Lyons, WB, et al. 2018 The impact of fossil fuel burning related to scientific activities in the McMurdo Dry Valleys, Antarctica: Revisited. *Elem Sci Anth,* 6: 33. DOI: https://doi.org/10.1525/elementa.288

RESEARCH ARTICLE

The impact of fossil fuel burning related to scientific activities in the McMurdo Dry Valleys, Antarctica: Revisited

W. Berry Lyons[*,†], Elsa Saelens[*,†] and Kathleen A. Welch[*,†,‡]

Fossil fuel use associated with scientific activities in the Taylor Valley, Antarctic has been examined to determine the fluxes of particulate organic and elemental carbon and nitrogen as well as NO_x for the 2015–2016 austral summer field season. These carbon and nitrogen fluxes are compared to our previously published calculations for the 1997–1998 austral summer. In addition, we compile fossil fuel usage and resulting C and N fluxes from the major field camp in Taylor Valley, Lake Hoare Camp (LHC) from the late 1990's through 2017. In general, the annual fluxes do vary from year to year, but there is no significant trend, at least during the primary summer field season. There is indication that increasing the length of scientific operations does increase the C and N inputs via fossil fuel burning. This works supports our original results demonstrating that over long periods of time the anthropogenic flux of N from local fossil fuel burning could become quantitatively important in the region. Although the particulate C fluxes remain very low, the recent finding of black carbon in the Taylor Valley landscape indicates more on-going monitoring of the source of this material is merited.

Keywords: McMurdo Dry Valleys; management; fossil fuels; emissions; carbon dynamics; nitrogen; science activites; helicopter

Introduction

Antarctica remains the most pristine continent on the planet. Both retrospective studies using ice core records, and more localized investigations around permanent scientific bases indicate that the continent has been, and is currently being, impacted by anthropogenic processes such as the burning of fossil fuels (Sheppard et al. 2000; Planchon et al. 2002; Tin et al. 2009; Ndungu et al. 2016). Although there are various sources of both long traveled and local carbon and nitrogen, our earlier study (Lyons et al. 2000) was the first to directly quantify the role of scientific operations in the production of C and N due to burning fossil fuel products over a specific geographical region.

The McMurdo Dry Valleys (MDVs) are the largest ice-free area on the continent (Levy 2013). They were first visited by humans during the initial exploration of R.F. Scott at the beginning of the 20th century, and have become the major base of scientific operations for a number of Antarctic national programs, in part because of their close proximity to Ross Island and major U.S. and New Zealand bases, and also because of their unique geological, ecological and climatological features. Although the region has been of great scientific interest since the 1957–1958 International Geophysical Year (IGY), research activities and human presence have increased since that time. The McMurdo Dry Valleys Long-Term Ecological Research (MCM-LTER) program was established in 1993 by the U.S. National Science Foundation, and one of the major goals of this program is to understand carbon and nutrient dynamics between all the landscape units and their associated biota (Barrett et al. 2007; Welch et al. 2010). Taylor Valley is the major operational area of the MCM-LTER program and is also visited by other U.S. and New Zealand scientists, depending on the year. Taylor Valley is considered a polar desert with a mean annual temperature of ~–20°C and annual precipitation of ~3 cm water equivalent annually (Doran et al. 2002; Fountain et al. 2010). Priscu and Howkins (2016) have recently described the increase in scientific activities in the MDVs and the increased potential of environmental impact from them over time. Because of its unusual scientific qualities and its extreme fragility, it is imperative that human impact is well documented and quantified.

The Protocol on Environmental Protection to the Antarctic Treaty (The Madrid Protocol) was established in 1991. The Protocol states that the environmental protection of the continent is a "fundamental consideration." Article 8 of the Protocol requires an environmental assessment of all activities, including scientific ones, and that each signatory ensures that assessment procedures are applied to the planning of scientific research. Article 5 of the Environmental Impact Assessment portion of the

* School of Earth Sciences, The Ohio State University, Columbus, Ohio, US

† Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, US

‡ Institute for Arctic and Alpine Research, University of Colorado, Boulder CO, US

Corresponding author: W. Berry Lyons (lyons.142@osu.edu)

Protocol (or Annex 1) states that procedures for environmental monitoring be put in place, and Article 3 states that "cumulative impacts" need to be considered. The work presented within was undertaken in this light. It is important to determine what impact scientific research activities actually have on the biogeochemistry of the continent. Because the MDVs are the largest ice-free region in Antarctica, and they have significant importance in establishing base-line information as the climate warms, understanding the degree of local, human-induced nutrient fluxes is imperative.

The connection between environmental management and science in the Antarctic is a strong one, especially within the Antarctic scientific community. Over the past five years, there have been a number of examples of calls for proposals or needs for science that have been tied to environmental management issues (Wall et al. 2011; Chown et al. 2012; Houghton et al. 2016). In addition, one of the six scientific priorities of the recently developed "Antarctic Horizon Scan" was to recognize and mitigate human influences in the Antarctic and the Southern Ocean environments (Kennicutt et al., 2014). The forecast of human activities and the understanding of their impacts are needed in order to provide "for effective Antarctic governance and regulation." Therefore the objectives of this work were to reassess the impact of local scientific activities on the overall C and N reservoirs in the Taylor Valley landscape, and to evaluate the fluxes from field camp operations on a year to year basis.

Materials and methods

Study area

Taylor Valley is one of the McMurdo Dry Valleys in Southern Victoria Land (76°30′–78°30′S and 160°–164°E). Taylor Valley trends northeast to southwest, has been glacially covered by movements of both the East and West Antarctic Ice Sheets, and is thought to have been a fjord in the Late Tertiary. The landscape is currently a composite of soils, ephemeral streams, closed-basin, ice-covered lakes, and glaciers (Fountain et al. 1999). Each of these landscape units is associated with characteristic fauna and flora, and their carbon and nutrient dynamics and ecosystems structure and function have been well documented in the past >20 years, especially by the research of the MCM-LTER program (Priscu et al. 1999; Barrett et al. 2006; Barrett et al. 2007). Because of this, the details of C and N biogeochemistry in Taylor Valley will not be repeated here.

There are four permanent field camps in Taylor Valley, one at Lake Hoare, one at Lake Bonney, and two in the Lake Fryxell basin (**Figure 1**). Lake Hoare is the largest of the camps and it is overseen by a camp manager and usually another contracted employee. F6 camp on the southern shore of Lake Fryxell is also usually occupied throughout the majority of the austral summer, from late October until the end of January, while Lake Fryxell camp on the north shore of the lake is usually occupied for the least amount of time of the four camps, and its occupation varies greatly year to year. The Lake Bonney camp is occupied sporadically throughout the field season. As noted in **Table 1**, JP5/8 (diesel fuel) is used for generators, for heating at the camps, and for melting sampling holes through the lake ice (which can be meters thick). Gasoline is also used for heating, for ice drills that are used during the initial creation of the sampling holes in the lake ice, and as fuel for ATVs used for the transport of scientific equipment on the lake ice only. Propane is also used for heating in some cases, but also for the refrigerators and stoves, and the toilets. The major users of these camps are MCM-LTER personnel (~30 deployments throughout the 3–3½ month science season), although other research groups from both U.S. and New Zealand can be in Taylor Valley at various times during any given austral summer. The 2007–2008 field season was extended into March in order to assess the role of seasonal change from the austral summer into austral winter on the lake ecosystems in Taylor Valley, but normally scientific operations cease by the first week of February. The late summer into fall work was done explicitly to assess the activity of aquatic autotrophs as the sun "sets". This activity was referred to as the "extended season".

Results and discussion

In our original paper, we considered the 1997–1998 field season as a "representative" field year and presented fuel combustion data from Lake Hoare camp in this light. In **Table 1** we present the Lake Hoare data from 1997–1998 along with similar data from 2002–2003 field season onward to the present, totaling 16 field seasons. The "extended season" was unique in that the MCM-LTER field season extended into April when a small group of scientists stayed to monitor the ecology and the biogeochemistry of the lakes as the sunset and the austral winter approached. If the "extended season" values are removed, the average annual diesel, gasoline and propane consumption is 754 gallons, 136 gallons, and 1990 lbs, respectively over the 2002–2017 period. There is year to year variation in camp fuel usage with no obvious trend, but the calculated coefficient of variation of diesel fuel use over the 14-year period is ± 36%. It can be now demonstrated that the 1997–1998 season was not a truly "representative" year in that it overestimated the mean diesel fuel consumption, and greatly underestimated the average propane usage. This variation in usage is dependent in large part on the person-days at the camp, the scientific activities that are occurring in any given field campaign, as well as upgrades to camp infrastructure since the 1990s. For example, during years when scuba diving is taking place in order to sample the benthic algal mats in the lakes, more hole melting through the lake ice cover is needed, which in turn consumes more gasoline to run gas-powered generators and more diesel to run the hole-melters. In addition, since the 1997–1998 field season, some changes have been made to the camp infrastructure to reduce the dependence on diesel fuel used for both heat and generation of electricity. Diesel-burning Preway stoves were replaced with propane burning heaters in the field labs and refrigeration was changed from electric to propane-powered units. Upgrades to the solar

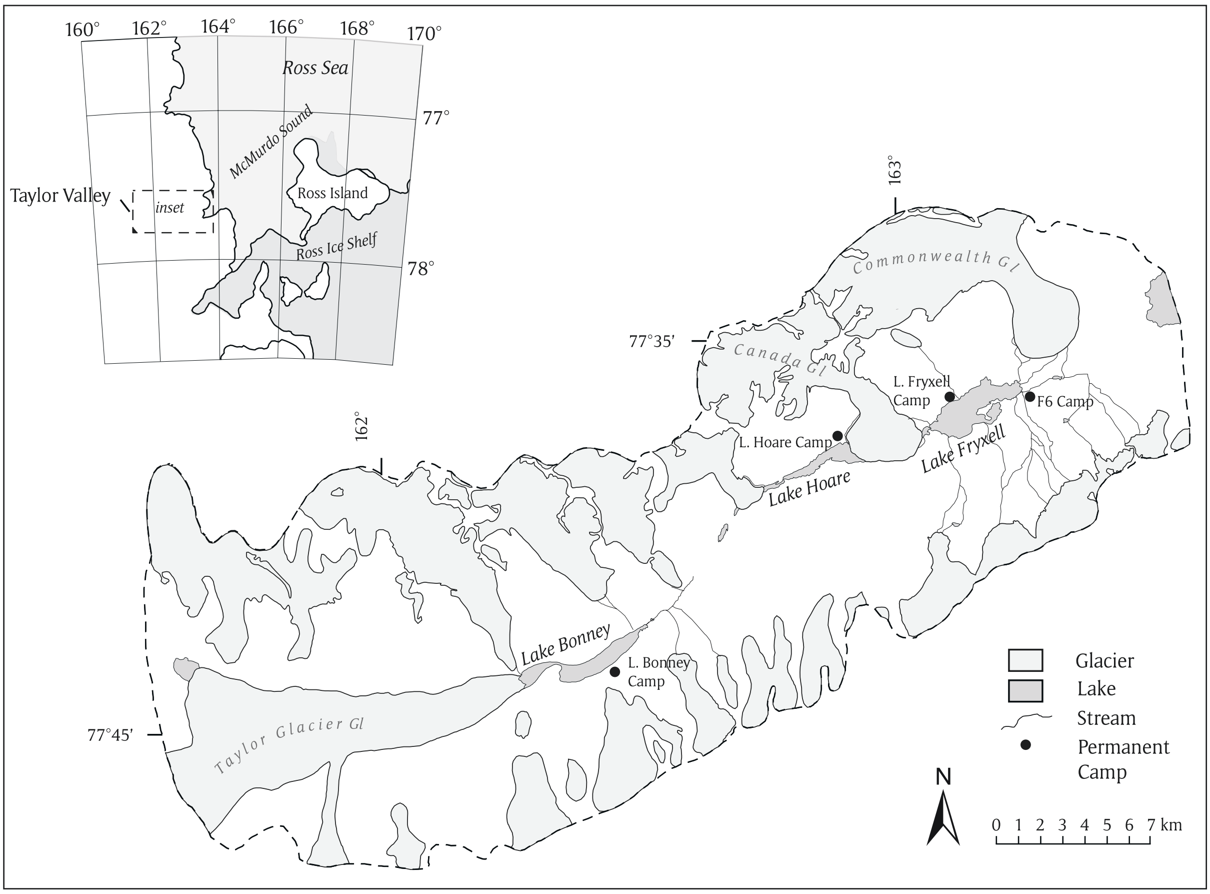

Figure 1: Map of the Taylor Valley. Taylor Valley is one of the McMurdo Dry Valleys (MDV), located in southern Victoria Land, Antarctica. Locations of permanent field camps, L. Bonney Camp, L. Hoare Camp, L. Fryxell Camp and F6 Camp (near Lake Fryxell) are marked. DOI: https://doi.org/10.1525/elementa.288.f1

power system were made with improved battery and an inverter system, which decreased the reliance on diesel-powered generators for electricity to run lab equipment.

We have compared the original 1997–1998 consumption and estimated emissions to those of a recent field season (2015–2016) in **Table 2**. The particulate elemental carbon (PEC) flux was determined using the conversion factors of Charlton and Ogren (1982) and Muhlbaier and Williams (1982), and the density values utilized in our original paper. Particulate organic carbon (POC) emissions were computed in a similar manner using data from Cass et al. (1982), Charlson and Ogren (1982), and Muhlbaier and Williams (1982). As in the original paper, we assumed the POC from helicopter emissions were 1/2.7 (the fraction of volatile to nonvolatile carbon for jet emissions) of the PEC emission for aircraft turbine emissions (Cass et al. 1982). NO_x was also calculated in the same manner as the original paper. The estimated emissions during the 2015–2016 austral are very similar to the 1997–1998 emissions. The emission rates of PEC, POC, and NO_x could be as high as 3.4, 1.25, and 10.6 × $10^5 ga^{-1}$, on the other hand, they could be as low as 0.6, 0.2 and 3 × $10^5 ga^{-1}$. Because of this variation, as in our previous paper, these fluxes should probably be considered as order of magnitude estimates. The highest POC flux, if equally deposited throughout Taylor Valley, would be 3.1 × 10^{-4}g m^{-2}, which is orders of magnitude lower than the estimated active organic carbon reservoir in the soils of 100g m^{-2} and in the lakes of 1250g m^{-2} (Burkins et al. 2001). Clearly the emission of POC from fossil fuel consumption from scientific activities is not environmentally significant.

The PEC fluxes are a factor of 2–3 times higher than those for POC (**Table 2**), but when integrated over the entire landscape, the flux is very low. However, dissolved black carbon (DBC) produced from fossil fuel burning has recently been observed in many of the lakes in the Dry Valley including Lake Fryxell in Taylor Valley (Khan et al. 2016). Although the concentrations of DBC range from about 1 to 350 μgCL^{-1} in the lakes, these data do suggest that contemporary anthropogenic sources of PEC are entering the aquatic systems in Taylor Valley. More recent work has measured black carbon deposition on the Commonwealth Glacier in Taylor Valley (Khan et al., 2018). The majority of this material is thought to be of local origin, and high wind events play a role in redistributing it from the soils onto the glacier surface. However, larger particles have been interpreted as originating from a longer travelled source (Khan et al., 2018). The total concentrations measured on the glacier are not enough to change the surface albedo.

Again, as demonstrated in the original work, the estimated flux of NO_x is the highest of all the fossil fuel

Table 1: Fossil fuels used at Lake Hoare camp, Taylor Valley, Antarctica[a]. DOI: https://doi.org/10.1525/elementa.288.t1

Year	Diesel Generators (gallons) JP5/8	Preway-Heater (gallons) JP5/8	Hole Melters (gallons) JP5/8	ATV/gas generators Drills (gallons) Mogas	Heaters/ Refrigerators (laboratory) (lbs) propane	Cook stove/ Refrigerators (Main Hut) (lbs) propane	Toilets (lbs) propane
1997–98	440	770	110	110	600		400
2002–03	0	1045	385	330	600	800	800
2003–04	0	550	110	27.5	600	300	600
2004–05	0	1045	110	55	400	300	600
2005–06	0	605	110	55	400	800	1000
2006–07	0	550	220	220	700	600	700
2007–08	165	715	220	220	2300	1300	2100
2008–09	0	660	165	220	900	700	700
2009–10	138	440	82.5	55	800	800	800
2010–11	55	275	275	220	500	600	700
2011–12	0	330	110	55	700	700	800
2012–13	0	440	110	110	800	800	1000
2013–14	110	275	110	55	300	900	500
2014–15	55	825	110	55	700	600	900
2015–16	0	550	110	330	900	1000	600
2016–17	110	440	55	55	600	700	800

[a]Data are compiled from the annual end of season reports from the Lake Hoare camp manager.

Table 2: Estimated carbon and nitrogen emissions from fossil fuels used in the McMurdo Dry Valleys during 1997–1998 compared to the 2015–2016 summer field season[a]. DOI: https://doi.org/10.1525/elementa.288.t2

	Emissions (10^3 g)					
	PEC		POC		NO_x	
	2015–16	1997–98	2015–16	1997–98	2015–16	1997–98
$JP5/8_{us}$	48–286	55–327	18–106	20–121	229–801	265–912
$JP5/8_{nz}$	8–45	n/a	3–17	n/a	36–127	n/a
Diesel	4–8	8–16	1.7	3.4	23–118	46–238
MOGAS	0.01–0.1	0.004–0.03	0.038	0.01	8–10	2.7–3.5
Propane	0.0002–0.1	0.0001–0.05	0.0004–0.008	0.0002–0.03	n/a	n/a
TOTAL	60–339	62–342	23–125	24–125	296–1056	314–1154

[a]JP8/JP5 is used in helicopters, while diesel, mogas and propane are used at Lake Hoare camp, one of the main scientific bases in the dry valleys. (US = United States program; NZ = New Zealand program).

burning products. Concentrations of nitrate in Taylor Valley soils increase with age of the surface and are higher in the older tills deposited in the western portion of the valley than the younger tills in the Lake Fryxell basin in the east (Barrett et al. 2007). This difference leads to N-limited aquatic ecosystems in the eastern part of the valley and P- limited ones in the west (Barrett et al. 2007; Priscu 1995). When melted, glaciers are also a major potential source of nitrate to the aquatic systems in the valley (Witherow et al. 2006).

We had previously estimated the flux of NO_x from fossil fuel burning would take ~150 years at the current rate to the double the N in the soil reservoir in Taylor Valley. The hydrologic systems in the MDVs only make up a very small percentage to the total surface area of the valley, and any N products deposited on the lake ice, the ablation zones of the glaciers, and the stream channels would eventually make its way into the closed-basin lakes. So the major impact of the N deposition would be to the soil ecosystem. Based on the more recent information discussed within, this is still the case, but we have assumed that all the NO_x produced by local scientific activity is deposited in Taylor Valley. This clearly would not be the case, as the helicopter traffic occurs throughout the McMurdo region, especially between the dry valleys and McMurdo Station to the SE, usually over the McMurdo Sound area. In addition, the chemical lifetime of NO_x due to gas phase oxidation to HNO_3 in the lower troposphere in the summer at polar latitudes is 1.25 to 3 days (Levy et al. 1999). Given the wind dynamics of the Taylor Valley (Doran et al. 2002), and the oxidation kinetics, much of NO_x produced, especially at higher altitudes from helicopter operations is probably transported out of the Taylor Valley proper.

The McMurdo Dry Valleys, Antarctica are a unique scientific research site, one that requires management, stewardship and environmental assessment. Taylor Valley serves as the major operational area of the McMurdo Dry Valleys Long-Term Ecological Research site, as well as other scientific investigations. During these scientific activities, fossil fuel is consumed and the by-products of burning are produced. In our initial evaluation of the consequences of these activities we concluded that the production of particulate carbon was extremely low and that the NO_x flux could be of significant consequence to the natural reservoirs N over century time scales. A second evaluation based on a longer time series of measurements from the largest scientific camp in Taylor Valley, and a comparison between our initial estimates in 1997–1998 to that of a recent field season, support our initial conclusions. However, the recent detection of dissolved black carbon in the surface waters of the lakes in the region indicates that fossil fuel burning by-products can be observed in this environment. A recent international workshop produced ten recommendations for better environmental assessment of the MDVs in the future. One of these was that the synthesis of all information available should occur in a timely manner so that the environmental footprint of all current activities be established. This information then could be used to make better informed decisions for the overall management of the MDVs (Priscu and Howkins, 2016). As outlined in the Madrid Protocol, the use of monitoring, and as recommended from this recent workshop, the integration and synthesis of all available information collected from both scientific investigations, like the MCM-LTER program, and from national Antarctic programs, such as the fuel burning data presented here, are needed in order to better assess the impact of scientific operations on the Antarctic continent. We hope this approach serves as an important tool for future evaluations.

Data Accessibility Statements
All data are given in the main text.

Acknowledgements
The authors would like to thank Sharon Rae Spain for discussion about changes to camp infrastructure and the records of fossil fuel use at Lake Hoare camp. We thank Elizabeth Kauffman for the data on helicopter operations. We are extremely grateful for the camaraderie, work ethic, and scientific discussions of our MCM-LTER colleagues through the years 1993 to the present. We thank Susan Welch for her help with the production of the manuscript.

Funding informations
This work was supported by the following National Science Foundation grants: OPP-ANT-9813061, OPP-ANT-0423595, and OPP-1115245.

Competing interests
The authors have no competing interests to declare.

Author contributions
- Contributed to conception and design: WBL, KAW
- Contributed to acquisition of data: WBL, ES, KAW
- Contributed to analysis and interpretation of data: WBL, ES, KAW
- Drafted and/or revised the article: WBL, KAW
- Approved the submitted version for publication: WBL, ES, KAW

References
Barrett, JE, Virginia, RA, Lyons, WB, McKnight, DM, Priscu, JC, Doran, PT, Fountain, AG, Wall, DH and **Moorhead, DL** 2007 Biogeochemical stoichiometry of Antarctic dry valley ecosystems. *J Geophys Res: Biogeosci* **112**(G1). DOI: https://doi.org/10.1029/2005JG000141

Barrett, JE, Virginia, RA, Parsons, AN and **Wall, DH** 2006 Soil carbon turnover in the McMurdo Dry Valleys, Antarctica. *Soil Biol Biochem* **38**(10): 3065–82. DOI: https://doi.org/10.1016/j.soilbio.2006.03.025

Burkins, MB, Virginia, RA and **Wall, DH** 2001 Organic carbon cycling in Taylor Valley, Antarctica: quantifying soil reservoirs and soil respiration. *Global Change Biology* **7**(1): 113–125. DOI: https://doi.org/10.1046/j.1365-2486.2001.00393.x

Cass, GR, Boone, PM and **Macias, ES** 1982 Emissions and air quality relationships for atmospheric carbon particles in Los Angeles. *Part Carbon: Atmos Life Cycle*, 207–244. DOI: https://doi.org/10.1007/978-1-4684-4154-3_13

Charlson, RJ and **Ogren, JA** 1982 The atmospheric cycle of elemental carbon. *Part Carbon: Atmos Life Cycle*, 3–18. DOI: https://doi.org/10.1007/978-1-4684-4154-3_1

Chown, SL, Lee, JE, Hughes, KA, Barnes, J, Barrett, PJ, Bergstrom, DM, Convey, P, Cowan, DA, Crosbie, K, Dyer, G and **Frenot, Y** 2012 Challenges to the future conservation of the Antarctic. *Science* **337**(6091): 158–9. DOI: https://doi.org/10.1126/science.1222821

Doran, PT, McKay, CP, Clow, GD, Dana, GL, Fountain, AG, Nylen, T and **Lyons, WB** 2002 Valley floor climate observations from the McMurdo Dry Valleys, Antarctica, 1986–2000. *J Geophys Res: Atmos* **107**(D24). DOI: https://doi.org/10.1029/2001JD002045

Fountain, AG, Lyons, WB, Burkins, MB, Dana, GL, Doran, PT, Lewis, KJ, McKnight, DM, Moorhead, DL, Parsons, AN, Priscu, JC and **Wall, DH** 1999

Physical controls on the Taylor Valley ecosystem, Antarctica. *Bioscience* **49**(12): 961–71. DOI: https://doi.org/10.2307/1313730

Fountain, AG, Nylen, TH, Monaghan, A, Basagic, HJ and **Bromwich, D** 2010 Snow in the McMurdo Dry Valleys, Antarctica. *International Journal of Climatology* **30**(5): 633–642. DOI: https://doi.org/10.1002/joc.1933

Houghton, M, McQuillan, PB, Bergstrom, DM, Frost, L, Van Den Hoff, J and **Shaw, J** 2016 Pathways of alien invertebrate transfer to the Antarctic region. *Polar Bio* **39**(1): 23–33. DOI: https://doi.org/10.1007/s00300-014-1599-2

Kennicutt, MC, Chown, SL, Cassano, JJ, Liggett, D, Massom, R, Peck, LS, Rintoul, SR, Storey, JW, Vaughan, DG, Wilson, TJ and **Sutherland, WJ** 2014 Six priorities for Antarctic science. *Nature* **512**(7512): 23–25. DOI: https://doi.org/10.1038/512023a

Khan, AL, Jaffé, R, Ding, Y and **McKnight, DM** 2016 Dissolved black carbon in Antarctic lakes: Chemical signatures of past and present sources. *Geophys Res Lett* **43**(11): 5750–5757. DOI: https://doi.org/10.1002/2016GL068609

Khan, AL, McMeeking, G, Schwartz, JP, Xian, P, Welch, KA, Lyons, WB and **McKnight, D** 2018 Near-surface refractory black carbon observations in the atmosphere and snow in the McMurdo Dry Valleys, Antarctica, and the potential impacts of foehn winds. *JGR: Atmospheres*. DOI: https://doi.org/10.1002/2017JD027696

Levy, H, Moxim, WJ, Klonecki, AA and **Kasibhatla, PS** 1999 Simulated tropospheric NO_x: Its evaluation, global distribution and individual source contributions. *J Geophys Res: Atmos* **104**(D21): 26279–26306. DOI: https://doi.org/10.1029/1999JD900442

Levy, J 2013 How big are the McMurdo Dry Valleys? Estimating ice-free area using Landsat image data. *Antarctic Science* **25**(1): 119–120. DOI: https://doi.org/10.1017/S0954102012000727

Lyons, WB, Nezat, CA, Welch, KA, Kottmeier, ST and **Doran, PT** 2000 Fossil fuel burning in Taylor Valley, southern Victoria Land, Antarctica: Estimating the role of scientific activities on carbon and nitrogen reservoirs and fluxes. *Environ Sci Technol* **34**(9): 1659–62. DOI: https://doi.org/10.1021/es990794l

Muhlbaier, JL and **Williams, RL** 1982 Fireplaces, furnaces and vehicles as emission sources of particulate carbon. *Part Carbon: Atmos Life Cycle*, 185–205. DOI: https://doi.org/10.1007/978-1-4684-4154-3_12

Ndungu, K, Zurbrick, CM, Stammerjohn, S, Severmann, S, Sherrell, RM and **Flegal, AR** 2016 Lead sources to the Amundsen Sea, West Antarctica. *Environ Sci Technol* **50**(12): 6233–6239. DOI: https://doi.org/10.1021/acs.est.5b05151

Planchon, FM, Boutron, CF, Barbante, C, Cozzi, G, Gaspari, V, Wolff, EW, Ferrari, CP and **Cescon, P** 2002 Changes in heavy metals in Antarctic snow from Coats Land since the mid-19th to the late-20th century. *Earth and Planet Sci Lett* **200**(1–2): 207–220. DOI: https://doi.org/10.1016/S0012-821X(02)00612-X

Priscu, JC 1995 Phytoplankton nutrient deficiency in lakes of the McMurdo Dry Valleys, Antarctica. *Freshwater Biol* **34**(2): 215–227. DOI: https://doi.org/10.1111/j.1365-2427.1995.tb00882.x

Priscu, JC, Wolf, CF, Takacs, CD, Fritsen, CH, Laybourn-Parry, J, Roberts, EC, Sattler, B and **Lyons, WB** 1999 Carbon transformations in a perennially ice-covered Antarctic lake. *Bioscience* **49**(12): 997–1008. DOI: https://doi.org/10.2307/1313733

Priscu, JP and **Howkins, A** (eds) 2016 Environmental Assessment of the McMurdo Dry Valleys: Witness to the Past and Guide to the Future, Special Publ. LRES-PRG 02, Department of Land Resources and Environmental Sciences, College of Agriculture, Montana State University, USA, 63.

Sheppard, DS, Claridge, GGC and **Campbell, IB** 2000 Metal contamination of soils at Scott Base, Antarctica. *Appl Geochem* **15**(4): 513–530. DOI: https://doi.org/10.1016/S0883-2927(99)00055-4

Tin, T, Fleming, ZL, Hughes, KA, Ainley, DG, Convey, P, Moreno, CA, Pfeiffer, S, Scott, J and **Snape, I** 2009 Impacts of local human activities on the Antarctic environment. *Antarctic Science* **21**(1): 3–33. DOI: https://doi.org/10.1017/S0954102009001722

Wall, DH, Lyons, WB, Chown, SL, Convey, P, Howard-Williams, C, Quesada, A and **Vincent, WF** 2011 Long-term ecosystem networks to record change: an international imperative. *Antarctic Science* **23**(03): 209. DOI: https://doi.org/10.1017/S0954102011000319

Welch, KA, Lyons, WB, Whisner, C, Gardner, CB, Gooseff, MN, McKnight, DM and **Priscu, JC** 2010 Spatial variations in the geochemistry of glacial meltwater streams in Taylor Valley, Antarctica. *Antarctic Science* **22**: 662–672. DOI: https://doi.org/10.1017/S0954102010000702

Witherow, RA, Lyons, WB, Bertler, NAN, Welch, KA, Mayewski, PA, Sneed, SB, Nylen, T, Handley, MJ and **Fountain, A** 2006 The aeolian flux of calcium, chloride, and nitrate to the McMurdo Dry Valleys landscape: Evidence from snow pit analysis. *Antarctic Science* **18**(4): 497–505. DOI: https://doi.org/10.1017/S095410200600054X

How to cite this article: Lyons, WB, Saelens, E and Welch, KA 2018 The impact of fossil fuel burning related to scientific activities in the McMurdo Dry Valleys, Antarctica: Revisited. *Elem Sci Anth,* 6: 33. DOI: https://doi.org/10.1525/elementa.288

Domain Editor-in-Chief: Oliver Chadwick, Geography Department, University of California, Santa Barbara, US

Knowledge Domain: Earth and Environmental Science

Submitted: 05 January 2018 **Accepted:** 03 March 2018 **Published:** 18 April 2018