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Waxing activity as a potential source of exposure to per- and polyfluoroalkyl substances (PFAS) and other environmental contaminants among the US ski and snowboard community

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ABSTRACT

Background: Skiers and snowboarders apply waxes and solvents to their equipment to enhance glide across the snow. Waxing results in exposures to per- and polyfluoroalkyl substances (PFAS) and particulate matter, which have been associated with adverse health effects among professional wax technicians in Scandinavia. However, little is known about exposure among people who participate at other levels of sport, including recreationally, in other regions.
Objective: We sought to characterize wax-related exposures among US skiers and snowboarders who participate across numerous levels of sport to expand scientific understanding of environmental health risks among this population.
Methods: We used an anonymous electronic survey to evaluate wax-related exposures among US cross-country and downhill skiers and snowboarders. Specifically, we assessed (Fang et al., 2020): duration of time involved with each sport in any role (Freberg et al., 2013), intensity of wax-related exposures based on time spent in waxing areas, wax use, and wax type (Rogowski et al., 2007), frequency of fluorinated wax application, and (Freberg et al., 2010) use of exposure interventions.
Results: Participants tended to be long-term winter sports enthusiasts (e.g., median downhill skiing duration: 31 years). Nearly all (92%) participants personally applied some wax to their skis/snowboards and most applied waxes containing PFAS (67%) and solvents (62%). Ski professionals waxed the most pairs of skis with fluorinated waxes annually (median (IQR): 20 (1, 100)), though individuals participating recreationally also applied fluorinated waxes regularly. Exposure interventions were not widely used.
Significance: Waxing activities may pose significant risk of exposure to PFAS and other environmental contaminants among the US ski and snowboard community. Efforts are needed to reduce these exposures through changes to wax use patterns and broader adoption of exposure reduction strategies.

1. Introduction

Skiers and snowboarders use waxes to impart desirable properties onto their equipment. Notably, waxes are applied to the base of skis and snowboards (referred to as "skis" throughout) to improve glide across the snow and, for cross-country skiers, to improve grip for classic technique. Many of these waxes contain per- and polyfluoroalkyl substances (PFAS) and other hydrocarbons (Fang et al., 2020; Freberg et al., 2013; Rogowski et al., 2007), as well as organic solvents that may be used to remove wax while cleaning ski and snowboard bases. The ski wax application process has been described previously (e.g., Freberg et al., 2013). Collectively, the waxing process releases environmental contaminants, including PFAS, hydrocarbons, and organic solvents into volatile, aerosol, and/or particulate fractions of air, which can then settle as dust in the vicinity (Freberg et al., 2010, 2013; Hämeri et al., 1996; Nilsson et al., 2013a). Wax residues left on the base of skis can also

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abrade onto snow, leading to contamination of snow, water, and wildlife near ski and snowboard venues (e.g., Carlson and Tupper, 2020; Grønnestad et al., 2019; Plassmann and Berger, 2013; Wang et al., 2021).

PFAS are a class of synthetic, fluorinated hydrocarbons with surfactant properties, which have been used extensively in industrial applications and consumer products. PFAS are widespread in the environment and in people globally (e.g., CDC, 2021; De Silva et al., 2021; Glüge et al., 2020; Muir and Miaz, 2021). Diet, including drinking water, is currently understood to be the predominant route of human exposure to PFAS, though inhalation is increasingly recognized as an understudied and important exposure route (De Silva et al., 2021; Morales-Mcdevitt et al., 2021). PFAS exposure is associated with numerous adverse health effects, including increased cholesterol levels, thyroid disease, liver damage, immunosuppression, developmental and reproductive complications, and cancer (Fenton et al., 2020). Particulate matter (PM) is produced via combustion of hydrocarbons and other products, as well as activities that generate dust. Exposure to PM occurs through inhalation and particles are classified by size, with fine particles penetrating more deeply into the respiratory tract than coarse particles (Kim et al., 2015). PM exposure is associated with respiratory and cardiovascular diseases, adverse pregnancy outcomes, and cancer (Kim et al., 2015; Manisalidis et al., 2020). Organic solvents are widely used as degreasers in industrial, commercial, and residential settings. Exposure to organic solvents occurs primarily through inhalation and dermal absorption, and these compounds are recognized as neurotoxicants, reproductive toxicants, and carcinogens (Joshi and Adhikari, 2019; NIOSH, 2018a). Targeting modifiable behaviors to reduce exposure to PFAS, PM, and solvents is an important step towards protecting public health and preventing additional release of these contaminants into the environment.

Exposure to environmental contaminants from ski waxing has been documented in occupational settings. In professional cross-country ski waxing spaces, PFAS have been measured in air and dust, with carboxylic acid and fluorotelomer alcohol compounds being detected most frequently (Freberg et al., 2010; Nilsson et al., 2013a). PFAS concentrations reported in these occupational settings are orders of magnitude higher than those reported in indoor air from residences (Winkens et al., 2017), offices (Fraser et al., 2012), classrooms, retail settings, and laboratories (Morales-Mcdevitt et al., 2021). While indoor air standards for PFAS do not exist in the US, the fact that PFAS concentrations in blood samples collected from people working in these waxing environments are much higher than the general public and at levels previously shown to be associated with adverse health effects suggests that ski wax-related exposures are unsafe (Freberg et al., 2010; Fenton et al., 2020; Nilsson et al., 2010). PFAS concentrations measured in blood collected from professional, full-time cross-country ski wax technicians were similar to levels measured among workers at a facility that manufactured perfluorooctanoic acid (PFOA) products (Freberg et al., 2010; Nilsson et al., 2010, 2013b; Olsen et al., 2000). These levels were 45–50 times higher than median concentrations reported in the general population (Nilsson et al., 2010, 2013b). Furthermore, blood PFAS concentrations were highest at the end of the ski waxing season and were positively associated with years working as a wax technician (Freberg et al., 2010; Nilsson et al., 2010), consistent with long half-lives of PFAS compounds (Li et al., 2018).

Prior research has shown that waxing also causes fine PM contamination of indoor air where waxing occurs (Freberg et al., 2013, 2014; Hämeri et al., 1996; Nilsson et al., 2013a; Dahlqvist et al., 1992; Liesivuori et al., 1994). PM concentrations varied by wax type and generally increase over time in indoor spaces during waxing activity (Freberg et al., 2013, 2014; Nilsson et al., 2013a). PM concentrations (inhalable: mean 32.2 mg/m^3; respirable: mean 18.6 mg/m^3) in indoor air where professional ski wax technicians work exceed health-based guidelines for PM in indoor occupational settings (inhalable: 10 mg/m^3; respirable: 3 mg/m^3) and ambient air (inhalable: 150 μg/m^3; respirable: 35 μg/m^3) (Freberg et al., 2013; EPA, 2021; NIOSH, 2018b). Concentrations of PM in indoor spaces where waxing occurs also exceeded health-based standards for ambient air quality by two orders of magnitude (Freberg et al., 2013; Nilsson et al., 2013a; EPA, 2021; NIOSH, 2018b). Acute respiratory toxicity has been reported among people waxing skis for multiple hours per day, and has specifically been attributed to PM and fluorinated compound exposure (Dahlqvist et al., 1992; Freberg et al., 2016; Bracco and Favre, 1998). These studies demonstrate that fluorinated wax use can be a significant source of PFAS exposures (Freberg et al., 2010, 2013; Nilsson et al., 2013a) and a potential threat to human health.

Additional wax-related chemistries may also pose human health risks. Notably, solvents used for ski base cleaning volatilize during use. For example, aliphatic hydrocarbons have been detected in wax cabin air at mean concentrations of 43.2 parts per million (ppm) (Freberg et al., 2013) and are known to pose health risks in humans (Tormoehlen et al., 2014). Waxing in ventilated spaces and using personal protective equipment (PPE) like respirators, dust masks, and gloves can reduce wax-related exposures (Freberg et al., 2013, 2014; Mundhal, 2019).

However, previously studied wax-related exposure scenarios among professional wax technicians may not be generalizable to the broader ski and snowboarding community, including people who participate in the sport recreationally or as amateur competitors, other industry professionals, or individuals who do not personally ski or snowboard, but may occupy spaces where waxing activity occurs (e.g., family members of a skier or snowboarder, or a ski or snowboard store employee). Further, anecdotal evidence shared through personal communication with United States (US) skiers and snowboarders suggests exposure interventions are not utilized equally across all levels of involvement with these sports and are often not employed in ways that fully address exposure-related concerns (Personnel, 2021).

Our research sought to expand the scientific understanding of waxing activity as a source for PFAS and other environmental exposures among a broader range of people who participate – directly or peripherally – in skiing and snowboarding. Specifically, we surveyed members of the cross-country and downhill skiing and snowboarding community throughout the US about their history of involvement in these sports and their exposure to ski wax through either personal wax use or proximity to where other people use wax. We also asked participants about their use of exposure interventions to reduce wax-related exposures.

2. Methods

2.1. Study participants

For the purposes of this study, we defined the "US ski and snowboard community" as anyone living in the US with a connection to cross-country or downhill skiing or snowboarding, regardless of whether a person participates in one of these sports themselves or is connected to these sports through another means (e.g., family member or friend, employment). We recruited participants through two mechanisms (Fang et al., 2020): four professional membership organizations and businesses in the US ski and snowboard industry, and (Freberg et al., 2013) "snowball sampling," a process where participants share the survey with other people to expand survey recruitment. To recruit participants from across the US, we sought partnerships with membership organizations and businesses operating at a national or regional scale, working with one or more of the three sports of interest in this study: cross-country skiing, downhill skiing, and snowboarding. In partnership with the professional organizations and businesses, we distributed an anonymous electronic survey to more than 50,000 people through their email distribution lists. Snowball sampling occurred on an ad-hoc basis and anyone living in the US who spoke English was eligible to participate in an effort to recruit people from as broad a range of engagement with these winter sports as possible. All participants were recruited between December 2020 and March 2021.

2.2. Survey

We developed an anonymous electronic survey in collaboration with the University of New Hampshire Survey Center to evaluate participants' history of involvement with cross-country and downhill skiing and snowboarding and their waxing behaviors, including fluorinated wax use. During the survey development process, we solicited feedback from ski and snowboard coaches and athletes, leaders of related professional organizations, and environmental epidemiologists specializing in risks from human exposure to PFAS.

We queried participants about sport affiliation (cross-country skiing; downhill skiing; snowboarding), roles within each sport (participant; competitive athlete; coach or technician; family member or friend of participant or athlete; other industry professional), and potential exposure to ski waxes and solvents. Broadly, we assessed duration, intensity, and frequency of wax-related exposures. We asked participants about the number of years they had participated in each sport and role to evaluate duration of potential wax-related exposures. We also evaluated intensity of exposure by asking whether participants had ever personally applied ski wax or whether they had spent significant time in spaces where ski waxing occurs. Finally, we evaluated the frequency with which participants are exposed to waxes or solvents by asking about the number of pairs of skis or snowboards they wax or use solvents on in a typical year, within each sport-role they had performed. To better understand participants' wax-related exposure history, we asked additional questions about the waxes they had used. Specifically, we asked about types of waxes used for different snow conditions (non-fluorinated; fluorinated; non-fluorinated dirt-repellent or antistatic), within different categories of fluorine concentration (low, high, pure "fluoro" waxes), and the form of pure fluorinated wax they had used (solid, liquid, powder) because fluorine content and the application process varies by pure fluorinated wax type (Fang et al., 2020). All survey questions about wax type were designed using terminology common in wax labeling and marketing so that participants would be familiar with the specific types of waxes, including different relative fluorine concentrations. Finally, we asked participants whether they used any of the following exposure interventions when applying non-fluorinated and fluorinated waxes and solvents: personal protective equipment (PPE; full- or half-face respirator, other mask, or gloves) or institutional controls (work in well-ventilated room or outdoors).

Participants also provided sociodemographic information, including age, height, weight, education, household income, and zip code of residence, as well as measures of physical activity (total number of hours per week of both cardiovascular activity and other forms exercise such as strength, yoga, or Pilates). Participants who completed the survey were eligible to enter a random drawing for a gift certificate to a ski and snowboard store. All research was conducted in accordance with human subjects research protocols approved by the Middlebury College Institutional Review Board and all participants provided informed, written consent (or written parental assent for individuals under 18 years of age) before initiating the survey.

2.3. Statistical analyses

To characterize study participants, we calculated descriptive statistics (counts and proportions for categorical variables, percentiles and ranges for continuous variables) for sociodemographic characteristics, physical activity, sport affiliation, roles within each sport, years in each sport-role, and wax use and application practices. All analyses were performed using R version 4.1.2 (R Core Team. R, 2019).

3. Results

3.1. Study participants

A total of 569 members of the US ski and snowboard community volunteered to complete the anonymous survey, 414 (73%) of whom were recruited via professional organization and business partnerships and 155 (27%) of whom were recruited through snowball sampling. The median age of participants, who resided in 33 US states, was 45 years (range: 7 to 82), and 61% identified as men (Table 1). Most participants held a Bachelor's degree or higher (82%) and most lived in households reporting total family income ≥$100,000 (60%) (Table 1). Participants in our study had a median BMI of 24 (IQR: 22, 26) and tended to be physically active with most reporting ≥7 h of exercise per week (67%) (Table 1).

Of the 569 participants, 403 (71%) currently or formerly participated in cross-country skiing, 401 (70%) in downhill skiing, and 173 (30%) in snowboarding (Fig. 1). Further, 236 (41%) participants reported currently or formerly participating in one sport, whereas 252 (44%) and 79 (14%) participated in two or three of the sports, respectively (Fig. 1). To understand how our participants engaged with these sports, we asked them which roles they currently or formerly held in each sport. Most participants identified as being either a current or former participant in the sport(s) they engaged in (Table S1). Among cross-country and downhill skiers, the second most prevalent role in each sport was a family member or friend of current or former participant, followed by coach or technician. Among snowboarders, the second most prevalent role was a current or former industry professional or organizer, followed by family member or friend of current or former participant (Table S1).

Table 1
Demographic characteristics of survey respondents (n = 569).

Demographics	Category	n (%)
Gender Identity[a]	Woman	212 (39%)
	Man	336 (61%)
	Transgender	<5
	Gender Non-Conforming	<5
	Prefer Not to Say	<5
	Missing	15
Highest level of education	High school or less	31 (6%)
	Tech school or some college	55 (10%)
	College graduate	228 (42%)
	Postgraduate	232 (42%)
	Missing	23
Total family household income in 2019	Less than $100,000	192 (40%)
	$100,000 to $200,000	180 (37%)
	Greater than $200,000	114 (23%)
	Missing	83
Average number of hours of exercise per week in past 3 months	0 to less than 7	183 (33%)
	7 to less than 12	178 (32%)
	Greater than 12	192 (35%)
	Missing	16
Age (years)		45 (31, 62)[b]
	Missing	16
Body Mass Index (BMI, kg/m^2)		24 (22, 26)[b]
	Missing	38

[a] For privacy purposes, all categories with fewer than or equal to five individuals were reported as "<5."
[b] Age and BMI are reported as median (IQR).

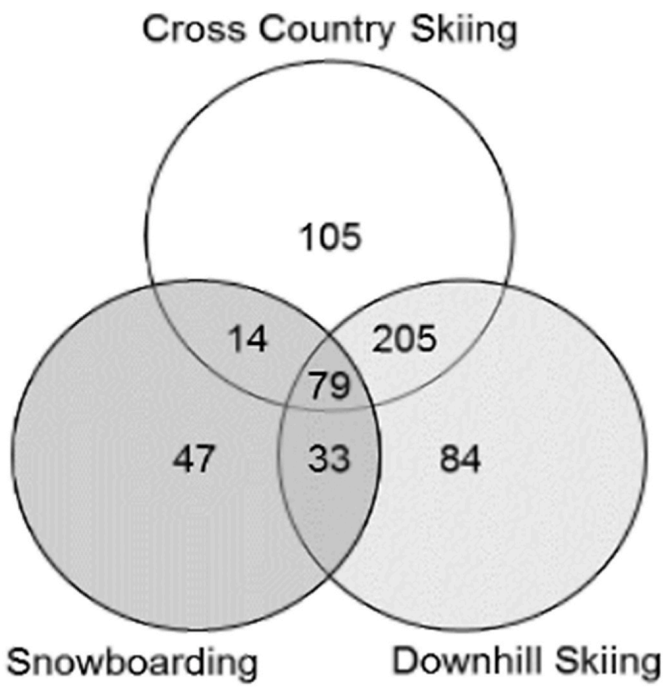

Fig. 1. Number of survey respondents (n = 567) who reported being affiliated with each sport. Two participants did not report participation in cross-country or downhill skiing or snowboarding. Data corresponds with that presented tabularly in Table S1.

3.2. Exposure duration

Overall, participants reported long-term participation in these sports (median years (IQR), cross-country skiing: Nilsson et al., 2013b (Wang et al., 2021; Winkens et al., 2017); downhill skiing: NIOSH, 2018b (Morales-Mcdevitt et al., 2021; Moran, 2020); snowboarding: Kim et al., 2015 (Freberg et al., 2010; Olsen et al., 2000)) (Fig. 2; Table S2). For each sport, people spent the greatest number of years engaged as a general participant and fewer years engaged as a competitive athlete or industry professional (Fig. 2; Table S2).

3.3. Exposure intensity and wax type

Nearly all (92%) participants had applied wax themselves at least once in their lifetime and most (78%) reported having spent significant time in a space used for applying waxes (e.g., a ski/snowboard shop, a basement, a garage, etc.); these proportions were similar across sport affiliations (Fig. 3, Table S3). Non-fluorinated hydrocarbon waxes were most commonly used (83%), followed by fluorinated waxes (67%), and solvents (62%) (Fig. 3, Table S3). More than half (57%) of participants also applied non-fluorinated dirt-repellent or anti-static waxes used when there is soil or debris in the snow (e.g., "dirty" snow conditions) (Table S3). Participants affiliated with cross-country skiing were most likely to report ever using fluorinated wax (75%), followed by downhill skiing (63%) and snowboarding (58%), and similar patterns were observed for non-fluorinated wax, solvents, and non-fluorinated dirt-repellent or antistatic wax (Table S3).

Given the broad range of ski and snowboard wax products on the market and our interest in potential PFAS exposure from wax-related activity, we asked additional questions about fluorinated wax use. The majority of participants had applied fluorinated waxes marketed as "low fluoro" (60%) and "high fluoro" (55%) (Fig. 3, Table S4). Overall, roughly a third of participants had also applied waxes containing higher fluorine content, marketed as "pure fluoro" (34%) (Fig. 3, Table S4). "Pure fluoro" waxes come in a variety of forms, which contain varying fluorine concentrations and require different application methods (Fang et al., 2020). Among our participants, solid blocks were most commonly used (28%), followed by powder (27%), and liquid (19%) forms (Fig. 3, Table S4). Reported use of fluorinated wax varied between sports, with more cross-country skiers reporting having used fluorinated waxes

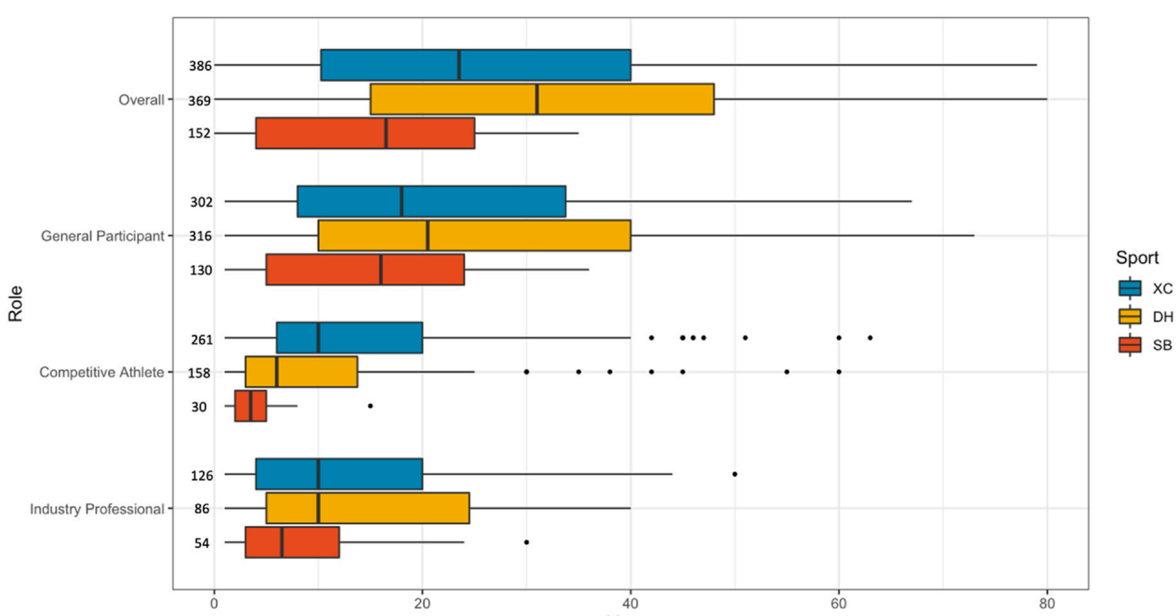

Fig. 2. Duration of time (years) that participants spent in each role, within each sport. Box and whisker plots represent the distribution of the number of years participated in each sport-role. Outliers were defined using the 1.5*IQR rule (<Q1 - 1.5*IQR or > Q3+1.5*IQR) and are represented as black dots (•). 'Overall' encompasses all sport-roles, including years someone was affiliated with these sports as a family member or friend of a participant; 'General Participant' encompasses all years spent personally participating in these sports for non-competitive or non-professional reasons; 'Competitive Athlete' includes years spent competing in these sports at any level of competition; 'Industry Professional' includes coaches, technicians, organizers, and other professional roles. XC – cross-country skiing; DH – downhill skiing; SB – snowboarding. Numbers located to the left of each boxplot inidicate the number of study participants (n) represented in each sport-role. Data corresponds to that presented tabularly in Table S2.

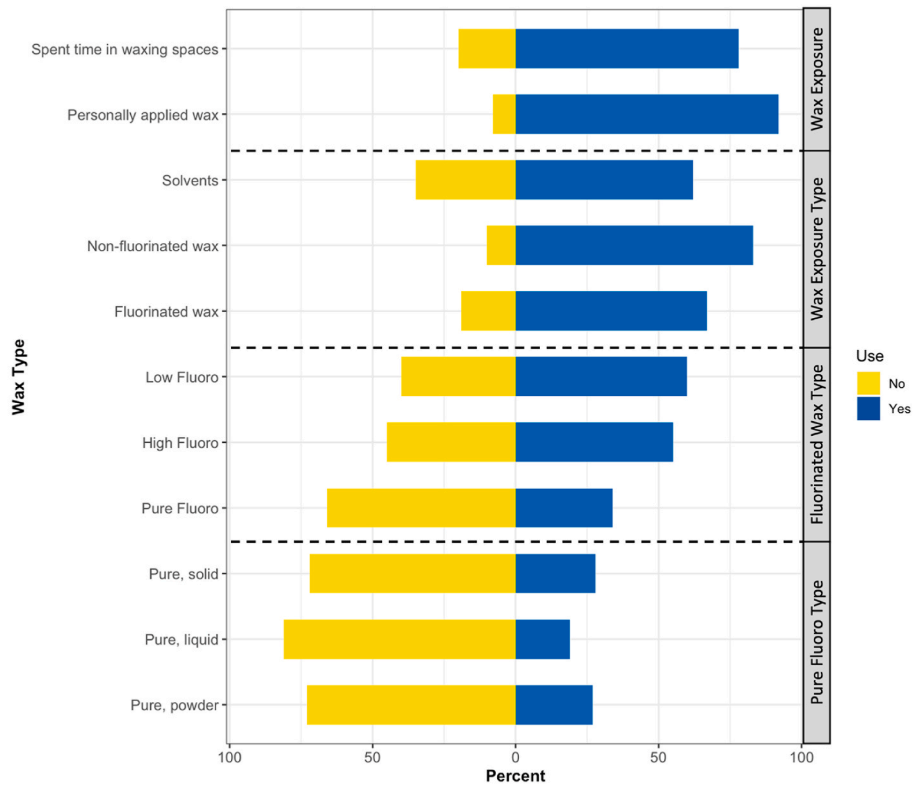

Fig. 3. Prevalence of wax exposure among US skiers and snowboarders from spending significant time in spaces where waxing occurs and personally applying waxes to ski/snowboard equipment. Fluoro: fluorinated wax product; Relative fluorine content: low, high, pure. Pure fluoro wax products are available in solid, liquid, and block forms. All percentages are calculated based on n = 569 participants. Data corresponds to that presented tabularly in Tables S3 and S4.

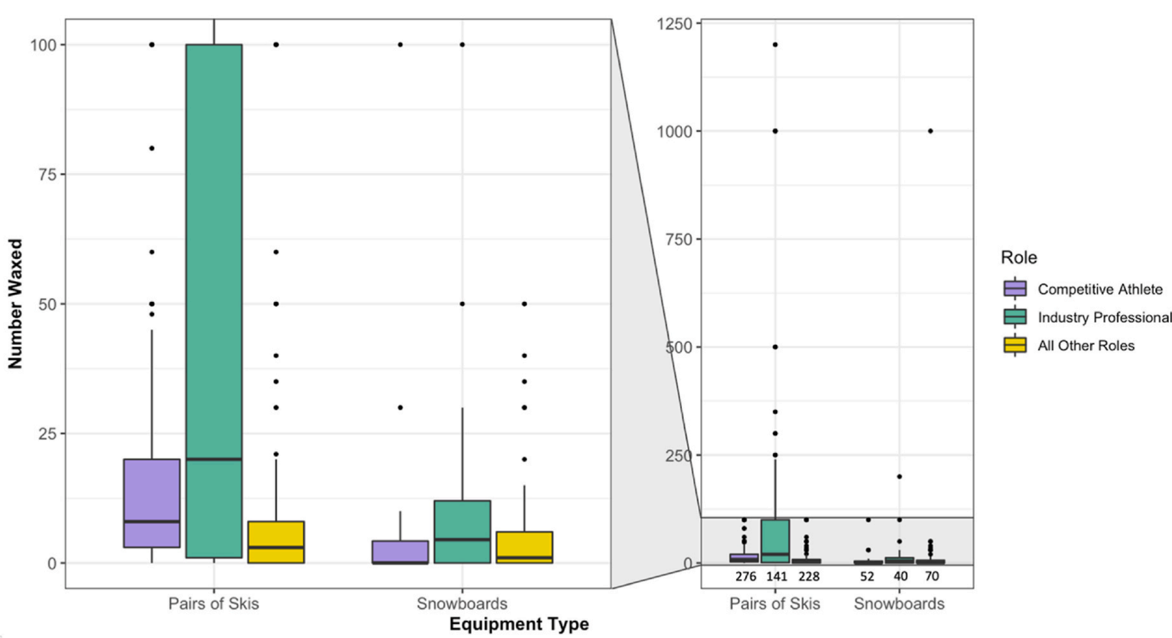

Fig. 4. Number of pairs of skis or snowboards to which participants applied fluorinated wax in a typical year, by role. Box and whisker plots represent the distribution of the number of pairs of skis or snowboards participants waxed with fluorinated wax in a typical year, within each role. Boxes reflect the median and IQR. Outliers were defined using the 1.5*IQR rule (<Q1 - 1.5*IQR or > Q3+1.5*IQR) and are represented as black dots (•). 'Competitive Athlete' includes competing in cross-country or downhill skiing or snowboarding at any level of competition; 'Industry Professionals' includes coach, technician, organizer, and other professional role; 'All Other Roles' encompasses personally participating in these sports for non-competitive or non-professional reasons or as a family member or friend of a participant. Numbers below each boxplot in the right-hand panel indicate the number of study participants (n) represented in each role. One participant was censored from "Pairs of skis" in the role of "Industry Professional" because the value reported was more than two orders of magnitude higher than the mean number of skis waxed annually by this subset of participants, which is not feasible for standard working hours. Data corresponds to that presented tabularly in Table S5. Additional detail about waxing frequency by sport-role is presented tabularly in Table S6.

compared to downhill skiers and snowboarders within each wax category. For example, pure fluoro wax use was most common among cross-country skiers (42%) compared to downhill skiers (33%) and snowboarders (16%) (Table S4).

3.4. Exposure frequency

To assess the frequency of fluorinated wax use, we also asked participants about the number of pairs of skis or snowboards they wax in a typical year. Among participants who reported applying fluorinated waxes, the frequency of use varied by equipment type (i.e., pairs of skis, which includes both cross-country and downhill skis, or snowboards) and role in the sport. In general, our study participants waxed a greater number of pairs of skis annually compared to snowboards regardless of their role within each sport. Industry professionals reported waxing the greatest number of pairs of skis (median (IQR): 20 (1, 100)) and snowboards (5 (0, 12)) annually (Fig. 4, Table S5) compared to other sport-role categories. Competitive athletes reported the second highest number of skis waxed in a typical year (Grønnestad et al., 2019 (Rogowski et al., 2007; NIOSH, 2018a)), whereas participants waxed very few snowboards annually as competitive athletes (0 (0, 4)) and in other roles (1 (0, 6)) (Fig. 4, Table S5).

In addition to fluorinated wax use being more prevalent among cross-country skiers (Tables S3 and S4), participants affiliated with cross-country skiing in all roles waxed more pairs of skis annually than downhill skiers. For instance, industry professionals who only cross-country ski reported waxing twice as many pairs of skis annually (median (IQR): 20 (1, 100)) as industry professionals who only downhill ski (10 (2, 78)) (Table S6). Snowboard industry professionals waxed fewer snowboards annually (5 (0, 12)) than the number of pairs of skis waxed by both cross-country and downhill skiers (Table S6). This pattern is consistent across roles between the sports.

3.5. Exposure intervention

Institutional controls, especially waxing in a well-ventilated area or outdoors, were the most common exposure interventions reported by participants in our study. Specifically, 51% of participants reported working in a well-ventilated area when applying non-fluorinated waxes, 61% while applying fluorinated waxes, and 52% while using solvents (Fig. 5, Table S6). A smaller proportion of our participants reported working outdoors when applying non-fluorinated (28%) and fluorinated (34%) waxes and solvents (28%) (Fig. 5, Table S7). Some participants reported using PPE (full- or half-face respirators, other masks, gloves). Respiratory PPE use was most common when applying fluorinated waxes, with 26% of participants using half-face respirators and 20% using other masks (Fig. 5, Table S7). Participants also reported wearing gloves when applying non-fluorinated wax (15%), fluorinated wax (23%), and solvents (23%) (Fig. 5, Table S7). Fewer than 20% of participants reported using other exposure interventions depicted in Fig. 5 when applying waxes or solvents.

When applying fluorinated waxes, exposure intervention use varied by participants' gender, education, and sport affiliation. Notably, men were more likely than women to work in a well-ventilated space (men 64%, women 55%) and wear a half-face respirator (men 30%, women 17%), though women were more likely to work outdoors (31% and 43%, respectively) and wear a full-face respirator (women 13%, men 10%) (Table S8). Participants with a four-year college degree or higher were more likely to work in a well-ventilated area (≥ College 63%, < College 55%) and wear gloves (≥ College 26%, < College 12%), however, they were less likely to work outdoors (≥ College 33%, < College 43%) (Table S8). Generally, cross-country skiers were more likely to use respiratory PPE (e.g., half-face respirator: XC 30%, DH 24%, SB 10%), whereas the use of institutional controls was relatively consistent between sports (Table S8). Participants who exclusively cross-country ski were much more likely than people who exclusively downhill ski to wear a half-face respirator (XC 42%, DH 20%) and work in a well-ventilated area (XC 54%, DH 37%) (Table S8).

4. Discussion

In a cross-sectional survey of members of the US ski and snowboard community, we observed high potential for exposure to PFAS and solvents as a result of long-term involvement with snow sports (i.e., proxy measure of exposure duration), high prevalence of wax and solvent use (i.e., a relative measure of exposure intensity due to direct contact with these products), and repeatedly waxing skis and snowboards over the course of a year (i.e., proxy measure of exposure frequency). Our research provides evidence that wax-related exposures are common among people engaged with cross-country and downhill skiing and

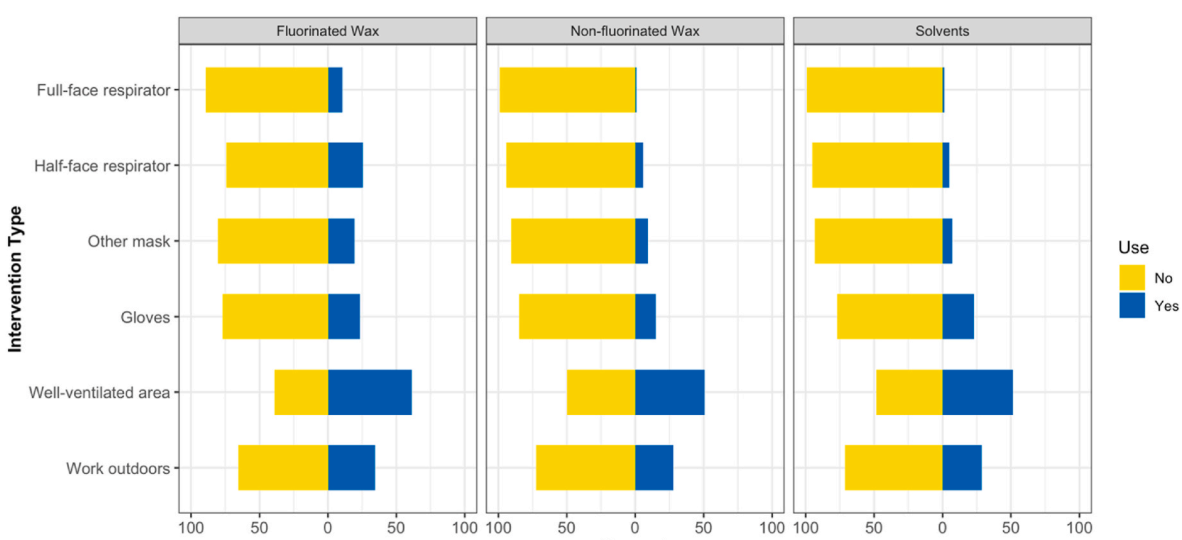

Fig. 5. Prevalence of exposure intervention strategies utilized by US skiers and snowboarders when applying waxes and solvents. Exposure interventions to protect against wax-related exposures through inhalation included PPE (full- or half-face respirators or other masks) and institutional controls (working in a well-ventilated indoor space or outdoors). Gloves may offer protection against dermal absorption and incidental ingestion via hand-to-mouth contact. Data corresponds to that presented tabularly in Table S7.

snowboarding at many levels of sport, including roles such as recreational participants, amateur athletes, industry professionals, and friends and family members of skiers and snowboarders who are not themselves participants.

Based on our survey data, wax use was most common among cross-country skiers regardless of wax category, followed by downhill skiers and snowboarders. This was especially true for fluorinated waxes and solvents. Cross-country skiers may therefore be at highest risk of wax-related exposures given the high prevalence of use among this community. We also found that people who ski and snowboard do so in multiple roles for many years, and may apply wax, including fluorinated wax, while in all roles. Yet, PPE and institutional control use lags behind wax use. Utilization of institutional controls was comparable between sports when applying fluorinated waxes, though cross-country skiers tended to use respiratory PPE more than downhill skiers and snowboarders. This may suggest that some heightened risk of wax-related expsoures among cross-country skiers is attenuated through exposure interventions, though utilization of even the most common intervention strategy (working in a well-ventilated area) was only used by 62% of cross-country skiers when applying fluorinated wax. Collectively, this implies the potential for long-term, frequent exposure to wax-related PFAS, PM, solvents, and other (non-fluorinated) chemistries. In many cases, the intensity of these exposures is also high since people are personally applying wax themselves or occupying spaces where waxing occurs.

Prior research has demonstrated significant concerns surrounding wax-related exposures among prefssional wax technicians in occupational settings (Freberg et al., 2010, 2014; Nilsson et al., 2010). In the current study, we show that members of the US ski and snowboard community tend to wax their equipment themselves. Although most participants in our study likely wax fewer pairs of skis or snowboards annually than professional ski wax technicians and thus are likely to have lower PFAS exposure from wax, they are nonetheless likely to have higher exposures than the general population. Given that typical homes, offices, and other indoor environments are increasingly recognized as important and concerning sources of PFAS exposure for the general public (Fraser et al., 2012; Winkens et al., 2017; Morales-Mcdevitt et al., 2021), any increase in exposure, such as from the use of fluorinated waxes, warrants attention and could present a serious exposure threat. Although not directly measured in our study, PM from ski waxing may also pose health risks for skiers and snowboarders given that PM concentrations in professional wax settings significantly exceeded health-based standards. In our study, "industry professionals" includes a broad range of roles, including coach, technician, organizer, and other professional roles. A subset of our "industry professionals" participants reported waxing a large number of pairs of skis and snowboards annually, suggesting that this subgroup may have PFAS and PM exposures that more closely reflect professional ski wax technicians reported in prior studies. Special attention should be given to this subgroup, especially those affiliated with cross-country skiing, when considering PFAS and other wax-related exposure reduction strategies.

Given the benefit conferred onto the user experience by modern ski and snowboard waxes, these products are popular among snow sport participants. Typically, people either wax their own skis and snowboards or have their equipment waxed by a professional technician on a fee-for-service basis. In our study, personal wax use was prevalent. Nearly all participants applied non-fluorinated waxes and approximately two thirds applied at least some fluorinated wax. Relatively few participants in our study reported being unsure which types of waxes they had used. We attribute this to both our study population of relatively serious skiers and snowboarders, as well as wax labeling. "Fluoro" was used as a marketing tool to imply performance enhancement and justify the higher cost of these products compared to non-fluorinated waxes, so skiers and snowboarders who wax their own equipment tend to be familiar with this term and fluorinated products. On the other hand, labeling, formulation, and use of non-fluorinated dirt-repellent or anti-static waxes have been less consistent over time (personal communication with industry professionals, BNS, 2010) thus explaining the higher percentage of participants who were unsure whether they had used these products.

Despite long-term involvement with skiing and snowboarding, frequent engagement with waxing activities, and being knowledgeable about the types of waxing products used, most participants in our study do not use interventions to reduce wax-related exposures. Ventilation was more common than other respiratory PPE by our participants, especially when applying fluorinated waxes. This finding is consistent with those from previous occupational studies (Freberg et al., 2014). However, most people waxing their own skis or snowboards in the US will not have access to the specialized ventilation systems used to protect against wax-related exposures in occupational settings, making reliance on non-specialized ventilation potentially risky to waxers' health. Industry leaders are aware of health risks posed by waxing activities and have recommended using respiratory protection while waxing for years (Knight, 2012; Swix USA). Yet, our study shows that adoption of these exposure reduction strategies remains low among US skiers and snowboarders. Glove use was moderately prevalent among our participants, especially when applying fluorinated and non-fluorinated waxes and solvents, which would reduce risk of incidental ingestion through hand-to-mouth contact and dermal absorption, respectively. However, dermal absorption is more likely to be a relevant route of exposure for solvents than PFAS (Poothong et al., 2020). Collectively, our findings suggest an opportunity for skier and snowboarder education to shift behaviors away from fluorinated wax use and towards the use of effective exposure interventions to reduce environmental health risks posed by waxing.

New developments in wax chemistry are emerging. This shift is partially driven by wax manufacturers' continual efforts to improve existing wax products for specialized snow conditions, such as non-fluorinated dirt-repellent or anti-static waxes used in "dirty" snow conditions, when soil or debris are present on the snow surface. Additionally, wax manufacturers are actively developing non-fluorinated replacement products for fluorinated waxes as consumer awareness of health and environmental risks posed by fluorinated waxes grows and regulations expand to address these issues (Catino, 2020; Rasmussen, 2019; Moran, 2020). Notably, the International Ski Federation (FIS) plans to ban fluorinated waxes in all competition within its purview beginning in the 2022–2023 competition season, however, this action has twice been postponed due to technical delays in developing rapid turnaround PFAS testing to enforce the policy at competitions (FIS, 2021). National and regional ski and snowboard governing bodies have also taken action to restrict fluorinated wax use in competition. The timing of FIS and other restrictions on fluorinated wax use follows the addition of certain PFAS to Annex A of the Stockholm Convention, an international environmental treaty to restrict the use of persistent organic pollutants, like PFAS (UNEP, 2019). Restrictions on fluorinated waxes also coincide with European Union (EU) efforts to restrict the use of PFOA and related substances in consumer products (ECHA, 2021). Since most waxes are manufactured in Europe, EU policies will likely serve to reduce fluorinated wax use globally.

Even with regulations restricting fluorinated wax use, environmental health risks from ski waxing will likely persist into the future for several reasons. First, people who already have fluorinated waxes may have incentives to continue using them because these products are expensive and highly effective at improving glide. Second, PM is generated when applying any glide wax and will continue even if fluorinated wax use is reduced. PM in waxing environments may also serve as a reservoir for PFAS residue even after fluorinated wax use has stopped. PM exposure may be reduced with proper ventilation and personal protective equipment; this is beneficial for professional technicians with access to specialized ventilation, but those who wax in non-professional settings may lack access and thus be more vulnerable to exposure. Third, other wax chemistries, like existing non-fluorinated anti-static waxes and emerging alternatives to fluorinated waxes, may also contain chemicals that pose human health risks when used for ski waxing. For example, some existing non-fluorinated waxes contain molybdenum, which may cause adverse health effects in humans and animal models (ATSDR, 2020). It is difficult to evaluate safety concerns of emerging wax products because their composition may be proprietary. Interestingly, wax formulations were recently evaluated and appear largely unchanged despite impending regulation (Fang et al., 2020). This is likely due to the superior performance of PFAS compared to chemical alternatives and the reality that regulation and enforcement will be needed to redirect the market towards PFAS-free wax products. Finally, wax dust and associated PFAS are highly stable and will remain in the environment when shed from equipment near ski venues as well as indoor spaces where waxing has occurred unless thoroughly cleaned and remediated. This will contribute to risk of ongoing exposure among individuals occupying these spaces in the future. Future research is needed to better understand wax chemistry of current products and also to track emerging formulations to protect the health of those who use these products.

Our study has several strengths. Importantly, this is the first study that we are aware of to investigate waxing activity among US cross-country and downhill skiers and snowboarders. Our sizeable study population ($n = 569$) included people from more than half of US states (33 of 50). The wide range of roles that our participants engaged in expands prior scientific knowledge of wax exposures that only included professional cross-country skiing and biathlon wax technicians in Scandinavia. Importantly, characterizing exposure variables allows us to identify which groups may be at highest risk. Information about waxing frequency, intensity, and duration and exposure interventions use may also be leveraged to assess exposure risks posed by emerging wax technologies in the future, as fluorinated wax bans continue to restrict the use of products containing PFAS.

There are also some limitations of our study. Our findings should be considered suggestive of wax-related exposures since we did not collect environmental samples or biospecimens from our participants to directly measure PFAS in waxing spaces or body burdens. Furture research should quantify wax-related exposures and body burdens in snow sport participants. Since we recruited participants through professional membership organizations and businesses within the ski and snowboard industry, we likely oversampled people who are more likely to wax their own equipment and be informed about ski wax products. To address this concern, we used snowball sampling to expand our recruitment to a broader skiing and snowboarding audience. Participants who reported engagement with snowboarding tended to be recruited from our business partner, whereas cross-country and downhill skiers tended to have been recruited through our professional organization partners; median duration of overall participation in snowboarding may have been lower than skiing as a result. Nonetheless, exposure duration (e.g., time spent participating in other roles) and exposure frequency were relatively consistent between sports. We inferred that years involved with each sport is a reasonable proxy for the duration over which wax-related environmental exposures might have occurred, though we did not directly ask participants how many years they had applied each wax type. When evaluating fluorinated wax use frequency, we distinguished between pairs of skis and snowboards to maintain consistent terminology about equipment types throughout our survey. However, we did not distinguish between fluorinated wax use frequency on cross-country versus downhill skis since our primary goal was to characterize overall exposure to wax-related environmental contaminants among our participants. We leveraged sport affiliation information (Fig. 1) to retrospectively assess frequency of fluorinated wax use by sport-role. Comparison between fluorinated waxing frequency among participants who engage in a single sport may not be representative of all participants who engage in each sport since the majority of participants engage in multiple sports. Our study is subject to recall bias and variability in participants' intepretations as participants' recollection of wax use, particularly the number of skis they wax in a typical year, may be imperfect and people may interpret spending "significant time" in a waxing space differently.

More research is needed to better understand wax-related exposures among a broad range of participants in winter sports, including measurement of PFAS concentrations in spaces where waxing occurs for occupational and recreational purposes, assessment of participants' attitudes about health and environmental risks from ski waxes, body burdens of PFAS in members of the ski and snowboard community, and the occurrence of adverse health conditions among wax users that may be associated with waxing activity. Additional research is also needed to assess incidental wax-related exposures occurring among people who are not personally applying wax but spend time in spaces where waxing occurs. With findings from the current study and subsequent research, education and outreach targeted at US winter sport participants across all levels is needed to encourage behavior modification to reduce wax-related environmental exposures.

5. Conclusion

In conclusion, snow sport participants often apply waxes to the base of skis and snowboards to improve performance. Available information about wax chemistry shows these wax products contain numerous complex chemicals with known adverse human health effects. Our research highlights that non-fluorinated and fluorinated wax use is common among members of the US ski and snowboard community at many levels of sport, including recreational participants, amateur athletes, industry professionals, and friends and family members of skiers and snowboarders who are not themselves participants. Furthermore, the duration, intensity, and/or frequency of wax-related exposure is high for many individuals. Participants tend to engage with skiing and snowboarding in a variety of roles for many years and may apply wax in multiple roles. Relatively few individuals utilize PPE to reduce exposure and only a moderate number employ institutional controls. Collectively, this implies long-term exposure to wax-related environmental health hazards. Importantly, our research expands prior knowledge of how wax-related exposures manifest outside occupational or professional ski settings. Our findings support the need to (Fang et al., 2020): further investigate wax-related exposures and associated health risks by measuring biomarkers of exposure and health outcomes among skiers and snowboarders who participate in these sports at all levels of involvement, and (Freberg et al., 2013) develop strategies to increase utilization of exposure interventions among US skiers and snowboarders.

Authors' contributions

All authors provided critical review and feedback of the manuscript. KAC led the study design, electronic survey development, and data management processes, oversaw all data analyses, and drafted the manuscript. BTD assisted with data management and conducted statistical analyses. BCH provided technical review of the study design, electronic survey, and data analyses, and contributed to manuscript preparation. MER and DGD provided technical review of the study design, electronic survey, and data analyses.

Ethics approval

Approval for this study was granted by the Institutional Review Board (IRB) at Middlebury College. Prior to enganging in all study activity, participants provided written, informed consent via IRB-approved consent protocols.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.114335.

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