}$ in July. Relative to newly fallen snow (100–200 kg m$^{-3}$), the snow in these piles was
closer in density to ice (900 kg m$^{-3}$). These measurements are supported by qualitative
observations of changes in snow crystal morphology over the summer (increased
rounding), increasing size (up to 5 mm by July), wet- ness (higher liquid water content),
and clarity (from white to clear by summer’s end). Continued volume loss over the
summer was predominately the result of melt. Average rates of volume change for both
piles were relatively similar (1.24 and 1.50 m$^3$ days$^{-1}$), representing 0.55 % to 0.72 % of
initial pile volume per day. Maximum loss rates, recorded in July, reached 1.98 and 2.81
m$^3$ day$^{-1}$ (Fig. 2.7). As summer shifted into fall, the loss rate decreased (Fig. 2.7).
Minimum rates of change for both piles occurred in September and were 0.29 and 0.88
m$^3$ day$^{-1}$.

As the piles decreased in volume over the summer, crevasses formed along the
edge of the plastic sheeting, which exposed the snow to direct sunlight and thus increased
rates of volumetric change (Fig. 2.6). On pile 1, a crevice formed from east to west where
the pile began to slope downward (Fig. 2.6b). Slope failure was a potential catalyst for
the formation of crevices. We did not observe meltwater around either of the piles,
suggesting that melt occurred at a rate which allowed for infiltration into the rocky sandy
loam soil below. The woodchips deeper in the cover remained cold and wet throughout the
summer, while the woodchips on the surface were consistently dry in the absence of rainfall.

2.6.3 Cover experiments

Thermal buffering is a function of air temperature, long-wave emissions, and turbulent fluxes. We chose temperature at the snow–cover interface to indicate cover efficiency because all experiments were subjected to similar external conditions and because we have continuous data series of temperature in, above, and below the cover during each of the experiments. Two experiments performed on 1 m$^2$ plots on each snow pile revealed that different combinations of cover materials resulted in a variety of cover efficiencies (Fig. 2.4). Each experiment lasted between 1 and 3 weeks and took place in June and July, respectively. We assessed cover efficiency by determining which material combination maintained the lowest and steadiest temperature at the snow–cover interface and which most effectively damped the diurnal temperature signal (detected using PSD analysis). On the rigid foam, open-celled foam, and woodchip plots, the highest temperature was measured in the air above the surface (max of 51 °C; Fig. 2.4f). During the first experiment, air temperatures above the reflective blanket were higher than above the non-reflective surface. When all plots were covered with a reflective blanket, all air temperatures above the pile were similar; however, temperatures at lower depths, and under different cover materials (woodchips and open-cell foam), varied significantly. The lowest and most stable temperatures at the snow–cover interface resulted when the stored snow was covered directly with an insulating concrete curing blanket, then with 20 cm of wet woodchips, and finally with a reflective sheet.

2.6.4 Power spectral density
PSD analysis provides insight into the dynamics of heat transfer in the snow piles. Figure 2.8 shows the log–log plot of temperature power spectral densities for three different cover experiments. It is important to realize that (i) each line represents the PSD at specific distance from the snow surface, (ii) that the integral under each line is equal to the standard deviation of the signal, or the energy of the signal fluctuations, and (iii) that the horizontal axis is frequency, thereby breaking down the total energy of the temperature signals into the individual contributions of each frequency involved in the PSD. Furthermore, the frequency is normalized by the frequency of 1 day or diurnal frequency $f_{\text{diurnal}} = 1/(24/3600)$. Consequently, the horizontal coordinates 1, 2, and 4 are the diurnal (1 per 24 h), half-diurnal (1 per 12 h), and quarter-diurnal (1 per 6 h) frequencies, with 2 and 4 being harmonics of the diurnal frequency. These frequencies are highlighted by the peaks in the PSD of temperature outside of the pile (the air T sensor at 46 cm). The PSD values at these frequencies are much higher than the values at surrounding frequencies, indicating that their contribution to the total energy of the signal, and therefore to the dynamics of heat transfer, is significant.

Detection of diurnal temperature swings and their harmonics in temperature records collected at different depths in the cover materials with various relative strengths is critical to understanding how cover materials minimize heat transfer. In the foam cover experiment (Fig. 2.8c), the diurnal frequency and its harmonics are detectable in all layers; however, the three-layer system (insulating blanket, wet wood-chips, and reflective cover; Fig. 2.8b) fully damps all oscillations, as shown by the flatness of the PSD below the cover (0 cm; snow T sensor; thick blue line). In the absence of an insulating blanket, the two-material cover system (reflective cover and woodchips) is
slightly less efficient at damping the diurnal oscillation (Fig. 2.8a). In the case of foam, the dynamics of heat transfer at the surface, or cyclic events that drive fluctuations of temperature, are directly and efficiently transmitted to the snow surface. Such a response can be modeled as quasi-steady heat transfer conduction, which is not surprising for an inorganic dry material.

Woodchips profoundly affect the dynamics of heat transfer, and in the most dramatic case (Fig. 2.8b), the snow surface temperature appears to be insensitive to the diurnal and harmonic frequencies of atmospheric temperature. This indicates that the system can no longer be modeled under quasi-steady-state conduction but requires at least the time- and depth-dependent heat transfer equations with a damping mechanism. The damping might be storage and release of heat through convection and/or the phase change of water from liquid to vapor and back within the woodchip layer. Overall, relative cover material effectiveness can be ranked in Fig. 2.8 as most efficient (Fig. 2.8b), efficient (Fig. 2.8a), and least efficient (Fig. 2.8c).

2.6.5 Summer 2019

The 9300 m$^3$ snow pile emplaced in 2019 lost volume at an average rate of 15 m$^3$ d$^{-1}$ (min of 5 m$^3$ d$^{-1}$ in early April and max of 25 m$^3$ d$^{-1}$ in early July). Between the initial TLS survey in March and the last survey in October, the pile lost 3700 m$^3$ of snow, a 40 % volume loss (not including woodchips). The average percentage loss per day was 0.16 % of the initial volume. In comparison to the 2018 snow piles, the pile lost volume more uniformly; no crevices formed and no slumping occurred (Fig. 2.9), although the surface did become rougher by October, and we noted more surface lowering near dark-colored rocks and logs emplaced to hold down the white, reflective covering. Volume loss
between 11 May and 25 August (the most intensive melt season) was similar in all four quadrants of the pile, each of which experienced an average of 0.9 m lowering. More lowering occurred on the pile boundaries, specifically along the western margin, as shown clearly by the blue and purple colors in Fig. 2.9a.

2.7 Discussion

Data we collected allow us to (1) determine the volumetric change rate of small snow piles stored over summer with different coverings, (2) suggest an optimal snow preservation strategy for low-elevation, midlatitude sites based on these data, and (3) test this optimized snow storage strategy at scale.

2.7.1 Experimental snow pile melt rate

The survival of small (200 m$^3$) snow piles through the warmer-than-average summer of 2018 and the results of both repeated TLS surveys and continuous in situ thermal data collected during a variety of different snow cover experiments suggest ways of optimizing over-summer snow storage at low elevations and midlatitudes. The 2018 snow piles experienced nonuniform cover and nonideal geometry and developed crevices that exposed snow to direct sunlight, all of which increased the rate of snowmelt and thus volume loss. Field observations and TLS surveys demonstrated that the thickness of woodchips covering the snow was not uniform and became less uniform over time as melt changed the pile shape (Fig. 2.3). Woodchip depth changed over the summer as crevices, which grew over time, exposed bare snow to direct sunlight, which led to rapid and nonuniform pile melting (Fig. 2.6). Crevices formed along boundaries of the large plastic sheets, which were emplaced to prevent woodchips from mixing with the snow. Openings in the woodchip cover also resulted from snow slumping within the pile – both piles had
steep sides, and the DSMs revealed snow moving downslope (Fig. 2.6). Lintzén and Knutsson (2018) reference similar snow pile and cover failure due to steep pile-side geometry.

Snow pile size impacts the rate of volumetric change significantly. The two test piles were small, only a few percent of the volume of snow typically stored over summer by Nordic ski areas. For example, in Davos, Switzerland, and Martell, Italy, test piles were about 6000 and 6300 m³ (Grünewald et al., 2018). The Nordkette nordic ski operation in Innsbruck, Austria, stores 13,000 m³ of snow, and Östersund, Sweden, stores 20,000 to 50,000 m³ piles. Small piles have a larger surface-area-to-volume ratio (SA / V), which allows more effective heat transfer through radiation, conduction, and latent heat transfer. A simple comparison of two hemispheres, one containing 200 m³ of snow and the other containing 9000 m³ of snow, indicates that SA / V changes from 0.66 to 0.23 between the smaller and larger pile. As larger piles have a SA / V ratio that is 3 times lower in comparison to smaller piles, there is comparatively less snow near the surface thermal boundary, which decreases heat transfer per unit snow volume and thus the melt rate as a percentage of pile volume.

2.7.2 Optimal approach for over-summer snow preservation at midlatitude and low-elevation sites

The 2018 survival of snow through the summer in small piles with only simple woodchip, foam, and reflective coverings suggested that larger piles, using an optimized cover strategy, will allow for practical over-summer snow storage at midlatitude (< 45° N) and low-elevation (< 350 m.a.s.l.) locations. Our results are encouraging given the relative warmth of the 2018 summer season, the simple and spatially inconsistent nature
of our cover material (20±10 cm of woodchips), and the small size of the test piles (200 m³). Previous snow storage studies found success with woody covers as well but in different geographic settings. Grünewald et al. (2018) suggested that a 40 cm layer of sawdust sufficiently optimized snow retention in Davos, Switzerland, and Martell, Italy. Skogsberg and Nordell (2001) reported that woodchips reduced snowmelt by 20%–30% at the Sundsvall Hospital in Sweden. Lintzén and Knutsson (2018) built snowmelt models and ran field tests in northern Scandinavia, revealing that thick layers of woody materials successfully minimized snowmelt. In practice, financial constraints often control the choice of cover strategies. For example, the thicker the layer of woodchips, the better protected the pile will be and the less over-summer melt will occur. However, using more chips increases cost (Grünewald et al., 2018).

The experimental data (Fig. 2.4) show that the magnitude of daily temperature oscillations at the snow surface below the covering (blue line in all panels) is highly dependent upon the cover strategy. For example, in Fig. 4c, the temperature within the rigid foam board increases above air temperature (purple line increasing above the yellow line). Due to the rigidity of the foam boards and the nonuniform melting of the pile, the foam shifted and exposed snow to direct solar radiation, allowing warm air to move between the snow and the foam. Such failure of the cover system allowed temperatures at the snow interface to rise significantly above 0 °C. The three-layer cover (insulating blanket, wet woodchips, and reflective cover) minimizes heat transfer into the stored snow, as evidenced by the lack of diurnal temperature oscillations at the snow surface during this and only this experiment (Fig. 4e). The comparison between foam and saturated woodchips PSDs (Fig. 2.8) shows the dramatic effect on the heat transfer
from the atmosphere to the snow caused by the high heat capacity and thus thermal inertia of wet woodchips. The damping of diurnal temperature peaks by the three-layer cover system suggests that it will be the most effective for preserving snow over the summer.

Although the relevant heat transfer mechanisms remain uncertain, Fig. 2.8 demonstrates the effectiveness of the three-layer cover approach to buffering heat transfer from the environment to the snow. Deducing specific heat transfer mechanisms will require different and more complex measurements, as heat transfer is dependent on not only air temperature but also surface temperature, long-wave radiation, and turbulent fluxes. Perhaps evaporation of water from the wet woodchips absorbs thermal energy during the day which is released as the latent heat of condensation at night when the reflective blanket cools – effectively increasing the thermal mass of the woodchip layer.

Depending on weather conditions, which influence long-wave radiation through cloudiness and turbulent fluxes through wind, the heat transfer may be directed toward the snow pile (warm nights) or radiated to the atmosphere (cold nights). In any case, the large thermal mass of wet woodchips, in concert with an underlying layer (the concrete curing blanket), and rejection of short-wave incident radiation from sunlight by the reflective cover, appears more important than the insulating capability ($R$ value) of the cover material in damping daily temperature fluctuations at the snow surface.

**2.5.3 Summer 2019, testing the optimized snow storage at scale**

Field data, TLS, and thermal observations from the 2018 experiments allowed for a full-scale test of our optimized snow storage strategy in 2019. Optimization began by further excavating the storage area so that the resulting pile would sit within a pit and have gently sloping sides to reduce the chance of mass movements and crevassing on the
pile margins. Snowmaking was tuned so that the density of the snow emplaced was already high; this minimized settling after covering. The snow was then compacted by repeated passes of large excavators and PistenBully groomers. Letting the snow settle and transform before covering also reduced the chance of mass movements which, in 2018, compromised pile and cover integrity. Results from the 2018 cover material experiments (most effective was a reflective cover, woodchips, and a concrete curing blanket) informed the 2019 covering method (Fig. 2.8). Rather than use metallized cover material, which was expensive, fragile, and impermeable, we used a high-albedo (0.75), white, permeable geofabric that allowed rain to infiltrate, thus mitigating regulatory concerns related to a large impermeable area. Concrete curing blankets were not used in 2019 due to cost and logistical complications of emplacement.

The 2019 pile, using an optimized strategy, confirmed the viability of snow storage at the COC. The most rapid volume losses in 2019 were in the midsummer; while they were higher in absolute terms than those in 2018 because the pile was 45 times larger, they were more than 3 times lower in percentage terms. Most melt was focused along the western boundary, perhaps because the snow here was thin or not as thickly covered by woodchips or because western sun exposure occurs late in the day when the air temperatures are warmer; there is likely less net radiative cooling along the western side of the pile, as there is a steep, forested slope immediately adjacent to the snow storage area. Compared with the average percentage loss per day of the 2018 piles (0.64 % per day), the 2019 snow pile average percentage loss per day was 0.16 %. We suspect that the difference in volume loss reflects primarily the surface-area-to-volume ratio of the 2019 snow pile, which is about 3 times less than the small piles tested in 2018. A 3-fold
change in the SA\(\, V\) ratio compared with a 4-fold reduction in the percentage volumetric change rate suggests the impact of an improved cover strategy. The complete covering of the 2019 pile with a reflective geofabric likely slowed melt by rejecting short-wave radiation as well as protecting the snow even if the woodchips shifted. TLS imagery from 2019 demonstrates that gentle side slopes of the pile prevented any large mass movements of snow, indicating that pile shape and snow pre-consolidation are important (Fig. 2.9).

TLS data show that from April until mid-October, about 60% by volume of the snow initially placed in the April 2019 pile remained. Considering the snow density data gathered from the 2018 piles, which increased from 500 to 700 kg m\(^{-3}\) over the summer, some of this volume loss could be accounted for by compaction rather than melting. This suggestion is supported by the lack of surface water draining from the 2019 pile, which is underlain by relatively impermeable rock and clay-rich glacial till. With fall temperatures and the sun angle dropping, incident solar radiation as well as convective and conductive heat transfer are diminished greatly from midsummer values. This means that the COC will have > 5000 m\(^3\) of snow to spread in November for early-season skiing. Covering 5 m wide trails 50 cm deep will allow at least 2 km of skiing at opening and will provide a base so that any natural snow that does fall will be retained.

### 2.8 Conclusions and Implications

Data presented here show that snow storage at midlatitudes and low elevations is a practical climate change adaptation that can extend the nordic ski season and the sport’s viability as the climate continues to warm. Using 14 terrestrial-laser-scan surveys between March and September 2018, we determined rates of volumetric change of two
200 m³ snow piles covered in woodchips. Average volume loss rates were 1.24 and 1.50 m³ d⁻¹, with the highest rates of volumetric change in July and the lowest rates of volumetric change in September. A three-layer cover approach was most effective: a concrete curing blanket, a 20 cm layer of woodchips, and a reflective covering. This cover approach reduces solar gain and buffers the effect of > 30 °C summer daytime temperatures and high (> 78 %) relative humidity on stored snow. Using data collected during summer 2018, we tested our experimental results in summer of 2019 by creating a 9300 m³ snow pile. Due to cost and logistical issues, we covered the pile using a two-layer approach – 650 m³ of woodchips and white, permeable geofabric. The average volume loss rate between March and October was 15 m³ d⁻¹ (or 0.16 % of the initial volume per day). About 5600 m³ of snow remained as the melt season ended in mid-October. This quantity of snow is sufficient for the COC to open their 2019 season and represents 60 % retention of snow by volume, comparable to storage losses at other storage sites (at higher elevation and latitude). Future research could analyze financial and environmental feasibility of snow storage at different global locations and focus on heat transfer mechanisms of different cover materials. Research could also explore other climate change adaptation strategies for nordic ski centers that minimize carbon emissions and maximize operational success.

2.9 References


Pestereva, N. M.: Modern engineering technology to adapt to the adverse weather and climatic conditions at mountain ski resorts, Life Sci. J., 11 (9), 800-804,, 2014


Skogsberg, K.: Seasonal snow storage for space and process cooling, Ph.D, Department of Civil, Environmental and Natural Resources Engineering, Luleå tekniska universitet, 2005.


2.10 Figures

Figure 2.1: Locations of known over-summer snow storage sites (both currently active and inactive). (a) Conical projection shows known locations of over-summer snow storage at nordic ski centers. The Craftsbury Outdoor Center is highlighted with a blue arrow, which is labeled COC. The relative elevations of ski centers are displayed as a color gradient, marked in the legend. (b) Scatterplot of same locations as shown in (a). The Craftsbury Outdoor Center (no. 3) is large yellow dot (COC). It has the lowest combination of elevation and latitude of any snow storage yet attempted.
Figure 2.2: Snow storage at Craftsbury Outdoor Center. (a) Aerial view of the Craftsbury Outdoor Center (COC) in Vermont, from http://maps.vcgi.vermont.gov (8 February 2019). Both study site locations shown by number. (b) Site 1 (225 m$^3$), covered in woodchips on 21 April 2018, with trees and solar panels for scale. (c) Site 2 (210 m$^3$) when installed. Site 1 received 24 m$^3$ of woodchips, and Site 2 received 42 m$^3$ of woodchips. Person for scale. (d) Site 2 in April 2019; 9300 m$^3$ of snow, eventually covered with 650 m$^3$ of woodchips. (e) Site 2 in July 2019, the snow pile overlain by a reflective geofabric. Trees for scale.
Figure 2.3 Woodchip thickness distribution maps of pile 1 (a) and pile 2 (b), with red indicating areas of high thickness and blue indicating areas of low thickness. Panel (c) represents the chip thickness histogram for pile 1, and (d) is chip thickness histogram for pile 2. Negative thickness values likely represent snow settling between bare-snow survey and survey after woodchip emplacement.
Figure 2.4: Cover experiments and resulting temperature records. (a) Site 1 – woodchips. (b) Site 1 – woodchips overlain by reflective cover. (c) Site 1 – foam. (d) Site 1 – foam overlain by reflective cover. (e) Site 2 – woodchips underlain by concrete curing blanket and overlain by reflective cover. (f) Site 2 – open-cell foam underlain by concrete curing blanket and overlain by reflective cover.
Figure 2.5: Meteorological conditions and soil temperature between 11 June 2017 and 16 October 2018. Weather conditions were collected by a Davis weather station at the Craftsbury Outdoor Center near Site 2. (a) Air temperature (grey), collected at 30 min intervals plotted with ground temperatures. Ground temperatures were collected at 20 min intervals adjacent to Site 1 by four HOBO Onset data loggers at depths below the ground surface of 5 cm (blue), 10 cm (orange), 50 cm (green), and 105 cm (red). Ground temperature record ends on 2 September 2018. (b) Relative humidity (%). (c) Precipitation (mm d\(^{-1}\)). (d) Solar radiation (W m\(^{-2}\)).
Figure 2.6: Snow pile topographic change over time in 2018. (a) Oblique view of digital surface model (1 m contours) of 2018 snow pile at Site 1 with cross sections A–A’ and B–B’ (21 April 2018). (b) Profiles for each terrestrial-laser-scan survey (21 April to 9 September 2018; n = 13) along section A–Ar. (c) Profiles for each survey along section B–B’. On 3 July 2018, 50 m³ of snow was removed from the pile at Site 1. (d) Oblique view of digital surface model (1 m contours) of 2018 snow pile at Site 2 with cross sections C–Cr and D–D’ (21 April 2018). (e) Profiles for each terrestrial-laser-scan survey (21 April to 9 September 2018; n = 12) along section C–Cr. (f) Profiles for each survey along section D–D’. Each scan represented by a line in panels (b), (c), (e), and (f) as indicated in key.
Figure 2.7: Volume change over time for snow piles at sites 1 and 2 measured by terrestrial laser scanning. (a) Volume of snow piles from placement in March 2018 until September 2018. Addition of woodchips in April and removal of snow in July at pile 1 shown by black arrows. Volumes are total, including woodchips. (b) Change in volume per unit time between surveys. The rate of volume loss increases midsummer for both piles. Site 1 received about 24 m$^3$ of woodchips, while Site 2 received about 42 m$^3$ of woodchips – this difference is due to pile geometry and the resulting difference in surface area. Site 1 snow was banked against the side of a hill, while the Site 2 pile was a hemisphere in the middle of an open depression. (c) Volumes of snow pile (2019) beginning in March and ending in October. Addition of woodchips throughout May and addition of white tarp are indicated by black arrows. Volumes include woodchip volume. (d) Change in volume per unit time between surveys.
Figure 2.8: Power spectral density of temperature records from three different cover experiments (Fig. 2.4b, e, and f). PSD normalizes frequency to 24 h 100 and displays the magnitude of each temperature oscillation frequency for each sensor per experiment (depth in centimeters measured above sensor at the snow – 0 cm). (a) Experiment with woodchips and reflective cover (Fig. 2.4b). (b) Experiment with a concrete curing blanket, woodchips, and a reflective cover (Fig. 2.4e). (c) Experiment with concrete curing blanket, open-cell foam, and a reflective cover (Fig. 2.4f). The lack of detectable signal (flat blue line) at snow level (0 cm) in (b) demonstrates that three-layer configuration with woodchips best damps the diurnal temperature signal. Colors correspond to colors from Fig. 2.4.
Figure 2.9: Volume change of 2019 snow pile. (a) Spatial variability of elevation change 2019 snow pile between 11 May and 25 August 2019. Cross sections $A-A'$ and $B-B'$ are marked in black. (b) Profile for each terrestrial-laser-scan survey (3 March to 13 October 2019; $n=12$). (c) Profile for each terrestrial-laser-scan survey (2 March to 13 October 2019; $n=12$). Each scan represented by a colored line in panels (b) and (c).
### 2.11 Tables

**Table 2.1** Weather parameters measured between June 2017 and October 2019 at the Craftsbury Outdoor Center, Craftsbury VT

<table>
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<tr>
<th></th>
<th>Air temperature</th>
<th>Humidity</th>
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<td></td>
<td>(° C)</td>
<td>(%)</td>
<td>(mm day⁻¹)</td>
<td>(W m⁻²)</td>
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<tr>
<td>Minimum</td>
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<td>14</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Maximum</td>
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<td>93</td>
<td>22</td>
<td>1144</td>
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<tr>
<td>Mean</td>
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<td>79</td>
<td>0.1</td>
<td>109</td>
</tr>
<tr>
<td>Standard Deviation</td>
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<td>15</td>
<td>0.4</td>
<td>205</td>
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</table>

**Table 2.2** Locations of sensors within experimental coverings, during insulation experiments. See Fig. 2.4 for reference.

<table>
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<th>Plot reference Fig. 4</th>
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<tbody>
<tr>
<td>(a)</td>
<td>1</td>
<td>None</td>
<td>20 cm layer of woodchips</td>
<td>None</td>
</tr>
<tr>
<td>(b)</td>
<td>1</td>
<td>None</td>
<td>20 cm layer of woodchips</td>
<td>Reflective covering</td>
</tr>
<tr>
<td>(c)</td>
<td>1</td>
<td>None</td>
<td>Two stacked rigid foamboards</td>
<td>None</td>
</tr>
<tr>
<td>(d)</td>
<td>1</td>
<td>None</td>
<td>Two stacked rigid foamboards</td>
<td>Reflective covering</td>
</tr>
<tr>
<td>(e)</td>
<td>2</td>
<td>Concrete curing blanket</td>
<td>20 cm layer of woodchips</td>
<td>Reflective covering</td>
</tr>
<tr>
<td>(f)</td>
<td>2</td>
<td>Concrete curing blanket</td>
<td>20 cm layer of open-cell foam</td>
<td>Reflective covering</td>
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CHAPTER 3: THE COST OF SNOW STORAGE AT THE CRAFTSBURY OUTDOORS CENTER, CRAFTSBURY, VT

3.1 Abstract

As climate change threatens the livelihood of vulnerable ski centers, the Craftsbury Outdoors Center in northeastern Vermont has already employed an adaptation strategy: over summer snow storage. Though technically functional, neither the financial nor environmental cost of the project are known. These data can provide valuable business management insights to the COC and other regionally-similar ski centers interested in storing snow.

Here, we compiled a list of snow storage steps and analyzed each step for cost in dollars and environmental impact in pounds of carbon dioxide (CO$_2$) emitted. To contextualize cost, we calculated amortization and discussed monetary vs. non-monetary motivators for decision-making with the COC directors. To contextualize CO$_2$, we compared the emissions from snow storage to emissions from a cross-country plane flight to an open ski center. We found that in 2019 the project cost $126,800 and subsequent years would cost $12,800 if replacement materials were not required. If the project lasts 30 years, the amortization is $34,700 per year. Snow storage would be carbon-neutral if it prevented 35 skiers in 2019 from taking a cross country flight to an open ski center, and 20-25 skiers in following years. As these numbers are smaller than the number of skiers who recreationally and competitively ski at the Center, snow storage is environmentally feasible. Snow storage not only benefits the environment through reducing CO$_2$ emissions, but also benefits the Craftsbury Outdoors Center’s reputation for consistent and early skiing and supports their sustainability mission. As there are many benefits to
pursuing over summer snow storage, they will continue storing snow to maintain the ski season in the face of climate change.

3.2 Introduction

3.2.1 Climate change & skiing

Within the past couple decades, studies have increasingly explored climate change impacts on winter, and the resulting effects on industries such as winter tourism. Climate change is decreasing the quantity of snow falling each winter and shortening the ski season (Zeng et al., 2018). Research shows that annual snow fall and days below freezing in the U.S.A will decrease by 50% by the end of the twenty-first century, which will negatively impact the winter tourism industry (Guilbert et al., 2014; Horton et al., 2014). According to a 2007 vulnerability assessment, a ski area must operate at least 100 days per season to succeed economically (Dawson & Scott, 2007). With warmer weather beginning earlier and extending later in the year, shortened winters decrease the number of days a ski center can be open and decreases overall season length. By 2050, the length of the ski season in the northeast is predicted to decrease by over 50% and by 2090, is predicted to decrease by close to 100% (Wobus et al., 2017). In the U.S.A, shorter winters indicate less consistent snow cover as well (Finlayson, 2019).

These changes in winter impact the economy. There is a positive correlation between snow cover and skier visits, and low skier visits due to less consistent snow cover directly impact the economy. In the U.S.A, this impact resulted in a decrease of $1 billion and a loss of 17,400 jobs in 2016 (Hagenstad et al., 2018). Decreasing season length also decreases the quantity of guests and revenue for both the ski center and the
host community. Recently, stakeholders have begun considering climate change a predictor of a ski business’s economic viability and it is likely that major stock markets in the 2020s will require ski centers to disclose physical climate risks (Scott et. al., 2020).

Due to decreased quantity of skiable days and decreased snow quality across the globe, the ski industry’s future is unstable. A recent study compared scenarios for skiing in northeastern North American between the RCP 8.5 and RCP 4.5, for 2050 and 2080 (Scott et. al., 2020). RCP, or Representative Concentration Pathways, detail possible climate scenarios for the future through different radiative forcing values, or the difference between sunlight that is absorbed by the earth and radiated back into space. RCP 8.5 represents the “business as usual” climate scenario, and RCP 4.5 represents a more preferable climate scenario; at this level of radiative forcing, the global temperature will not increase by 2°C (I.P.C.C., 2014). All states and areas suffer under any of these scenarios – especially those areas that are either at low elevation or low latitude (Yang & Wan, 2010). Research also found that larger ski centers are better prepared to handle climate impacts due to larger income, while smaller centers will suffer more financially (Moreno-Gené et. al., 2018).

3.2.2 Innovation and skier behavior

The ski industry is accustomed to addressing climate change through innovation. The advent of snowmaking improved the ski industry’s global outlook when it was first introduced at a ski resort in 1949 (Leich, 2001). Snowmaking has increased substantially since then. Today, 91% of ski areas in operation in the United States have invested in snowmaking and the average ski resort’s snowmaking operations have increased 60% in the last 21 years (NSAA, 2020). A 2019 global review of climate change risk for ski
tourism concludes that ski centers must rely less on natural and more on machine-made snow to survive, prepare for shortened and more variable winter conditions, and accept that some centers may be forced to close (Steiger et. al., 2019). Snowmaking requires cold nights and lower humidity; these weather conditions were realistic until the early 2000s when climate change’s winter impacts became more pronounced. These ideal snowmaking conditions become less predictable as the global temperatures increase, winters begin later, and are warmer (Guilbert et. al., 2014). Ski centers may still struggle to open, despite adopting snowmaking.

To understand the impact of this seasonal unpredictability on ski centers, it is important to understand how their guests - recreational and competitive skiers - will react to suboptimal skiing conditions. If a ski center is closed, or cannot open on time due to poor conditions, research shows that skiers are likely to choose one of three alternative options (Steiger et. al., 2019). They may prefer 1) a temporal substitution – meaning the skier will likely postpone their trip until their desired ski center opens, 2) a spatial substitution – they would travel to a different location if their chosen ski center was not open, or 3) a shift in activities – instead of skiing, they may pursue a different, available activity. If recreational skiers have the option to postpone their trip, they will likely still ski at their preferred/home ski center. Competitive skiers are on training schedules that are more time-sensitive. If ski teams cannot train at their preferred/home ski center, they will likely travel somewhere else (choosing the spatial, instead of temporal substitution). If a local ski center is closed, skiers often need to travel far distances to find open ski centers in different climatic environments; this mode of travel often includes flying. Unfortunately, flying is both financially costly to the individual (or team) and
environmentally costly. Flying contributes significant Green House Gases (GHG) into the atmosphere; one gallon of jet fuel emits 21.1 lbs. of CO$_2$ and releases between 0.4 and 0.7 lbs. of CO$_2$ per mile of travel (“EIA”, 2020). If local ski centers cannot open, flying to an alternative, open ski center may become more common.

3.2.3 Snow Storage

To address these suboptimal snowmaking conditions and to avoid the costly and carbon-intensive flying alternative, over-summer snow storage (here, referred to as snow storage) was introduced. This process involves making a large pile of machine-made snow during a cold month, storing it throughout the summer under protective layers, and then spreading it on a trail to begin the center’s winter season on time. Though over 28 nordic ski locations around the world store snow consistently to open their ski season on time (Weiss et. al., 2019), the first study emerged in 2018 (Grünewald et. al., 2018) to analyze the process. This study was produced as a result of multiple requests, demonstrating outside interest in the technical feasibility of snow storage. Their findings supported a thick (40 cm) layer of sawdust overlaying piled snow and suggested that incoming solar radiation was the largest driver of melt. This new method functions better at nordic ski centers as compared to downhill/alpine centers, as there is less snow required to create a nordic ski trail. The new method may also extend the lifetime of the ski centers most vulnerable to climate change at lower elevations and/or latitudes.

Understanding the financial and environmental costs associated with snow storage is essential to determining whether a ski center can feasibly implement this new climate change adaptation. Each step in the process requires energy. Many snow storage steps require using large construction equipment to move or shape the snow and coverings,
which burn diesel. Diesel produces several pollutants/GHGs: Carbon dioxide (CO₂), Nitrous oxides (NOₓ), Particulate Matter (PM), and Volatile Organic Compounds (VOCs). Both financial and environmental costs are important if snow storage is to be a viable climate change adaptation strategy for nordic ski centers.

3.3 Methods

3.3.1 Study Area

The goal of this research is to create a case study to calculate both environmental and financial cost of snow storage at a local ski center. This case study was conducted at the Craftsbury Outdoors Center (COC) in Craftsbury, Vermont, USA. The COC is a non-profit, all-year outdoor recreation center at a low elevation (300 m asl) and mid latitude (45°N). Directors of the COC were interested in the feasibility of snow storage after experiencing an uncommonly warm 2014-2015 ski season (J. Geer, personal communication, November 13, 2019). They reached out to researchers at the University of Vermont to conduct this study. Investigating the feasibility of this location could support their sustainability mission and, if successful, could guide other similarly-located ski centers interested in snow storage. A study was completed to test the technical feasibility of snow storage (Weiss et. al., 2019) and found that a low-sloping pile, covered in 20 cm of woodchips, overlain by a white tarp, saved sufficient snow over the summer to allow the COC to open their ski season on time. To more broadly answer the feasibility question, we then focused on the overall financial and environmental cost of snow storage.

This study focuses on these two cost calculations. We first recorded and validated steps the COC followed to store snow. We then interviewed COC staff to acquire cost
and energy-use data related to each step. We fact-checked the data and calculated total financial and carbon costs for year one, and future costs through estimating maintenance costs and cost to replace equipment. We contextualized financial cost through amortization, and contextualized carbon emissions by comparing them to emissions from a cross country flight to another, open ski center.

### 3.3.2 Steps of Snow Storage

There are three main snow storage steps: 1) site preparation, 2) snow pile preparation, 3) snow spreading. Each of these steps were broken into smaller steps, twelve in total (Fig. 3.1). Site preparation involved clearing vegetation, shaping the site (which had previously been a pond) into a more consistent and deeper depression with a level rim, and installing snow gun infrastructure. In the snow pile preparation step snow guns made machine-made snow, COC staff shaped the snow pile with dump trucks and excavators, and finally they covered the snow pile in wood chips and tarp. To spread the snow, COC staff removed the tarp and woodchips, loaded the snow into dump trucks, and moved it to the desired trail where their PistenBulleys groomed it into a skiable surface. Unlike other locations, the COC filled an empty pond with snow instead of using a flat surface as more snow could be contained in the same area and use less wood chips (Grünewald et. al., 2018; Weiss et. al., 2019). Step one is more unique to the COC’s goals and spatial limitations; other locations have not dug specific pits. Steps two and three are globally common to the snow storage process, with the caveat of snow pile coverings; other locations have used a variety of materials, including geotextiles, foam panels, and other organic material. Previous research at this location shows that, a wood chip covering overlain by a white tarp, produces the best outcome (Weiss et. al., 2019).
3.3.3 Cost and Carbon Calculations

To gather quantitative data on costs associated with each step of the snow storage process, I conferred with COC staff who worked directly on snow storage. The meeting took place December 13, 2019 with seven staff members at the COC. They answered questions relating to who worked on each step of the process, how long each step took, what equipment was used, and how many gallons of diesel each piece of machinery used per hour. New purchases specifically related to snow storage were recorded as capital investments. They also discussed snow storage qualitatively and provided insights into their predictions for the future of snow storage. Non-monetary benefits of snow storage were recorded and categorized by theme.

Once the data from staff conversations had been recorded, it was compiled and verified with COC staff and machinery user manuals. These calculations produced total cost for year 1, cost for years in the future, amortization, total CO\textsubscript{2} produced in year 1, and total CO\textsubscript{2} produced for years in the future (Table 3.1).

Total financial cost ($C_t$) included labor and diesel cost of each step and cost of capital investments.

\begin{equation}
C_t = L_t + Ca_t + D_t
\end{equation}

Labor cost ($L_t$) of each action was calculated through multiplying total hours worked ($hr_x$) by hourly wage ($r_w$) by the number of staff necessary ($w_x$).
Total cost of diesel fuel ($D_t$) is calculated through multiplying total hours ($hr_x$) by gallons used per hour ($r_g$) by cost per gallon ($r_c$).

$$D_t = \sum hr_x \cdot r_g \cdot r_c$$

Overall cost for year 1 was calculated through adding cost from the steps with cost of diesel, and cost of capital investments. Capital Investments ($Ca_t$), is the total capital investment with $p_n$ being individual purchases.

$$Ca_t = p_1 + p_2 \ldots + p_n$$

Total cost represents an uneven flow; to convert this value to an even stream (equal annual payments for the life of the investment), we calculated the amortization ($A_t$), which is to say we converted it. Since different costs recur at different time intervals, we calculated amortization separately for each. We estimate that woodchips and white tarps require replacement every 4 years ($A_4$), and the dump trucks and snow guns require replacement every 20 years ($A_{20}$). Per climate research and future climate modeling, we estimate snow storage will be able to occur for at least 30 years, therefore the project’s estimated lifetime is 30 years ($A_{30}$). These time intervals yield three different amortizations, which are summed to find total amortization ($A_t$). Annual recurring costs ($R$) are included as well. The discount rate ($r$), or their opportunity cost of
money, at the COC is 6% (J. Geer, personal communication, November 13, 2019). The principle, \( P \), represents the capital/initial investments to begin the project.

\[
A_n = P \frac{r(1 + r)^n}{(1 + r)^n - 1}
\]

\[
A_t = A_4 + A_{20} + A_{30} + R
\]

To address environmental impact, we first defined system boundaries and then calculated CO\(_2\) emissions within those systems. We focused on two types of environmental impact: (1) the emissions from the snow storage process and (2) the emissions from the transportation of new products/equipment to the COC. We focus on emissions from the process and transportation because these factors capture the majority of the CO\(_2\) emitted specifically due to snow storage. We did not include emissions to create the products, or to dispose of the products.

To determine CO\(_2\) emissions from snow storage, we mapped the inputs and outputs of each step onto the outline of steps (Fig. 3.2). Energy inputs were determined to be the gallons of diesel fuel used during each step of the snow storage process. We focused on CO\(_2\) emissions from diesel fuel as they are the GHG produced in the highest quantity. The gallons of diesel calculated for financial cost were then converted to pounds (lbs.) of CO\(_2\) through multiplying values by the EPA’s provided conversion factor. To determine the environmental cost of the transportation of products/equipment (e.g., wood chips, tarp) to the COC, we mapped likely transportation routes from the manufacturer to arrival of the product at the COC and calculated pounds of CO\(_2\) released during transit. (Table 3.2).
To calculate total CO₂ emissions (Eₜ), emission from burning diesel (E_D) were added to emissions from transportation of the products (E_L).

\[ E_t = E_D + E_L \]

Eq. 7

To calculate emissions from diesel burned, total gallons of diesel (Gₜ) were multiplied by CO₂ emissions per gallon (rₑ).

\[ E_D = G_t \times r_E \]

Eq. 8

To calculate emissions from transportation, emissions from individual product transportation to the COC were calculated (Eₙ) and summed.

\[ E_L = \sum_{n=1} E_n \]

Eq. 9

To contextualize CO₂ emissions through comparison to a flight, we referred to the International Civil Aviation Organization (ICAO) Carbon Emissions Calculator (“Carbon Emissions Calculator”, 2017). The user inputs information such as number of passengers, departure and arrival airports, cabin class, and whether it is a one-way or round-trip flight (Fig. 3.3). These data are incorporated into ICAO calculations, and produce the CO₂ emissions produced per passenger per flight.

3.4 Results

3.4.1 Financial Cost of Snow Storage
Results from Table 3.1 indicate that the combined capital and recurring costs for the first year are $126,800 (Table 3.2). Non-discounted subsequent recurring costs total $12,800, without purchase of new equipment/materials. Table 3.1 shows all data collected from conversations with COC staff and directors, parsed out by task. These data were used for the financial calculations. Table 3.2 shows the capital investments for snow storage, and notes their longevity (e.g., the tarp covering the wood chips may need replacement every 4 years). Table 3.3 shows a summary of all costs for year 1 and year 2. Listing both year 1 and 2 show the difference between snow storage maintenance and the installation. If the wood chips and white tarp require replacing every 4 years, that yearly cost would increase to $44,000. For full replacement of the snow guns and addition of extra dump trucks every 20 years, that year’s cost increases to $65,500. Given a 6% discount rate, this project’s projected amortization over the entire project’s lifetime of 30 years would be $34,700 per year. The 20 year amortization would be $4600 and the 4 year amortization would be $9000 (Table 3.4). These values are based on maintenance cost and the cost of replaced items at 4 and 20 year intervals. To break even, revenue for the COC would need to match this yearly cost.

If the COC did not previously own the dump truck and excavator, they would need to rent them for an additional $9000 in year 1, and an additional $6000 in following years (this value is less due to a shorter estimated rental period, as they would not need to reshape the snow storage site in following years). If they did not previously own either Pistenbulley, they would need to purchase them for $50,000-$100,000 each, depending on year and brand.

3.4.2 Flying Comparison
Carbon emissions from year 1 were 46,100 lbs., or 21 metric tons (Table 3.6). This number is equivalent to the emissions from 4.5 passenger vehicles driven for 1 year in the U.S., or the emissions from energy use of 2.4 homes for 1 home (EPA, 2020, “Greenhouse Gas Emissions Calculator”). For subsequent years that do not require the replacement of items, carbon emissions will be 36,000 lbs., or 16 metric tons.

To contextualize carbon produced, we compared emissions from storing snow to emissions from a likely alternative, flying cross-country. In the northeast, if centers are not open, skiers are likely to fly to either Colorado, USA, or Vancouver, Canada (P. Bierman, February 25, 2020, personal correspondence). To offset carbon emissions from year 1, >35 people would need to have been prevented from flying from Burlington, VT to Denver, CO, USA and for subsequent years without new material additions (such as wood chips, tarp, snow guns, dump trucks), <29 people would need to be prevented from flying (Table 3.6). If they chose to fly out to Vancouver, Canada, <25 people would have needed to be prevented from flying to offset CO$_2$ for the first year, and <20 people would need to be prevented from flying during a following year. Comparatively, an average ski team has 20-30 skiers on their rosters, (and 5-10 additional coaching staff); preventing this one entire team and their coaches from flying out west would render snow storage the option that emits less CO$_2$. There are many ski teams who train at the COC, indicating that snow storage emits less CO$_2$ than this flight alternative.

3.4.3 Benefits

Though cost was quantifiable, benefits of snow storage were summarized qualitatively through tangible (Table 3.7) and intangible (Table 3.8) benefits. Tangible benefits were monetary benefits and include revenue each year from room and ski rentals
and membership fees. These are only some of the benefits accrued and represent a lower boundary of total financial benefits, as financial benefits will also accrue to the host community as guests at the COC are likely to spend money in surrounding towns as well. We can assume that the longer the COC is able to remain open, more skiers can use their facilities and these financial benefits would increase. Intangible benefits, the non-monetary rationales for pursuing snow storage, were grouped by theme. Themes were a consistent reputation, strengthening themselves as a community resource, supporting environmental stewardship, supporting their mission in general, and personal motivation driven by passion for their work.

3.5 Discussion

Results confirm that financial cost is not the driver of decision-making; there are non-monetary benefits gained from storing snow, and the combination of reasonable financial cost (as confirmed by directors of the COC) and substantial non-monetary benefits indicate that the cost snow storage is feasible. Results also show that snow storage is more environmentally-friendly than the likely alternative of flying to a different, open ski center.

3.5.1 Financial

Results suggest that snow storage is financially feasible for the Craftsbury Outdoors Center, and these costs may be useful for other interested ski centers. To establish snow storage for 2019, the COC spent $126,800. For subsequent years, it is predicted they will spend $12,800 if replacement of equipment is not needed. The amortization over 30 years of the project was calculated to be $34,700.
There are two financial questions businesses assess when considering a project: 1) should they undertake the project, and 2) should they continue if costs or benefits turn out to be different from their initial calculations? The COC has already invested to start the project; as this initial investment cost is a sunk cost or fixed cost, they should not take it into account for financial decision making until the costs recur. As there are three different possible years of cost, there are 3 different “shut down” rules, which are indicators that they should abandon the project. The first is if annual benefits < annual recurring costs, they should abandon the project immediately; they should abandon the project after 4 years if annual benefits < annual recurring costs plus the amortized value of 4 year recurring costs, and they should continue for another 20 years if annual benefits < annual recurring costs plus the amortized value of 4 and 20 year recurring costs. Other ski centers can use the amortized value of total costs to determine whether snow storage is worth the initial investment; they should invest if annual benefits > average total costs. These considerations are the long run and short run shut down rules. If benefits fall below total costs, then a ski center should not invest; these are the ‘do not start’ conditions and called the long run shut down rule. If benefits are below the minimum variable costs, then they should continue. If financial benefits are above the minimum variable costs, they should desist; this decision is the short term shut down rule. Note that the short run shutdown rule is determined by the time between recurring investments, which, in this project, has three distinct life-spans (full-project lifetime, 4 years, and 20 years) and those different life-spans leads the COC to three distinct short runs decision points.

For other ski centers considering snow storage, it is important to define the costs necessary for snow storage, and the costs that the COC chose to take on but are not
necessary. For example, the COC chose to store snow in a pit, which required resources (labor cost, diesel cost, carbon emissions) to clear and shape the pit. Other ski centers store snow in a cleared area on the ground (Weiss et. al., 2019). The COC also purchased new snow guns and bought their own woodchipper; snow guns are necessary as the northeast does not receive enough natural snow; however, the snow guns are not required to be new. The woodchipper was purchased to increase their self-sufficiency with wood chips, but not necessary for a center looking to store snow.

Cost, however, was not the primary motivator for pursuing snow storage; COC directors stated adherence to their mission as a driving factor. Their mission is; “To support and promote participation and excellence in lifelong sports with a special focus on rowing, nordic skiing, biathlon and running; To use and teach sustainable practices; And to protect and manage the surrounding land, lake and trails.” (“Craftsbury Outdoors Center Mission”, 2020).

Environmentalism as a motivator was revealed when asked, "In terms of revenue, what would lead the center to no longer support Nordic skiing/biathlon?”. COC directors responded, “It’s our mission—we will keep doing it regardless. We are different from normal ski areas this way." When asked "What do you see as the future of the center? What adjustments do you plan on making to respond to climate change?”, they responded, “We will continue to work to improve our energy efficiency and sustainable practices.” They show commitment to addressing climate change through stating sustainability as a driver for choosing snow storage.

COC directors revealed other non-monetary rationales for supporting snow storage, such as building and maintaining a good reputation, when asked, “How long
does it take to build up a reputation for consistently having snow? Do you already have that? If so, long did it take to build it?”, COC directors responded, “We started building it when we got our first snow guns. It didn’t take too long to build it regionally, and then spread pretty quickly nationally. The storage enables us to continue to maintain this reputation even as the weather gets worse.”. If they are able to retain the image of a nordic ski center that opens early and consistently, they will be dependable. This reputation of dependency may lead more ski teams to train there, improve their chances for receiving national races, and increase outreach to more visitors. Research shows that reputation is a powerful motivator for successfully adopting sustainable practices (Baden, 2017; Postmus 2017; Chandra, 2015).

They also stated personal motivation; when asked, "What does the center mean to you as a place of work, as something you’ve created?”, they responded, “It’s a passion and sort of more of a hobby than a job." This exchange touches on a point of contention within common (neoclassical) economic theory and is addressed by the field of ecological economics. Neoclassical economics assumes that people work to gain money and will thus only work proportionally to what they are paid – however, working for personal enjoyment, or, as Geer states, because it is “more of a hobby than a job”, does not fit into the neoclassical narrative. Choosing snow storage, the sustainable option, is not always coupled with the most short-term financially-beneficial decision; however, the center has emotional meaning to its directors. This deeper meaning prompts them to choose the sustainable option.

3.4.2 Carbon
Results suggest that for the first year, combined CO\textsubscript{2} from snow storage and transportation was 46,100 lbs. Compared to other projects, this amount of CO\textsubscript{2} is similar to three average American home’s yearly CO\textsubscript{2} production (Goldstein et. al., 2020). For the second year, combined CO\textsubscript{2} output will be 36,000 lbs.; less CO\textsubscript{2} is emitted in following years as the COC did not need to re-dig or shape the pit or transport new equipment. The quantity of CO\textsubscript{2} emitted per year will change based on replacement of key components, such as the white tarp and wood chips, which are estimated to need replacement every 4 years (though further research could improve this estimate of product longevity used in this context). The NIVIS Ecosticks are estimated to need replacement every 20 years, (D. Dreissigacker, personal communication, July 15, 2018). The dump trucks which transport the snow and wood chips are likely to need replacement as COC staff stated that they are purchased used and operated until they mechanically cannot work any longer. Overall, any of these replacements will increase the CO\textsubscript{2} production during that year.

When compared with an alternative option of flying, results indicate that the snow storage process produces less CO\textsubscript{2}, which renders this option more environmentally-friendly. If the COC were to not store snow and instead rely on the weather to provide ideal snowmaking conditions, they are risking being unable to open their season on time consistently. This risk means their visitors may turn to other options. A recent study revealed that skiers prefer to wait until their desired ski center opens, however, if that does not occur, they will physically travel somewhere else (Steiger et. al., 2019). There are many competitive ski teams that train at the COC who are likely to travel to open ski centers; often those are across the country. Flying west from Vermont produces
significant amounts of CO$_2$. Results indicate that snow storage would need to prevent <20-30 people from flying out to the western United States or Canada. This number assumes only one round trip per person and would decrease if, for example, families who prioritize skiing or entire ski teams make multiple trips throughout a winter season from the northeastern United States to the west. Overall, these values indicate that snow storage for the COC produces less carbon than the carbon emitted from likely alternative of flying to a different, open ski center.

3.5 Conclusion

This analysis calculated the financial and environmental cost of snow storage at the COC. It then contextualized these values to gauge long-term feasibility of snow storage. Through both confirmation from COC directors, and comparison to an alternative, snow storage is both financially and environmentally feasible at the COC. Non-monetary benefits of snow storage were large motivators for continuing to pursue this strategy. Other similarly-located ski centers can use these data to determine whether snow storage will benefit their operations as well. If more ski centers pursue more sustainable climate change adaptations, they can collaboratively reduce their sector’s contribution to atmospheric CO$_2$ and increase the ski industry’s viability into the 21st century.

3.6 References


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3.7 Figures

Snow storage steps

Figure 3.1: Twelve steps involved in the Craftsbury Outdoor Center’s 2019 snow storage/spreading. The process begins with prepping the location to store snow (steps 1-4). Snow is then made, shaped, and covered (steps 5-9). The snow is uncovered after spring, summer, and fall, removed, and spread on trails to open the ski season (steps 10-12).
Figure 3.2: The inputs and outputs for snow storage. Inputs are marked as blue arrows while outputs are marked as red arrows. Inputs involve people, equipment, energy, time, and money, while outputs are pollutants (COx, NOx, PM, and HC), money, and qualitative benefits. Most steps require labor and diesel fuel and produce pollution.
Figure 3.3: The ICAO Carbon Emission Calculator tool with example of a flight from the Burlington Airport in VT to Denver, CO for one passenger on a round-trip. This trip emits 464.4 total kg of CO₂ per individual (https://www.icao.int/environmental-protection/CarbonOffset/Pages/default.aspx)
3.8 Tables

Table 3.1: Snow storage steps and the associated variables to calculate labor and fuel costs of each task and cumulative cost of all steps. Data was acquired from conversations with COC staff and cross-checked with online resources.

<table>
<thead>
<tr>
<th>Step Description</th>
<th>Equipment Used</th>
<th>(HR)</th>
<th>(W)</th>
<th>(R₆₅)</th>
<th>(G₇)</th>
<th>(R₈₅)</th>
<th>(L₇)</th>
<th>(D₇)</th>
<th>(R₆₅)</th>
<th>Price of diesel 2018/2019</th>
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<td>10</td>
<td>1</td>
<td>3</td>
<td>30</td>
<td>300</td>
<td>3000</td>
<td>95</td>
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<td>INSTALL CULVERTS</td>
<td>CAT 311 CU Excavator</td>
<td>7</td>
<td>2</td>
<td>6</td>
<td>42</td>
<td>21</td>
<td>294</td>
<td>134</td>
<td>3.18</td>
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<td>SHAPE THE SITE</td>
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<td>5</td>
<td>6</td>
<td>240</td>
<td>21</td>
<td>4200</td>
<td>763</td>
<td>3.18</td>
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<tr>
<td>MAKE SNOW</td>
<td>NIVIS Snow guns</td>
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<td>6</td>
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<td>1</td>
<td>6</td>
<td>9</td>
<td>21</td>
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<td>28</td>
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<tr>
<td></td>
<td>PistenBully 100 woodchopper</td>
<td>1.5</td>
<td>1</td>
<td>2.5</td>
<td>3.75</td>
<td>21</td>
<td>31.5</td>
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<td>2</td>
<td>4</td>
<td>96</td>
<td>21</td>
<td>1008</td>
<td>293</td>
<td>3.06</td>
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<tr>
<td>ADD WOOD CHIPS TO COVER PILE</td>
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<td>11</td>
<td>2</td>
<td>6</td>
<td>66</td>
<td>21</td>
<td>462</td>
<td>202</td>
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<tr>
<td></td>
<td>PistenBully 100</td>
<td>11</td>
<td>1</td>
<td>2.5</td>
<td>27.5</td>
<td>21</td>
<td>231</td>
<td>84</td>
<td>3.06</td>
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<td></td>
<td>5500i Dump Truck</td>
<td>11</td>
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<td>5</td>
<td>55</td>
<td>21</td>
<td>231</td>
<td>168</td>
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<td>WHITE TARP COVERING</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>REMOVE TARP/ WOOD CHIPS</td>
<td>PistenBully 100</td>
<td>20</td>
<td>3</td>
<td>4</td>
<td>80</td>
<td>21</td>
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<td>3</td>
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<td>25</td>
<td>21</td>
<td>315</td>
<td>76</td>
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Table 3.2 Total capital investments during year 1. Quantity, unit price, and total price are noted. Recurring sums are noted that correspond with replacement items. Every 4 years, the wood chips and tarp will be replaced and every 20 years, the snow guns and dump truck will be replaced.

<table>
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<th></th>
<th>CAT 311 CU Excavator</th>
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<th>2</th>
<th>60</th>
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<th>21</th>
<th>210</th>
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<tr>
<td>NIVIS ECOSTICKS SNOWMAKING UNITS</td>
<td>15</td>
<td>1</td>
<td>4</td>
<td>60</td>
<td>21</td>
<td>315</td>
<td>183</td>
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<td>CULVERT PURCHASE (PER UNIT)</td>
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<td>4</td>
<td>60</td>
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<td>315</td>
<td>183</td>
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<td>1000</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>WOODCHIPPER</td>
<td>1</td>
<td>12000</td>
<td>12000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LIME KILN WOOD CHIPS *M CUBED (IN TONS)</td>
<td>700</td>
<td>40</td>
<td>28000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>BECHTEL TARP</td>
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<tr>
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<td>2000</td>
<td>4000</td>
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<tr>
<td>LWI: NIVIS STANDS, PLATE STEEL, PIPE, STANDS</td>
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Table 3. 3 Carbon Dioxide from the transportation of products in both kg and lbs. Journey description contains known and estimated locations based on conversations with COC staff. This method was assisted by [https://carbonfund.org/calculation-methods/](https://carbonfund.org/calculation-methods/)

## Carbon from Transportation of Products

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>Journey (description)</th>
<th>Method</th>
<th>Legs of journey</th>
<th>One way?</th>
<th>Kg CO₂ produced</th>
<th>Total Kg CO₂</th>
<th>Total lbs. CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIVIS ECOSTICKS</td>
<td>Sterzing Vipiteno Italy -&gt; Genoa Italy Port</td>
<td>Trucked</td>
<td>340</td>
<td>340</td>
<td>0.202</td>
<td>69</td>
<td>151</td>
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<tr>
<td></td>
<td>Genoa Italy Port to Boston, MA port</td>
<td>Shipped</td>
<td>4403</td>
<td>4403</td>
<td>0.0603</td>
<td>266</td>
<td>585</td>
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<tr>
<td></td>
<td>Boston, MA -&gt; COC, VT</td>
<td>Trucked</td>
<td>225</td>
<td>225</td>
<td>0.202</td>
<td>46</td>
<td>100</td>
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<td>CULVERTS</td>
<td>Johnson Hardware and Rentals Store -&gt; COC,</td>
<td>Trucked</td>
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<td>MISC. HARDWARE</td>
<td>Local</td>
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<td>100</td>
<td>100</td>
<td>0.202</td>
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<td>45</td>
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<tr>
<td>WOODCHIPPER</td>
<td>Local</td>
<td>Trucked</td>
<td>100</td>
<td>100</td>
<td>0.202</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>LIME KILN WOOD CHIPS</td>
<td>Country Comfort Firewood, LLC in Landaff NH -&gt; COC</td>
<td>Trucked</td>
<td>70</td>
<td>140</td>
<td>0.202</td>
<td>28</td>
<td>62</td>
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<tr>
<td>*M CUBED (IN TONS)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BELTECH 2911 TARP</td>
<td>Belton Industries, Belton, South Carolina -&gt; COC</td>
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<td>1130</td>
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<td>0.202</td>
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<td>45</td>
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<td></td>
<td><strong>706</strong></td>
<td><strong>1558</strong></td>
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</tbody>
</table>

Table 3. 4 Amortization cost in dollars, assuming the project lasts 30 years. Year 20 and year 4 reflect costs of replacement of items while year 30 represents the full cost of the project, including setup costs. Total cost represents the amount of money per year spent to store snow.

<table>
<thead>
<tr>
<th>PRINCIPLE</th>
<th>DISCOUNT RATE</th>
<th>YEARS</th>
<th>RECURRING COST</th>
<th>AMORTIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>P ($)</td>
<td>r (*100%)</td>
<td>n (yrs.)</td>
<td>R ($)</td>
<td>A ($)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>YEAR</th>
<th>GALLONS</th>
<th>CO2</th>
<th>LBS CO2</th>
<th>KG CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>31263</td>
<td>0.06</td>
<td>12761</td>
<td>9022</td>
</tr>
<tr>
<td>20</td>
<td>52783</td>
<td>0.06</td>
<td>12761</td>
<td>4602</td>
</tr>
<tr>
<td>30</td>
<td>114071</td>
<td>0.06</td>
<td>12761</td>
<td>8287</td>
</tr>
<tr>
<td>TOTAL</td>
<td>34673</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.5 Conversion from gallons of diesel to lbs. and kg of CO2, from [https://www.eia.gov/environment/emissions/co2_vol_mass.php](https://www.eia.gov/environment/emissions/co2_vol_mass.php). 1 gallon diesel = 22.4 lbs. CO2.

<table>
<thead>
<tr>
<th>GALLONS DIESEL USED YEAR 1 (CAPITAL + RECURRING)</th>
<th>GALLONS TO LBS CO2</th>
<th>LBS CO2 TO KG CO2 (FOR FLIGHT COMPARISON)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1919.25</td>
<td>44549</td>
<td>20207</td>
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</table>

<table>
<thead>
<tr>
<th>GALLONS DIESEL USED YEAR 2 (RECURRING ONLY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1431.25</td>
</tr>
<tr>
<td>36002</td>
</tr>
<tr>
<td>16330</td>
</tr>
</tbody>
</table>

Table 3.6: CO2 produced by one passenger on a flight to Denver, Colorado (DEN) and Vancouver, Canada (YVR). “Journey” refers to a round trip and “pax” refers to a passenger. Data from: [https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx](https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx)
<table>
<thead>
<tr>
<th>DEP AIRPORT</th>
<th>ARR AIRPORT</th>
<th>NUMBER OF PASSENGERS</th>
<th>TRIP</th>
<th>AIRCRAFT FUEL BURN/JOURNEY (KG)</th>
<th>TOTAL PASSENGERS’ CO2/JOURNEY (KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTV</td>
<td>YVR</td>
<td>1</td>
<td>Round Trip</td>
<td>25962.5</td>
<td>813.4</td>
</tr>
<tr>
<td>DEP AIRPORT</td>
<td>ARR AIRPORT</td>
<td>Distance-km</td>
<td>Aircraft Fuel Burn/leg (KG)</td>
<td>Passenger CO2/pax/leg (KG)</td>
<td></td>
</tr>
<tr>
<td>BTV</td>
<td>ORD</td>
<td>1225</td>
<td>3481.6</td>
<td>149.8</td>
<td></td>
</tr>
<tr>
<td>ORD</td>
<td>YVR</td>
<td>2831</td>
<td>9542.2</td>
<td>255.7</td>
<td></td>
</tr>
<tr>
<td>YVR</td>
<td>ORD</td>
<td>2831</td>
<td>9457.4</td>
<td>258.1</td>
<td></td>
</tr>
<tr>
<td>ORD</td>
<td>BTV</td>
<td>1225</td>
<td>3481.3</td>
<td>149.8</td>
<td></td>
</tr>
<tr>
<td>Tangible Benefits (Financial)</td>
<td>Description from craftsbury.com</td>
<td>Example</td>
<td>Quotes from Judy Greer, COC Director</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td>---------</td>
<td>-------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dormitory reservations</strong></td>
<td>The COC provides both private cabins and dormitory rooms for rent throughout the year.</td>
<td>Ex. Lodging for 1 adult/night, $100, and ~$700 for weekend cabin rental</td>
<td>“Anecdote: I just heard that someone has reserved accommodations for 17 weekends next winter! I guess this reflects the reputation we have been developing!”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Food purchases</strong></td>
<td>The COC sells full meals at the lodge with reservations required, as well as snacks and beverages in the central campus building.</td>
<td>Ex. Breakfast: $12 non-member; $10.20 member, with reservation by 7 pm the evening before. Lunch: $14 non-member; $11.90 member, with reservation by 10 am. Dinner: $22 non-member; $18.70 member, with reservation by 2 pm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sports lessons</strong></td>
<td>The COC offers several seasonal outdoor and indoor physical activities, such as skiing, biathlon, running, sculling, biking, yoga, and CrossFit</td>
<td>Ex. Private ski lessons are $30 per person or $45 for two. Lessons for 3-8 people are $60 for the group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Entry fees</strong></td>
<td>There are entry fees to use COC trails, as well as entry fees for races.</td>
<td>Ex. Bike race entry fee: $100 for ages 15 &amp; up, $25 for ages 14 and below.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rentals</strong></td>
<td>The COC rents gear to those interested in pursuing any of their outdoor activities.</td>
<td>Ex. XC ski rental equipment is available at $15 for a full day for an adult. The fee to rent ski gear for students and seniors is $10. Skis, boots, or poles can be rented separately, too. Snowshoe rentals are $5 and a pulk sled is $10 for 2 hours.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Memberships</strong></td>
<td>The COC allows for the purchase of a membership, which includes several benefits and decreased prices for</td>
<td>Ex. Kids Under 14 - $25, Individual Student or Senior (65+) - $50, Individual Adult - $75, Family - $150</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Race bids

The COC hosts several types of races throughout the year, such as biking, running, sculling in the summer and Nordic skiing/biathlon in the winter.

Ex. January 2020 had two race weekends scheduled:
- January 11-12, 2020: NorAm Cup 3
- January 24-26, 2020: UVM Carnival/NENSA Eastern Cup/Supertour

"Just had a request for another biathlon event the week before Thanksgiving 2020. # of races is also affected by the organization: USSA likes to spread their races around."

### Backup for other races

Specifically, for winter races, if the COC has snow while other ski centers do not, they have acted as backup for other ski centers.

"We may get some additional unexpected races due to being back-up site, when other venues don’t have snow."

---

**Table 3.8** Intangible benefits from personal correspondence with Judy Greer, one of the directors at the COC.

<table>
<thead>
<tr>
<th>Intangible Benefits</th>
<th>Q/A with Judy Greer, COC Director</th>
</tr>
</thead>
</table>
| **Reputation builder** | Q: "What does revenue look like for a great year? Average? Bad?"  
A: "Building the long-term reputation of having snow when others don’t is all helpful here."  
Q: How long does it take to build up a reputation for consistently having snow? Do you already have that? If so, long did it take to build it?  
A: We started building it when we got our first snow guns. It didn’t take too long to build it regionally, and then spread pretty quickly nationally. The storage enables us to continue to maintain this reputation even as the weather gets worse. |
| **General support of mission** | Q: "In terms of revenue, what would lead the center to no longer support Nordic skiing/biathlon?"  
A: "It’s our mission—we will keep doing it regardless. We are different from normal ski areas this way." |
| **Community resource** | Q: "How much impact does revenue have on determining whether the center has experienced “success” or not? What are the other factors? (Can be intangible, hard to measure pieces too).  
A: "Developing a reputation for holding high quality races, having great skiing, serving lots of kids and families with our programming, and in general achieving our mission." |
| **Personal** | Q: "What does the center mean to you as a place of work, as something you’ve created, as something you’re physically and emotionally invested in?"  
A: "It’s a passion and sort of more of a hobby than a job." |
| **Environmental Stewardship** | Q: "What do you see as the future of the center? What adjustments do you plan on making to respond to climate change?"  
A: "We will continue to work to improve our energy efficiency and sustainable practices." |
CONCLUSION

Analyses of the technical, financial, and environmental components of snow storage indicate that this climate change adaptation is feasible at the Craftsbury Outdoor Center in Craftsbury, VT. Experimentation in 2018 and 2019 showed that a gently sloping snow pile covered in a thick (20 cm), uniform layer of wood chips, overlain by a reflective covering (white tarp) would decrease volume loss and preserve enough snow for the COC to open their winter ski season on time.

If the snow storage project’s lifetime is 30 years, its amortization cost is $34,700 per year. Snow storage was financially viable for Craftsbury Outdoor Center as they are also strongly motivated by non-monetary benefits (such as adherence to their mission of sustainability, community, and land stewardship), instead of money alone. This analysis shows that snow storage is environmentally-friendly in comparison to the alternative of not opening their season on time; competitive ski teams would likely fly cross-country to an open ski center. These cross-country flights, for two ski teams alone, release more CO₂ than storing snow over the summer. As all three components of snow storage are feasible, the COC will “… continue to store snow until [they] physically can’t” (J. Geer, January 12, 2020; personal correspondence).

Analyzing the effectiveness of this climate change adaptation would benefit from future research. Further research at the COC would strengthen this study’s results; monitoring their snow pile over a several-year span would decrease the influence of specific weather and would render the results more generalizable. Testing the snow’s density to distinguish between compaction and melt over the summer would also strengthen results. Due to the case study nature of this project, their results provide a
baseline for other interested ski centers; however, generalizing these results would also require conducting similar studies at different ski centers. It is possible that different types or quantities of covering materials would function better at different geographic locations.

A full Cost-Benefit Analysis would improve the project’s broad applicability; for many ski centers, finances are a larger driving motivator than they were at the COC. Future research could monitor the revenue flows during snow storage years to include monetary financial benefits, in addition to cost, in these calculations. We can use these costs and benefits to produce a CBA that would assist other ski centers in their decision to adopt snow storage. A full Life Cycle Assessment of the environmental impact of snow storage would strengthen its applicability and accuracy. Instead of analyzing the CO₂ from each step and the transportation of each product, a Life Cycle Assessment follows specific, widely-used methods that take into account broader impacts and produces a more inclusive and comprehensive result.

Finally, a ski-center-specific guest survey on behavior, impressions of the future, and motivations for choosing specific ski centers would improve results from the guest perspective. A survey of the skiers at the COC would reveal the rationale behind their decisions to ski at the COC and their views of snow storage. These data could be used to strengthen marketing, determine the success of snow storage from their guest’s perspective, and determine skier behavior if the COC could not open on time.

This research provides a case study with baseline data for determining the success of a climate change adaptation strategy, snow storage, at the COC. Further analysis and data collection of the technical, financial, and environmental components would improve
snow storage’s implementation at the COC and broaden its applicability to other interested ski centers.
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