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Analyzing golf course pesticide risk across the US and Europe—The importance of regulatory environment

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HIGHLIGHTS

- Pesticide risk did not vary as a function of climate in the USA.
- In the southern US, greens contribute most to pesticide risk.
- In all other regions of the study, fairways contribute most to pesticide risk.
- Pesticide risk in the UK, Norway, and Denmark is lower than in the USA.
- Regulatory environment appears to greatly influence golf course pesticide risk.

GRAPHICAL ABSTRACT



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ABSTRACT

This study quantifies golf course pesticide risk in five regions across the US (Florida, East Texas, Northwest, Midwest, and Northeast) and three countries in Europe (UK, Denmark, and Norway) with the objective of determining how pesticide risk on golf courses varied as a function of climate, regulatory environment, and facility-level economic factors. The hazard quotient model was used to estimate acute pesticide risk to mammals specifically. Data from 68 golf courses are included in the study, with a minimum of at least five golf courses in each region. Though the dataset is small, it is representative of the population at confidence level of 75 % with a 15 % margin of error. Pesticide risk appeared to be similar across US regions with varied climates, and significantly lower in the UK, and lowest in Norway and Denmark. In the Southern US (East Texas and Florida), greens contribute most to total pesticide risk while in

Abbreviations: ABSO-HQ, Absolute product hazard quotient; AN-HQ, Area normalized product hazard quotient; AAR, Average application rate; AT, Area treatment; A_{GCC}, Area of all golf course components; A_G, Area of greens; A_T, Area of tees; A_F, Area of fairways; A_R, Area of roughs; AN-HQ_G, Area normalized pesticide risk for greens; AN-HQ_T, Area normalized pesticide risk for tees; AN-HQ_F, Area normalized pesticide risk for fairways; AN-HQ_R, Area normalized pesticide risk for roughs; CWA, component-weighted-average; Daily-HQ, Daily product hazard quotient; GCC, Area of a golf course component; LD_{50}, Lethal dose at which 50 % of the experimental population dies; NASS, National Agricultural Statistics Service; PDSO, Petroleum derived spray oil; PGR, Plant growth regulator; P_G, percentage of turfgrass that is greens; P_T, percentage of turfgrass that is tees; P_F, percentage of turfgrass that is fairways; P_R, percentage of turfgrass that is roughs; Rfd_p, reference dose of a pesticide product; RIQ, Risk to Intensity Quotient; W_p, weight of pesticide product.

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nearly all other regions fairways make the greatest contribution to overall pesticide risk. The relationship between facility-level economic factors such as maintenance budget was limited in most regions of the study, except in the Northern US (Midwest, Northwest, and Northeast) where maintenance and pesticide budget correlated to pesticide risk and use intensity. However, there was a strong relationship between regulatory environment and pesticide risk across all regions. Pesticide risk was significantly lower in Norway, Denmark, and the UK, where twenty or fewer active ingredients were available to golf course superintendents, than it was in US where depending on the state between 200 and 250 pesticide active ingredients were registered for use on golf courses.

1. Introduction

Games similar to modern golf began to emerge around the European continent in the 14th and 15th centuries. The first of these games to require a cultivated field was the Dutch game kolf (Labbance and Witteveen, 2002). The cool and rainy European climate and native turfgrasses were conducive to cross-country ball and stick games, which were often played across grazed turfgrass on marginal agricultural land. In Scotland, where the game most similar to modern golf emerged in the early 16th century, the land deemed agriculturally marginal was commonly the thin strip of sandy soil along coastlines between the ocean and arable agricultural land further inland. By the late 18th century, golf in Scotland greatly increased in popularity and the first golfing societies were formed with rules of the game documented (Browning, 1955). The turfgrass species native to Scotland along with grazing animals that kept the grass short, moving sand dunes that provided natural hazards, and periodic wind-blown sand topdressing meant that golf courses required very little, if any, maintenance. One could argue that at this early stage of development golf reached peak sustainability; the courses required virtually no resource inputs.

Beginning in the late 19th century, golf's popularity increased exponentially, and the game spread out of Europe and around the world to different climates and geographies. Turfgrasses were shipped out from northern Europe to areas where no native turfgrasses existed. Not surprisingly, for these turfgrasses to grow successfully and survive foot traffic in climates for which they were not native, resource inputs such as water, fertilizer, pesticide, and fuel for mowing became both necessary and essential. As the game developed in the 20th century, golfers steadily demanded faster and smoother playing surfaces which were made possible by developments in mowing technology. This meant mowing turfgrass to shorter heights which increased the stress on the plant making it more susceptible to pests. In the 1920s golf greens, the most highly maintained area of a golf course, were typically mowed at approximately 20 mm, which was lowered to around 5 mm by the 1970s, and lowered further to approximately 3 mm today.

Rossi and Grant (2009) found that golf greens in New York state, USA, struggled to survive without the application of pesticides. Thus, at least in the cool humid climate of the northeastern US, pesticides have become an essential tool for the golf industry's maintenance toolkit. Conversely, many European countries have severely restricted pesticide use on golf courses, and several have banned pesticide use entirely (R&A, 2020). The golf industry in Europe shows no sign of contracting (KPMG, 2019), indicating that, at least in some climates, modern golf courses can be successfully maintained with minimal use of pesticides.

In the US, the wide variety of pesticides that are allowed on golf courses concerns environmental groups (Beyond Pesticides, 2021; Perfect Earth Project, 2022), as well as many people living near golf courses (Brenner, 2012; Garris, 2018; Hilson, 2017). Previous research has indicated that chronic inhalation and dermal risk of pesticides to golfers was low (Murphy and Haith, 2007; Putnam et al., 2008; Wong and Haith, 2013); however, golf course pesticide application programs do pose ecological risks. Several studies have concluded that offsite transport of pesticides from golf courses routinely affects surrounding aquatic ecosystem health (Haith and Rossi, 2003; King and Balogh, 2010; Metcalfe et al., 2007). In addition, high levels of arsenic have been detected in golf course soils and groundwater because of arsenic containing pesticides that have been applied to courses (Cai et al., 2002; Feng et al., 2005; Pichler et al., 2008).

Bekken et al. (2021) developed a framework for estimating ecological risks from pesticides applied to golf courses using pesticide risk indicator models and applied the models to 22 golf courses in New York and Wisconsin. This study uses that same framework but applies the analysis to 68 golf courses in eight different regions. Five of these regions are in the US (Midwest, Northwest, Northeast, East Texas, and Florida) and three are in Europe (Norway, Denmark, and UK). The goal of this study is to compare pesticide risk on golf courses across climates and geographies to determine how pesticide risk varies both as a function of climate and regulatory environment. Within the US, we hypothesize that pesticide risk will be higher in warmer climates and lower in cooler climates because of the longer growing season in the warmer climates. In Europe, we hypothesize that pesticide risk will be lower than in the US because of laws which limit the number of pesticides available to golf course superintendents.

Despite the best efforts of all authors of this study to obtain a statistically representative sample of golf courses from each region, many golf course superintendents who were asked to partake in this study either decided they did not want to voluntarily provide pesticide application information or did not have pesticide records in sufficient detail to participate in the study. Thus, the sample size in each region of the study is smaller than originally intended. To the authors knowledge, this is the first study to compare golf course pesticide risk across geographies. As such, this research is an important first attempt to understanding how pesticide risk on golf courses varies as a function of climate and regulatory environment.

2. Methods

2.1. Survey

Data used for this study were collected via the *University of Wisconsin-Madison Resource Efficiency Survey*, which was conducted by the authors (Table 1). The original sampling plan of this study included distributing the survey in three regions of the northern US, three regions of the southern US, and in the regions of Europe where English is commonly spoken (this study did not have the resources to translate the survey into other languages). The three Northern US regions were the Northeast, Midwest, and Northwest, while the three southern US regions were Florida, East Texas, and the Southwest. In Europe the survey was distributed in the UK, Norway, Sweden, and Denmark.

Golf course superintendents in each region were invited to take the survey via an initial email solicitation from an author of this study that lives and works in the region. Three follow up emails were sent after the initial solicitation, and if necessary to achieve the desired sample size, superintendents were contacted by phone or met in person and asked to take the survey. The exact method of survey follow-up varied in each region and was based upon what the author in each region thought would return the greatest number of survey responses.

The original goal of this study was to achieve a sample that was representative of the population of golf courses within each region at an 85 % confidence interval and 15 % margin of error. However, it was more difficult to obtain survey responses than we anticipated in all regions. As such, we adjusted the target confidence level and margin of error to 75 % and 15 %, respectively. The following equation was used to relate the

Table 1
Sample size (i.e., number of complete survey responses), success of survey efforts in each region, states and countries represented in each region, and the distributing organization of the *University of Wisconsin-Madison Resource Efficiency Survey* by region. A complete response was one in which the golf course superintendent supplied a pesticide application record that met all criteria for pesticide risk calculation (product applied, date, rate, and area of application).

Region	Sample size (number of complete responses)	Survey effort successful? (>5 responses)	State/country represented	Distributing organization
US-Midwest	24	Yes	Wisconsin (22), Minnesota (1), Illinois (1)	UW-Madison Turfgrass Program, WGSCA, MGCSA
US-Northeast	11	Yes	New York (11)	Cornell Turfgrass Program
US-East Texas	7	Yes	Texas (7)	Texas A&M Turfgrass Program
Norway	6	Yes	Norway (6)	NIBIO, Norwegian Greenkeepers Association
Denmark	5	Yes	Denmark (5)	Danish Golf Union
US-Florida	5	Yes	Florida (5)	University of Florida Turfgrass Program
UK	5	Yes	England (4), Scotland (1)	GEO Foundation
US-Northwest	5	Yes	Oregon (2), Montana (2), Washington (1)	Oregon State Turfgrass Program, OGCSA, Peaks and Prairies GCSAA
Sweden	3	No	Sweden (3)	Swedish Golf Union
US-Southwest	1	No	Nevada (1)	Cactus and Pine GCSA

desired confidence interval and margin and error to a required sample size (Smith, 2022).

$$Required\ sample\ size = \frac{(Z)^2 * SD\ (1 - SD)}{(ME)^2} \quad (1)$$

Where the required sample size is the number of golf courses that needed to respond to our survey in each region, Z is the *Z*-score for a given confidence level, SD is the standard deviation of survey responses, and ME is the margin of error. To achieve 75 % confidence level and 15 % margin of error with a standard deviation of 0.5, at least five golf courses needed to respond to the survey in each region.

Thus, survey efforts were considered successful if at least five golf courses submitted survey responses from each region. Survey efforts were successful in eight of the ten regions surveyed (Table 1). In regions where survey efforts were not successful (e.g., US-Southwest and Sweden), the data obtained from these regions were not used in this study.

All survey respondents were promised confidentiality and all data reported from the study would remain anonymous. The pesticide section of the survey asked golf course superintendents to submit pesticide application records from their golf course over a three-year period within a five-year window from 2016 to 2021. To be included in the study, pesticide applications records needed to include the name of the pesticide product applied, as well as date, rate, and area of application. Fifty-four golf courses supplied records over a 3-year period, five supplied records over a 2-year period, and nine supplied records over a 1-year period.

2.2. Growing season length determination

Growing season length was determined using the Growth Potential model (Gelernter and Stowell, 2005) in a manner consistent with the methods of Bekken and Soldat (2022).

2.3. Pesticide risk

This study applies the golf course pesticide risk framework of Bekken et al. (2021) using a hazard quotient (HQ) model to quantify pesticide risk. The hazard quotient (HQ) is the ratio of pesticide *exposure* to *toxicity* (Eq. (2)). See Bekken et al. (2021) for a detailed discussion of the advantages and disadvantages of the HQ model.

$$HQ = \frac{Exposure}{Toxicity} \quad (2)$$

Consistent with Bekken et al. (2021), the exposure term in the HQ model was quantified as the application rate of the pesticide. The toxicity term in the model was quantified as the acute mammalian toxicity (i.e., rat acute oral LD_{50}) of the pesticide product being applied. Acute mammalian toxicity was chosen as the toxicity value for the HQ model because it has implications for human health, and because it is one of the most widely available toxicological values for golf course pesticides.

The annual absolute product hazard was used to quantify total pesticide risk and henceforth is abbreviated as ABSO-HQ (Eq. (3)). The annual area normalized product hazard quotient was used to quantify area normalized pesticide risk and henceforth is abbreviated as AN-HQ (Eq. (4)). Lastly, the daily area normalized product hazard quotient was abbreviated as Daily-HQ (Eq. (5)). The Daily-HQ was determined by dividing the AN-HQ by the growing season length (days) to determine a daily hazard quotient (HQ) score.

$$ABSO\text{-}HQ = \sum_{1}^{n} \frac{W_p}{Rfd_p} \quad (3)$$

$$AN\text{-}HQ = \sum_{1}^{n} \frac{(W_p/GCC)}{Rfd_p} \quad (4)$$

$$Daily\text{-}HQ = \frac{\sum_{1}^{n} \frac{(W_p/GCC)}{Rfd_p}}{Season\ length} \quad (5)$$

Where n equals the number of pesticide applications to a given golf course component in an annual pesticide program; W_p equals the weight of product applied (mg), GCC is the area of the golf course component (ha), Rfd_p equals the reference dose associated with the pesticide product (mg pesticide product/kg rat), and where season length is measured in days.

2.4. Golf course wide pesticide risk metrics

Golf courses are made up of four components (greens, tees, fairways, and roughs) all of which are managed independently. When the areas of each of these components are summed, they equal the total turfgrass area of the golf course (Eq. (6)).

$$A_{GCC} = A_G + A_T + A_F + A_R \quad (6)$$

Where A_{GCC} equals the combined turfgrass area of all golf course components, A_G equals the area of greens, A_T equals the area of tees, A_F equals the area of fairways, and A_R equals the area of roughs. All areas were measured in ha. Dividing the area of each component by the total area gives the percent area that each component occupies on the course (Eqs. (7)–(10)).

$$P_G = \frac{A_G}{A_{GCC}} \quad (7)$$

$$P_T = \frac{A_T}{A_{GCC}} \quad (8)$$

$$P_F = \frac{A_F}{A_{GCC}} \quad (9)$$

$$P_R = \frac{A_R}{A_{GCC}} \quad (10)$$

Where P_G, P_T, P_F, and P_R equals the percentage of the total golf course area that is covered by greens, tees, fairways, and roughs, respectively.

Pesticide risk was calculated for each component of the course and then multiplied by the percent area of that component to determine a component-weighted-average hazard quotient (CWA-HQ) (Eq. (11)). The CWA-HQ is a golf course wide metric, which can be used to compare area normalized pesticide risk between golf courses (golf course A vs. golf course B).

$$CWA\text{-}HQ = AN\text{-}HQ_G * P_G + AN\text{-}HQ_T * P_T + AN\text{-}HQ_F * P_F + AN\text{-}HQ_R * P_R \quad (11)$$

Where $AN\text{-}HQ_G$, $AN\text{-}HQ_T$, $AN\text{-}HQ_F$, and $AN\text{-}HQ_R$ equals the area normalized pesticide risk for greens, tees, fairways, and roughs, respectively.

2.5. Petroleum derived spray oils

Bekken et al. (2021) found that because of a high application rate, petroleum derived spray oils have a high impact on pesticide risk estimations. In this study, six golf courses in the Northeast used petroleum derived spray oils (PDSO). However, there were not any golf courses in any of the other regions of the study that used PDSO's. Because the environmental risks of golf course PDSO use have not been studied to date, PDSO's applied on golf courses in the Northeast were not included in the risk estimations of this study. As such, the methods of this study align with Scenario 1 of Bekken et al. (2021).

2.6. Pesticide use intensity

Also consistent with Bekken et al. (2021), the area treatment (AT) formula was used to quantify pesticide use intensity (Eq. (12)). Area treatment is analogous to the Treatment Frequency Index (TFI).

$$AT = \Sigma_1^n \frac{(W_p/AAR)}{GCC} \quad (12)$$

Where AT equals area treatment, n equals the number pesticide applications to a given golf course component annually, W_p equals the weight of product applied (mg), AAR is the average application rate of the pesticide product, and GCC is the area of the golf course component (ha). ATs were calculated for each golf course component. A component-weighted-average (CWA) was also applied to obtain a golf course wide AT value (CWA-AT).

An AT value of one for any golf course component (e.g., fairways) can be achieved by applying a pesticide at the average rate to all fairways. An AT value of 0.5 for fairways can be achieved either by applying the pesticide at half the average rate, or by applying at the average rate to half of the fairway area. An AT value of two for the fairway can be achieved by applying a pesticide at double the average rate to all fairways.

2.7. Risk to intensity quotient

The risk to intensity quotient (RIQ) was defined as the ratio of pesticide risk to AT. In this study, RIQ was the ratio CWA-HQ to CWA-AT (Eq. (13)).

$$RIQ = \frac{CWA\text{-}HQ}{CWA\text{-}AT} \quad (13)$$

2.8. Mean pesticide risk and use intensity

For golf courses that provided multiple years of pesticide application data, calculated pesticide risk and use intensity were averaged across years to obtain values as representative as possible to mean pesticide risk and use intensity at a golf course.

2.9. Exploring variance in pesticide risk and use intensity

For golf courses that provided three years of data, the coefficient of variation of pesticide risk was calculated across years to determine the variance in pesticide risk on each golf course from one year to the next (Table S1). Variance in pesticide risk on golf courses between years was high, highlighting the importance of collecting multiple years of data if possible.

The relationship between pesticide risk (i.e., hazard quotient) and pesticide use intensity (i.e., area treatment) and six continuous economic variables (i.e., average yearly rounds of golf played, peak season green fee, total number of maintenance employees, average yearly maintenance budget per ha, average yearly pesticide budget per ha, and average yearly revenue per ha) was estimated using Pearson correlations. *P*-values are reported for each correlation performed. See Table S2 for hypotheses regarding how each economic variable would correlate to pesticide risk.

To obtain a sufficient sample size to run correlations between the economic variables and golf course pesticide risk, golf courses in the eight regions were placed in one of three groups: northern US (Northeast, Midwest, and Northwest), southern US (Florida and East Texas), and Europe (UK, Norway, and Denmark).

To analyze the effect of regulatory environment on pesticide risk, golf courses were grouped based on the number of pesticide products and active ingredients permitted. For pesticide products, golf courses were grouped by those that were allowed to use >20 pesticide products and those that were allowed to use <20 pesticide products. For active ingredients, golf courses were grouped by those that were allowed to use >100 active ingredients and those that were allowed to use <100 active ingredients. Means separation was determined by using the protected Fisher's least significant difference test.

2.10. Data analysis software

All descriptive statistics, linear regressions, and data visualizations were completed in JMP Pro (Version 15.0, SAS Institute Inc., Cary, NC, 1989-2022).

3. Results

3.1. Golf course wide pesticide risk by region

Pesticide risk was highly variable in the five regions in the US, but comparatively much lower in the three European regions of the study (Fig. 1). The median CWA-HQ in each region ordered from highest to lowest was 13,686 in the Northwest, 9818 in Florida, 7893 in East Texas, 7404 in the Midwest, and 4731 in the Northeast, 2418 in the UK, 248 in Norway and 64 in Denmark. The range in CWA-HQ scores was highest in Florida (40,806), followed by the Northeast (31,736), Midwest (25,683), Northwest (17,658), East Texas (9299), UK (5703), Denmark (2246), and Norway (547). The golf course with the highest CWA-HQ value was in Florida (42,507), and the golf course with the lowest value was in the Norway (15). All golf courses in the study applied at least one pesticide in each year of the study. No golf course had an HQ score of 0.

The median Daily-HQ was highest in the Northwest (62), followed by the Midwest (49), Florida (34), East Texas (28), Northeast (23), UK (12), Denmark (3) and Norway (2) (Fig. 2).

3.2. Golf course wide pesticide risk by region and pesticide type

Analyzing CWA-HQ scores by pesticide type, fungicides made up the greatest proportion of risk by pesticide type in four out of eight regions: Florida, Midwest, Northeast, and Norway (Fig. 3). Herbicides contributed the greatest proportion of pesticide risk by pesticide type in East Texas,

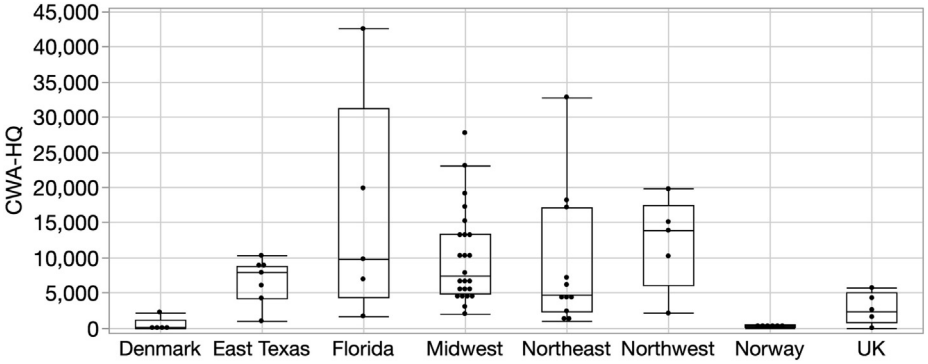


Fig. 1. Component-weighted-average of the area normalized hazard quotient (CWA-HQ) in each region of the study. Black dots indicate pesticide risk for individual golf courses.

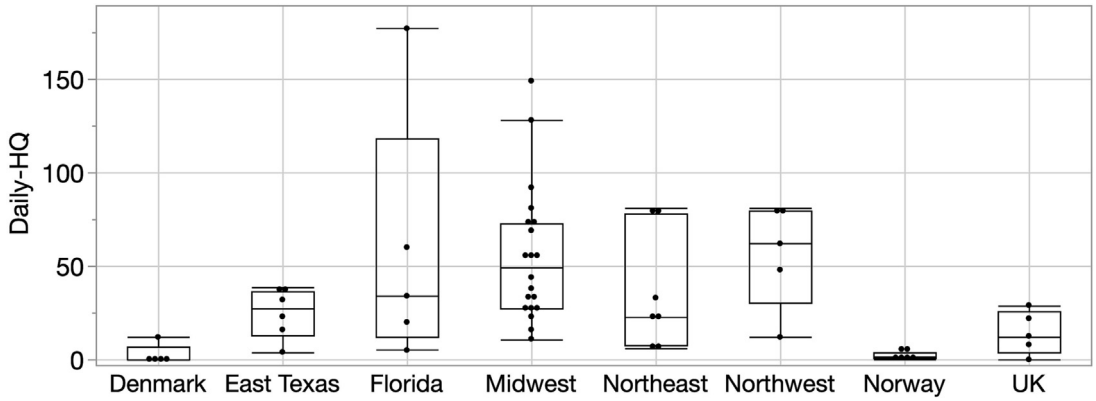


Fig. 2. Daily component-weighted-average of the area normalized hazard quotient (Daily-HQ) in each region of the study. Black dots indicate pesticide risk for individual golf courses.

the Northwest, and in Denmark. In the UK, insecticides contributed most to pesticide risk by pesticide type.

3.3. Golf course wide pesticide risk by region and component

The median AN-HQ score by golf course component was highest on greens in all regions of the study (Fig. 4). East Texas and Florida had the highest median greens AN-HQ scores of 141,420 and 153,322, respectively. These pesticide risk values on greens were almost three times higher than the next highest regional value of 56,502 on greens in the Midwest. The Northeast and Northwest had similar greens AN-HQ scores as the Midwest. The median greens AN-HQ score was lower in the European regions and was 8078 in the UK, 1525 in Norway, and 446 in Denmark.

Greens contributed the most to Abso-HQ in East Texas, Florida, Northeast, Denmark, and Norway, while fairways contributed most to Abso-HQ in the Midwest, Northwest, and UK (Fig. S1).

3.4. Golf course wide pesticide use intensity by region

Golf course-wide pesticide use intensity as quantified by median CWA-AT was similar in the Midwest (7.8), East Texas (7.0), and Florida (6.8) (Fig. S2). Median CWA-AT was slightly lower in the Northeast (3.6) and

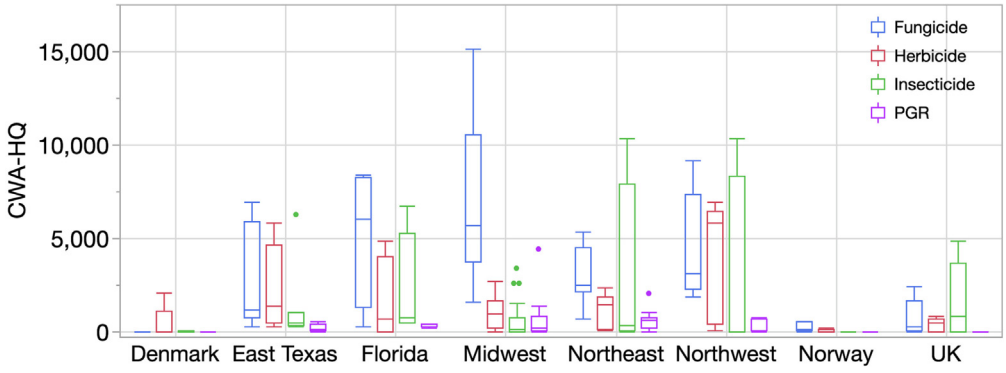


Fig. 3. Component-weighted-average of the area normalized hazard quotient (CWA-HQ) of fungicides, herbicides, and insecticides, and plant growth regulators (PGRs) in each region of the study. One golf course from Florida not shown on graph that had an insecticide CWA-HQ of 35,602.

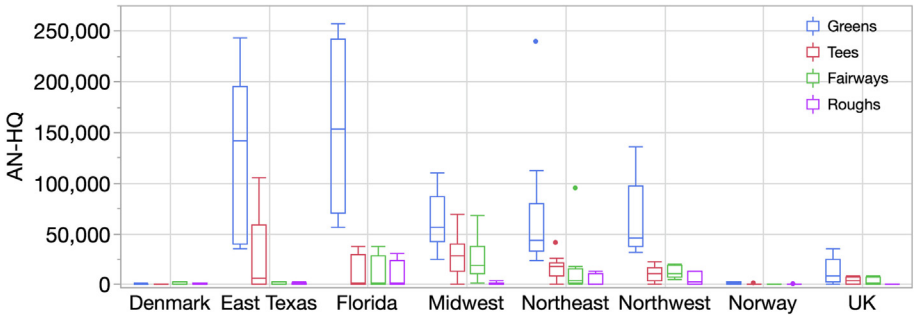


Fig. 4. Area normalized hazard quotient (AN-HQ) on greens, tees, fairways, and roughs in each region of the study.

Northwest (3.2), and lowest in the UK (1.5), Norway (0.4), and Denmark (0.4) (Fig. S2).

3.5. Pesticide use intensity by pesticide type and region

In Denmark, East Texas, the Northwest, and the UK, applications of herbicides contributed the most to pesticide use intensity (Fig. S3). In the remaining regions, Florida, Midwest, the Northeast, and Norway, fungicides contributed the most to pesticide use intensity. Insecticides had the lowest use intensity in all regions, except the UK, where the use intensity of plant growth regulators (PGRs) was lower than insecticides.

3.6. Pesticide use intensity by golf course component and region

Greens had the highest median AT value in all regions of the study (Fig. S4). The median greens AT value was highest in Florida (91.8). However, values from Florida had a high level of variation with greens AT ranging from 104 to 5.7. East Texas also had a high level of variation in greens AT with a maximum of 83.6, a minimum of 15.0, and a median of 23.2. Greens AT in the Midwest, Northeast, and Northwest showed a lower range of variation. In these three regions, AT on greens ranged from 15 to 60. The median number of ATs on greens was much lower in all three regions in Europe, where the UK, Norway, and Denmark had median AT values of 6.8, 3.3, and 2.3, respectively.

3.7. The risk to intensity quotient

The Risk to Intensity Quotient (RIQ) correlation line defines average risk for every AT value (Fig. S5). All golf courses in Norway and Denmark were below the correlation line, indicating that, on average, pesticide products used in these two countries were lower risk than the average as defined by all golf courses in the study. Despite having relatively low risk overall, two golf courses in the UK were above the RIQ correlation line, indicating that these golf courses used pesticides with higher-than-average risk. All golf courses in the Northwest used pesticides with higher-than-average risk. Of the 24 golf courses in the study from the Midwest, ten were above the correlation line and the remaining 14 were below.

The Northwest and UK had the highest median RIQ values of all regions. Median RIQ values were lower and similar in Florida, the Midwest, the Northeast, and East Texas. Norway and Denmark had the lowest and similar RIQ values (Fig. S6).

3.8. Economic predictors of pesticide risk

With one exception, none of the six economic variables tested correlated significantly with pesticide risk as quantified by HQ in all regions, in Europe, or in the southern US. In Europe, pesticide budget significantly correlated with pesticide risk. In the northern US, maintenance budget per ha and pesticide budget per ha correlated with pesticide risk significantly (Table 2A).

Pesticide use intensity as quantified by AT correlated significantly with the the number of maintenance employees and pesticide budget per ha in all regions (Table 2B). Maintenance budget per ha, pesticide budget per ha, and revenue per ha correlated significantly with pesticide use intensity in the northern US, but not in the southern US or Europe.

3.9. Regulatory predictors of pesticide risk

The number of pesticide products and active ingredients available to golf course superintendents in each region is listed in Table 3. Despite the best efforts of all the authors of this study, we were not able to obtain the number of registered products and active ingredients for golf courses in all regions of the study. However, pesticide availability appears to have a strong effect on pesticide risk. Golf courses in regulatory environments where <100 pesticide products were available had a median CWA-HQ of 248, which was significantly lower than mean pesticide risk on golf courses located in regulatory environments which allowed >100 pesticide products, which had a mean CWA-HQ of 7031 (Fig. 5A). Golf courses in regulatory environments in which <20 active ingredients were available had a median CWA-HQ of 180, which was also significantly lower than mean pesticide risk on golf courses located in regulatory environments which allowed >20 active ingredients had a median CWA-HQ of 5944 (Fig. 5B).

4. Discussion

4.1. Limitations of a small sample size

The sample size in this study is small. Even though the sample size is representative of the population of golf courses in each region, it is representative at a low confidence interval with a high margin of error (Smith, 2022). As such, definitive statements about pesticide risk across regions of the study cannot be made. However, several patterns emerged from the dataset that are clear, while other trends require more data to confirm. This discussion clarifies our level of confidence in accepting some conclusions while arguing for additional data to clarify potential trends.

4.2. Trends across regions

Surprisingly, pesticide risk (AN-HQ) on golf courses in the southern US, with longer growing seasons, did not have higher pesticide risk than golf courses with shorter growing seasons in the northern US, refuting our original hypothesis. Golf courses in Denmark and Norway had lower pesticide risk than golf courses in all other regions, even when normalizing for season length (Daily-HQ). The average Daily-HQ across all US regions was 46, whereas in Europe, the UK had 14, Denmark had 3, and Norway had 2. Thus, Daily-HQ was at least 15 times higher in the US than in either Norway or Denmark. Daily-HQ in the UK was at least 5 times higher than in Norway or Denmark, but approximately three times lower than in the US. Mean use intensity as quantified by AT was also lower in Norway and Denmark than all other regions. In addition, the Risk to Intensity Quotient (RIQ) values of pesticide programs on golf courses in Denmark and Norway were all below average, indicating that the products available in these two countries are low risk. The number of pesticide active ingredients available to golf course superintendents in Norway (12) and Denmark (13) was lower

Table 2
Pearson correlation coefficients and *p*-values between pesticide risk (A) and pesticide use intensity (B) and six economic variables: rounds of golf played, green fee, total maintenance employees, maintenance budget per ha, pesticide budget per ha, and revenue per ha.

A. Pesticide Risk	All regions (n = 68)	Europe (n = 16)	Northern US (n = 40)	Southern US (n = 12)
	R value (p-value)			
Average yearly rounds	−0.19 (0.17)	−0.10 (0.74)	0.30 (0.09)	−0.54 (0.06)
Peak season green fee	0.06 (0.61)	0.31 (0.73)	0.20 (0.24)	0.10 (0.76)
Total maintenance employees	0.22 (0.09)	0.28 (0.30)	0.10 (0.55)	0.01 (0.97)
Maintenance budget per ha	0.16 (0.24)	−0.20 (0.46)	0.41 (0.02)*	0.06 (0.85)
Pesticide budget per ha	0.20 (0.13)	0.61 (0.02)*	0.39 (0.03)*	−0.13 (0.69)
Revenue per ha	−0.16 (0.23)	0.08 (0.77)	0.30 (0.10)	−0.12 (0.72)
B. Pesticide use intensity	All regions (n = 68)	Europe (n = 16)	Northern US (n = 40)	Southern US (n = 12)
	R value (p-value)			
Average yearly rounds	−0.11 (0.41)	−0.09 (0.74)	0.32 (0.08)	−0.41 (0.19)
Peak season green fee	0.05 (0.67)	0.02 (0.94)	0.24 (0.15)	0.20 (0.52)
Total maintenance employees	0.30 (0.02)*	0.11 (0.67)	0.22 (0.21)	0.24 (0.45)
Maintenance budget per ha	0.19 (0.14)	0.27 (0.32)	0.47 (0.006)*	0.16 (0.61)
Pesticide budget per ha	0.32 (0.01)*	0.12 (0.67)	0.40 (0.03)*	0.20 (0.56)
Revenue per ha	−0.11 (0.42)	0.08 (0.78)	0.40 (0.03)*	0.15 (0.63)

* Correlation coefficient significant at $\alpha < 0.05$.

Table 3
The region, regulatory environment in which the majority of the courses in the region were located, and the number of products and active ingredients registered for use on golf courses in each regulatory environment in 2022. *the authors were unable to determine the number of registered pesticide products or active ingredients in these regions.

Region	Regulatory environment	Registered products for golf course turf in 2022	Registered active ingredients for golf course turf in 2022
Midwest	US-Wisconsin	726	*
Northeast	US-New York	1967	246
East Texas	US-Texas	*	*
Norway	Norway	18	12
Denmark	EU-Denmark	19	13
Florida	US-Florida	1419	241
UK	UK	74	17
Northwest	US-Oregon	1147	226

than in the UK (17), and far lower than the number allowed in the US where depending on the pesticide rules in the specific state, between 200 and 250 active ingredients are allowed for use on golf courses. Regulatory environment appears to be the single most important factor driving pesticide risk in our dataset.

4.3. Pesticide regulation in the US and Europe

Pesticide regulation on golf courses across the regions of this study varied greatly. In the European Union (EU) pesticides are assessed primarily based on hazard and not on risk (Möhring et al., 2022). The current law governing pesticide use in the EU is the 2009 EU-Directive titled the Sustainable Use of Pesticides (SUD), which gives individual countries flexibility to implement pesticide reduction targets and strategies. The SUD greatly restricts pesticide use on golf courses in the EU. Currently only 12 active ingredients are registered for use on golf courses in Norway, and 13 are registered for use on golf courses in Denmark (Table 2). However, it appears likely that pesticide legislation will soon become even more strict for golf courses in the EU. As part of the European Green New Deal and the associated Farm-to-Fork strategy, evaluations were carried out across the EU that highlighted serious deficiencies in the implementation, application, and enforcement of SUD. As such, the EU has produced a draft Regulation, titled the Sustainable Use of Pesticides (SUP), which targets a 50 % reduction in overall pesticide use by 2030. As the proposed law is currently interpreted, SUP would ban all pesticide use, both chemical and biological, on areas outside of agriculture, including on golf courses (and also in public parks, gardens, playgrounds, and protected areas). EU-Regulations overrule national laws, and thus they do

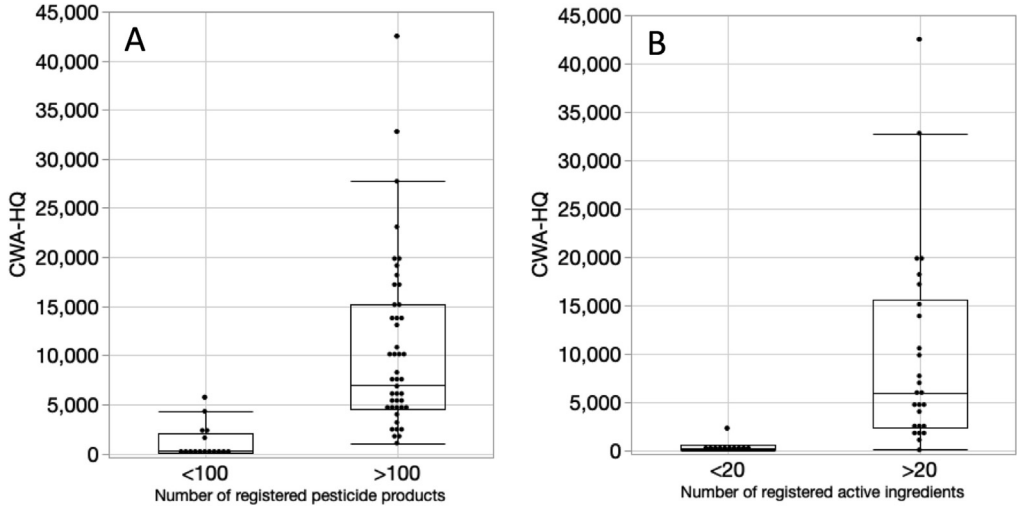


Fig. 5. Component-weighted-average of the area normalized hazard quotient (CWA-HQ) and the number of A) registered pesticide products, and B) registered active ingredients in the regulatory environment where each golf course resides.

not provide member states flexibility. It is unclear if the draft SUP will become law, however it is clear that the EU's current strategy for regulating pesticide use outside of agriculture, and on golf courses, is to severely restrict pesticide use at present with the goal of eliminating pesticide use entirely in the future.

The strategy for regulating pesticides in the US contrasts sharply with the EU. The US Environmental Protection Agency (EPA) is responsible for determining if new pesticides can enter the market and if existing pesticides can stay on the market (Environmental Protection Agency, 2022). The EPA does not use a hazard based system as is used in Europe, but uses a risk based system to determine the chance of a pesticide having a harmful effect on human health or ecological systems. The risk assessment system that the EPA uses involves hazard identification, dose response assessment, exposure assessment, and risk characterization. The EPA registers pesticides for use only if they "will not pose any unreasonable risks." The risk based system used by the EPA has led to a much higher number of pesticides being available for golf courses in the US. The number of registered active ingredients for golf courses in the three US states where data could be obtained ranged from 226 to 246. Unlike in the EU, where pesticide legislation is stricter for golf courses than for agricultural producers, to the authors knowledge the EPA uses the same risk based system to authorize pesticides on golf courses as it does in agriculture.

The Health and Safety Executive (HSE) in the UK assesses pesticide risk and authorizes pesticide products. During Brexit, EU pesticide regulations were transferred with amendments into UK law. Whether the UK retains the stricter hazard based system of pesticide regulation or transitions to a more risk based system like the US is currently being debated (Parliamentary Office of Science and Technology, 2021). As of this writing, only 17 active ingredients are allowed in the UK, which is only slightly higher than the number of pesticides allowed on golf courses in Norway and Denmark. However, the number of pesticide products allowed in the UK (74) is far higher than the number allowed in Norway (18) and Denmark (19). Because the UK rules for pesticide registration are still largely inherited from previous EU law, pesticide regulation in the UK is stricter for golf courses than in agriculture.

4.4. Region specific summaries

4.4.1. Denmark

There are eight registered fungicide products (five of which are biological) that are allowed for use in Denmark. These fungicides are used primarily to control grey snow mold (*Typhula incarnata*) and dollar spot (*Clarireedia* spp.) on greens. However, golf courses in Denmark had a median of just 2.3 AT on greens, and fungicide use overall only accounted for 3 % of absolute pesticide risk (Abso-HQ) on Danish golf courses. Meanwhile, seven herbicides were available to control broadleaf weeds. Herbicides accounted for 91 % of Abso-HQ on Danish golf courses, with over two thirds of that risk coming from fairway herbicide applications. Only two insecticides were registered for golf courses to control leatherjackets (*Tipula* spp.) and June beetles (*Phyllophaga* spp.). Insecticides accounted for 6 % of the Abso-HQ on Danish courses. Overall, pesticide risk on Danish golf courses was low and resulted from herbicide applications to fairways.

In 2005, an agreement to phase out the use of pesticides on Danish golf courses was signed by the Danish Golf Union (DGU), the Danish Ministry of Environment (MoE), and the Municipalities Organization in Denmark. Subsequently, the MoE built a mandatory online tool for golf courses which tracks pesticide risk using a model similar to HQ, called Pesticide Load (PL). PL is a risk based metric that is based on human health, ecotoxicology, and environmental fate (Kudsk et al., 2018). The MoE sets a maximum allowable PL value for fungicides, herbicides, insecticides, and PGRs that golf courses in Denmark cannot exceed. If a golf course exceeds their allowable pesticide risk for a given pesticide type, the course could be subject to a fine by the MoE. The MoE periodically reduces the maximum allowable pesticide risk on golf courses.

According to the MoE, pesticide risk on golf courses has been reduced 97 % since the agreement was signed in 2005. Ninety-eight percent of golf courses are compliant in tracking their pesticide risk with values below the maximum allowable. To remain under this threshold, golf course superintendents must tolerate higher levels of disease, weeds, and insects. Assessments completed by the DGU indicate that the majority of golfers surveyed were satisfied with the quality of golf courses and were not concerned by the higher pest thresholds; however, golfers with a ten handicap and below were less satisfied with course conditions, but only 7 % of players are in this group (Petersen, 2022).

4.4.2. Norway

The pests that cause the greatest economic damage on golf courses in Norway include Microdochium patch (*Microdochium nivale*) and grey snow mold, which are most damaging to greens and fairways in the winter. To control for these diseases, Norwegian golf course superintendents apply one, two, or three applications of fungicides in the late fall. The four fungicides registered for use on golf courses in Norway are azoxystrobin, fludioxonil, propiconazole, and trifloxystrobin. Fungicide use accounted for 93 % of the total pesticide risk (Abso-HQ) on Norwegian golf courses in the study. Forty-one percent of Abso-HQ in the Norwegian sample was from fungicide use on fairways, 26 % was from greens, 22 % from roughs, and 4 % from tees.

4.4.3. UK

There are currently 17 pesticide active ingredients that are allowed on golf courses in the UK. Fungicides account for 46 % of the overall risk, insecticides 42 %, and herbicides 12 %. Fungicides are primarily applied to greens on UK golf courses in the study. Thirty nine percent of total pesticide risk (Abso-HQ) came from fungicide applications to greens. These fungicides primarily target anthracnose (*Colletotrichum cereale*) and Microdochium patch.

Thirty eight percent of the total or absolute pesticide risk on UK golf courses in this study came from insecticide applications to fairways, which makes fairways in the UK the highest risk golf course component in the region. Leatherjackets and chafer grubs (*Amphimallon majale*) are primary insect pests on UK golf courses. Leatherjackets are the larvae of craneflies and live in soils with higher clay content. Chafer grubs are the larvae of chafer beetles and live in soils with high sand content. If either species of larvae are present in the soil at high enough numbers, mammals and birds will dig through the soil to find and eat them. In the process these animals will often destroy large areas of turf. Currently, acelepryn is the only insecticide registered for use on golf courses in the UK.

4.4.4. Florida

The greens on all golf courses from Florida in this study were planted with bermudagrass, and despite its reputation as a relatively disease tolerant turfgrass, median AN-HQ on greens in Florida was nearly three times higher than in the Northeast, Midwest, and Northwest. Greens on these Florida golf courses accounted for 4 % of the total turfgrass area but were responsible for 40 % of absolute risk (Abso-HQ). Abso-HQ attributable to fungicides was six times higher than risk attributable to insecticides on greens in Florida, and herbicides were not used on greens on any of the Florida golf courses studied. Golf courses in Florida averaged over 60 fungicide AT on greens each year. Fungicide applications in Florida commonly target anthracnose, leaf and sheath blight (*Rhizoctonia* spp.), dollar spot, leaf spot (*Bipolaris sorokinia),* fairy rings (multiple Basidiomycete spp.), and occasionally pythium (*Pythium aphanidermatum*).

Despite high pesticide risk on greens in Florida, median pesticide risk on fairways was lower than any of the regions from the courses studied in the northern US. Superintendents in Florida commonly choose to fertilize fairways to recover from disease instead of applying pesticides frequently. When managers apply pesticides to fairways, they commonly apply fungicides and target leaf spot and dollar spot.

4.4.5. East Texas

Median AN-HQ on greens studied in East Texas was three times higher than it was in the Midwest, Northeast, and Northwest and roughly equivalent to that in Florida. Fungicides in East Texas are applied preventatively and primarily to greens to control pythium diseases, take-all root rot (*Gaeumannomyces graminis*), and leaf spot.

In our study, golf course-wide median pesticide risk (CWA-HQ) from herbicides was approximately equivalent to risk from fungicides on golf courses in East Texas. Common weeds on the golf courses studied in the region included annual bluegrass (*Poa annua*), crabgrass (*Digitaria* spp.), goosegrass (*Eleusine indica*), and sedges (Cyperaceae family).

4.4.6. Midwest

Dollar spot is the most common disease on golf course turfgrass in the Midwest (Smiley et al., 2005; Salgado-Salazar et al., 2018) and is the primary driver of pesticide risk in the region because it is active for nearly 6 months of the year. Grey snow mold and anthracnose are also common in the Midwest. Median Abso-HQ and AN-HQ on fairways in the Midwest samples of the study were higher than in any other sampled region of the study, likely because of fairway fungicide applications targeting dollar spot. Abso-HQ and AN-HQ on greens was similar to courses studied in the Midwest to the Northeast and Northwest.

4.4.7. Northeast

Fungicides accounted for the greatest pesticide risk by pesticide type in sampled courses in the Northeast. Similar to the Midwest, applications of fungicides on greens and fairways are frequently required to control dollar spot in the Northeast. Median absolute pesticide risk (Abso-HQ) was highest on greens in the Northeast, which was unexpected given that fungicides are applied to fairways to control dollar spot. This finding may be an artifact of the dataset. The eleven golf courses in the dataset from the Northeast are part of the New York State Park system. These courses are public with lower budgets than average for courses sampled in other regions. The average maintenance budget of a golf course in this study was 19,150 USD per ha, while golf courses in the Northeast region had an average maintenance budget of 8740 USD. Bekken et al. (2021) found that maintenance budget was the best predictor of pesticide risk and use intensity with risk increasing with maintenance budget. Thus, because the Northeast sample is limited to state run public courses, it may not be representative of fairway fungicide use in the region.

While median Abso-HQ from insecticides was the lowest of all pesticide types in the Northeast, for two of the eleven golf courses in the region, insecticides contributed twice as much to their overall pesticide risk as any other pesticide type. Annual bluegrass weevil (*Listronotus maculicollis*) has recently become a significant pest throughout the region, with their asynchronous life cycle and multiple generations per year requiring frequent insecticide applications to large areas (e.g., fairways and roughs) to control the population (McGraw and Koppenhöfer, 2017). Additionally, annual bluegrass weevils' propensity to develop resistance to pyrethroid chemistries can lead to ineffective applications before golf personnel recognize that insecticide resistance may be an issue. Annual bluegrass weevil can be a facility-specific pest, and it is responsible for the high use of insecticides by two of the Northeast golf courses in the study.

4.4.8. Northwest

The original intention for this region was to separate data collected on courses from Montana and Oregon. However, given a low survey response rate from both regions, we decided to group survey responses from the Northwest and Pacific Northwest together. Thus, the five golf courses in the Northwest region spanned a large geographic area and included golf courses east and west of the Cascade Mountain range. Three golf courses in the study were in eastern Oregon (2) and Washington (1), and two golf courses were in Montana. East of the Cascades, the primary pests included grey snow mold, billbugs (*Sphenophorus* spp.), and broadleaf weeds. West of the Cascades, the primary pests included microdochium patch, anthracnose, leatherjackets, and again broadleaf weeds.

Contrary to expectations that fungicides would account for the majority of CWA-HQ, herbicides contributed to CWA-HQ more than any other pesticide type sampled in the region. Insecticide use was either zero or high (CWA-HQ > 5000). It is unclear whether this pattern would hold with a larger dataset, but CWA-HQ and Daily-HQ in the Northwest were the highest of all regions in the US.

4.5. Hesitancy of US-based superintendents to supply pesticide records

This study was primarily limited by the hesitancy of US-based superintendents to share pesticide records. Had all golf course superintendents who took the UW-Madison Resource Efficiency Survey agreed to share pesticide records, the sample size in this study would have more than doubled. Eighty-three percent of golf course superintendents in Norway, Denmark, and the UK supplied pesticide records, however only 47 % of US-based golf course superintendents shared pesticide records. It is unclear as to why US superintendents hesitate to share pesticide records which are reported in an anonymous manner but may be related to the concern that supplying records would damage the golf course's reputation in its community, if published. Perhaps of greater concern to golf course superintendents may be that higher levels of public awareness of golf course pesticide use could lead to regulation that could limit the wide variety of pesticides currently available for use on golf courses in the US. Whatever the reason, the lack of publicly available pesticide records on US golf courses hampers our ability to determine the risk associated with golf course management and to create more sustainable strategies for the future.

4.6. Contextualizing golf course pesticide risk

Bekken et al. (2021) found that pesticide risk on golf courses sampled in Wisconsin and New York was within the range of agricultural crops grown in both states. With data from the National Agricultural Statistics Service (NASS) the authors found that mean pesticide risk on golf courses, as estimated by the HQ model, was eight times higher in golf than in corn production. However, golf course pesticide risk was approximately equivalent to grape production, three times lower than apple production and twelve times lower than potato production.

Pesticides applied to golf courses do not appear to present acute toxicity risks to golfers (Murphy and Haith, 2007; Putnam et al., 2008; Wong and Haith, 2013). Less is known about the chronic risks of pesticides to golfers. Only one study could be located that analyzed the health effects of pesticide exposure to golf course superintendents (Kross et al., 1996). This study analyzed the death certificates of 686 deceased members of the Golf Course Superintendents Association of America (GCSAA) from 1970 to 1992. The study found elevated mortality from three cancers (non-Hodgkin's lymphoma, brain, and prostate) and diseases of the nervous system, which are common in other occupations that expose workers to pesticides. Whether this pattern will hold true for golf course superintendents living today is unknown.

The ecological effects of pesticide risk on golf courses are clearer. Pesticides applied to golf courses negatively affect beneficial soil biota, but the effect of pesticides applications on various functional groups of soil biota depend on the nature of a golf course's pesticide application program (Gan and Wickings, 2017). King and Balogh (2010) found that pesticides were regularly transported offsite by streams draining a golf course, but pesticide concentrations did not exceed US Environmental Protection Agency guidelines. Finally, several studies suggest that pesticide applications to golf courses routinely affect surrounding aquatic ecosystem health negatively (Metcalfe et al., 2007; Haith and Rossi, 2003).

5. Conclusion

Despite the small dataset, our analysis reveals that regulatory environment is the best predictor of pesticide risk. Our original hypothesis, that climate would influence pesticide risk most, is not supported by this limited dataset. Golf courses in the southern US, with longer growing seasons, did not have higher pesticide risk than golf courses in the Northern US.

This study found that maintenance budgets were correlated to pesticide risk in the Northern US, but not in other regions. Lowering maintenance budgets could in some circumstances lead to lower pesticide risk. However, restricting pesticides available to golf courses, either through product bans (i.e., UK and Norway) or the implementation of mandatory software tools that impose limits on pesticide risk (i.e., Denmark) appear to be the most effective ways to reduce pesticide use, and therefore risk, on golf courses sampled in this study.

To the author's knowledge, this is the first study to compare pesticide risk on a sample of golf courses across a wide variety of climates and geographies. The study also attempts to explain why pesticide risk varies as it did between regions, and finds that regulatory environment, not climate or economic factors, to be the most salient factor in determining risk. Even though the sample size of this study is low, given the complete lack of data on golf course pesticide risk across regions in the existing literature, the sample size achieved in this study provides an initial indication of golf course pesticide risk across the US, UK, and Europe. Further data collection is needed to increase confidence in the results of this study. Golf industry groups, especially golf course superintendent associations (e.g., the Golf Course Superintendent's Association (GCSAA) in the US), are best positioned to collect more pesticide use data and further analyze golf course pesticide risk. Future work could also apply a similar pesticide risk methodology to other sectors of the turfgrass industry, especially lawns, which cover more area and have the greater environmental impact than all other turfgrass surfaces.

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Michael A.H. Bekken: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization. **Douglas J. Soldat:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration. **Paul L. Koch:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. **Carl S. Schimenti:** Conceptualization, Methodology, Writing – review & editing, Project administration. **Frank S. Rossi:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration. **Trygve S. Aamlid:** Project administration, Writing – review & editing. **Karin J. Hesselsøe:** Project administration, Writing – review & editing. **Torben K. Petersen:** Project administration, Writing – review & editing. **Chase M. Straw:** Project administration, Writing – review & editing. **J. Bryan Unruh:** Project administration, Writing – review & editing. **Alec R. Kowalewski:** Project administration, Writing – review & editing. **Christian Spring:** Project administration, Writing – review & editing.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Frank Rossi reports a relationship with Petro-Canada that includes: consulting or advisory.

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