LIFE CYCLE ASSESSMENT OF FIREARMS AND AMMUNITION

Alyssa Amorim, Dakota Black, Pranati Borkhetaria, Mary Gambill, Megan Gray, Hannah Jin, Sean Pergola, Kelly Qiang, Michael Rosenberger, Aidan Smires, Kevin Tang and Nolan Vilim

Advisor: Lisa Jordan
Assistants: Molly Murphy, David Van Dongen

ABSTRACT

Objectives: To demonstrate the application of life cycle assessment (LCA) to firearms and ammunition in order to connect injury prevention and control research to scholarship in environmental and occupational health.
Methods: We collected data from the ATF on manufacturers, from the EPA and OSHA compliance databases, from the CDC detailed mortality tables, and from two state firearm law databases to explore the upstream and downstream impacts of firearms and ammunition.
Results: We identified significant environmental and occupational health violations among firearms manufacturers, and occupational health violations among shooting range facilities, most commonly related to lead emissions and exposures. An exploration of the correlation between firearm deaths and state firearm laws revealed significant associations between all deaths due to firearms, and suicide deaths due to firearms, but insignificant results for firearm homicides. Last, we found evidence that state implementation of Stand Your Ground policies is associated with firearm homicide rates that significantly exceed the national average.
Conclusion: The LCA approach to firearms and ammunition opens up new avenues for public health interventions that extend beyond traditional injury prevention and control research to include negative health outcomes attributed to environmental and occupational health hazards.

INTRODUCTION

This article uses a product life cycle assessment framework to demonstrate the multiple opportunities for public health intervention across different stages in the life of firearms and ammunition. Life cycle assessment (LCA) offers a compelling complement to the Haddon matrix, described by Hemenway,[1] and the expanded Haddon matrix, described by Runyon,[2] for communicating the type and intention of public health policies, and for comparing multiple products. Additionally, an LCA or "cradle to grave" framework for firearms and ammunition connects environmental health methods to research in injury prevention: a methodology that has also been applied to the study of motor vehicles,[3] alcohol[4] and consumer tobacco products.[5] While scholarly use of LCA has explored lead in ammunition,[6] and stores of ammunition,[7] the application to firearms presents a novel use.

The Haddon matrix was instrumental in public health work related to motor-vehicles because its application enabled researchers to identify multiple points of policy intervention: before, during and after the accident or injury. Hemenway[1] extended the Haddon matrix to explore opportunities for intervention for three forms of injury: accidental firearm injuries, homicides, and suicides. A variety of policy options exist to help prevent injuries, respond to injuries and develop mechanisms for recovery and rehabilitation. Hemenway's[8] interpretation of firearms in public health has been transformative to the field of injury prevention. In the spirit of extending this work to further identify multi-pronged approaches to firearms in public health, this paper explores the application of Life Cycle Assessment (LCA) to firearms and ammunition.

Using LCA, a consumer product can be understood as an object that operates in a system with multiple phases (shown in Figure 1), beginning with design and material extraction, proceeding to manufacturing, followed by distribution and retail, to reach the consumer, who is not the beginning of the cycle, but one piece of the journey of the product. Consumption of the product is followed by disposal, perhaps with opportunities for looping back into the cycle through reuse or recycling. Like the Haddon matrix, applying the LCA to firearms and ammunition helps to convey the many, varied options for public health action.

Figure 1. Schematic of the Life Cycle Analysis as Applied to Firearms and Ammunition

While the complete and thorough life cycle of firearms and ammunition is beyond the scope of this article, it is possible to identify a few areas to better understand the processes of production and use and to quantify their effects on public health. Working as a team in a summer research setting, we identified four subtopic areas to explore in greater depth. These include: the environmental health impact of firearms and ammunition manufacturing, the occupational health impact of firearms manufacturing and recreational shooting ranges, summaries of the public health impact of firearms as the injury mechanism in comparison to state firearm laws, and the specific policy impact of Stand Your Ground laws on firearm homicides.

METHODS

Supplementary Table 1 summarizes the data and methods explored in each of the subtopic areas. Quantifying the environmental health impact of production is an important component to any LCA. The environmental health research conducted here emphasizes collection of recent data on toxic emissions from small arms and ammunition manufacturing. EPA Compliance and Toxic Release data were obtained for all active facilities engaged in small arms and ammunition manufacturing. Using reports from the Bureau of Alcohol, Firearms, Tobacco and Explosives (ATF), we first identified the top twenty locations where the majority of all firearms in the United States are produced[9,10] to identify current and historical records related to emissions and compliance with federal laws, including: the Clean Air Act (CAA), the Clean Water Act (CWA), the Resource Conservation and Recovery Act (RCRA), and the Emergency Planning and Community Right-to-Know Act (EPCRA). Specific chemical emissions, such as lead and chromium were quantified, and environmental justice summaries, known as "EJReports" were aggregated. The facility locations were also geocoded and visualized using ArcGIS Online and ArcGIS Pro.

The second topic explores occupational health hazards attributed to firearms manufacturing and recreational shooting ranges. Using commerce reports from the ATF,[10] all current manufacturers were identified. These records were then cross reference with recent data from the Occupational Safety and Health Association's (OSHA) Integrated Management Information System (IMIS)[11] on recent inspections, from 2014-2019, using NAICS code 332994 which specifically targets inspections within firearms manufacturers. These records included facilities with and without violations. The facility database was georeferenced and visualized using CARTO software.[12] In our work, it emerged that shooting ranges were a recurring source of hazardous occupational exposure related to firearms, so the project was extended to include records for four thousand shooting ranges compiled on the website Range Listings.[13] As with firearms manufacturers, these facilities were cross-referenced with OSHA inspection reports to quantify compliance. Exposure to lead was identified as a primary source of violations and exposures for workers in both firearms manufacturing and recreational indoor and outdoor shooting ranges.

For the third topic area, we obtained and summarized detailed mortality data from Centers for Disease Control and Prevention (CDC) WONDER to quantify the recent public health burden of firearm injuries, focusing on the most recent five year period for data collection: 2013-2017.[14] This work explores associations between total firearm deaths, firearm homicides and firearm suicides in relation to state firearm laws. We did not include unintentional deaths due to firearms because there was insufficient data for each year. State Firearm Laws were quantified in *The Changing Landscape of U.S. Gun Policy* report from the Boston University School of Public Health. States were given one point for every one of 133 listed firearm laws they had, except for the five of the 133 that were categorized as a preemption, immunity, or stand your ground law. Zero points were given for each preemption, immunity, or stand your ground law, and one point was given for each one of these laws that the state did not have.[15] We used the total number of gun laws in each state from 2015 because it is the median year of the range (2013-2017) that was examined for crude homicide and suicide rates, as well as total gun death rates. Correlation analysis for the datasets were explored in both Google Sheets and RStudio statistical software. An alpha level of 0.05 was used to determine if p-values generated from statistical analysis were statistically significant. State-level residuals were visualized and examined in Google Sheets.

Last, the fourth topic examined the impact of Stand Your Ground policies on firearm homicides. Expanding traditional self-defense doctrine, these laws permit the use of deadly force in both public and private settings, which eliminates the duty to retreat from danger. Using the RAND State Firearm Law Database,[16] the statutory code and start date for Stand Your Ground (SYG) policies was identified. To retrieve additional information on each state's SYG policy, we used data from Everytown for Gun Safety.

ArcGIS Pro 2.3 was used to visualize and characterize the severity of Castle Doctrine and Stand Your Ground policies across states. CDC WONDER detailed mortality records for the five years before and the five years after implementation were compared. Google Sheets was used to visualize national and state-level firearm homicide records, contrasting Stand Your Ground states to other states.

Though these subtopics within the Life Cycle Assessment of firearms and ammunition do not provide a comprehensive analysis, they illustrate the value of LCA in opening ideas for possible public health interventions that may positively influence the health of communities and individuals both upstream and downstream of this dangerous consumer product.

RESULTS

Environmental Health

EPA ECHO[17] results for NAICS 332994, small arms, ordnance, and ordnance accessories manufacturing, and NAICS 332992, small arms ammunition manufacturing, identified 155 and 93 facilities, respectively. Among these facilities, over 100 quarters of non-compliance was found over the past three years. The combined penalties paid for non-compliance total 0.8 million US dollars. Nearly 50 million pounds of toxics were released in 2017, as uncovered by reporting requirements mandated by the 1986 Emergency Planning and Community Right-to-Know Act, monitored by the EPA Toxics Release Inventory.[18]

Fortunately, most of the toxics used in the production of firearms are recaptured and recycled. Many firearms manufacturers participate in the voluntary EPA TRI P2 program, which implements the Pollution Prevention Act of 1990[19] to document and encourage energy recovery and recycling. However, given current manufacturing practices, as production increases, it is inevitable that toxic releases will increase. Figure 2 illustrates the relationship between firearms production[9] and toxic releases not recycled or recovered, as quantified by the EPA Risk Screening Environmental Indicators (RSEI).[20] During the ten year period, shown in the figure, 1.4 million pounds of toxics were released, while 42.6 million firearms were manufactured. This is roughly equivalent to a half ounce (14 grams) or one tablespoon of toxic emissions for every firearm produced.

This estimate does not include the larger costs of energy used to produce the firearm, or in transportation from manufacturers to distributors, or internally along the supply chain. However, these emissions tend to be borne in a few geographic locations, often over long periods of time, affecting air, soil and water, and nearby communities. Additionally, recaptured and recycled raw materials, while certainly preferable to direct emissions, also enter into a new supply, processing and distribution sequence. The overall impact of these systems is not known; however, there are many more companies involved in the processing of recycled materials than in manufacturing.[20]

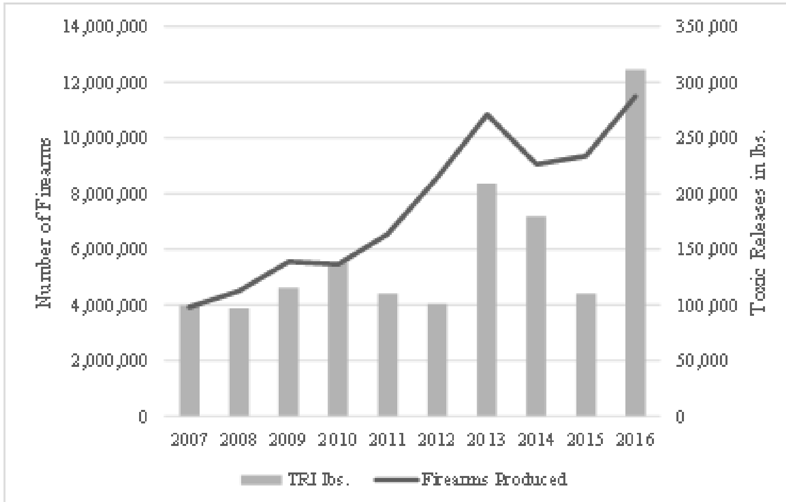

Figure 2. Domestic Firearms Production (ATF) and Toxic Releases Not Recovered (EPA TRI, RSEI), 2007-2017

Of these releases, 54 percent were lead or lead compounds, second and third most common releases included sodium nitrite (13.2%) and chromium and chromium compounds (11.1%).[20] Several major companies were confirmed to have released lead and lead compounds: the top five emission sites are summarized in Figure 3. All of them had violations pertaining to the Clean Air Act (CAA), the Clean Water Act (CWA), or the Resource Conservation and Recovery Act (RCRA). Notably, Remington Arms Company LLC, the largest emitter of lead compounds by over 1.5 million pounds compared to the second highest lead emitter, received three formal enforcement actions, and one informal enforcement action at their Lonoke, Arkansas facility, including a significant violation of the CWA. The Remington Arms facility affects Hall Creek-Bayou Meto and Coleman Creek-Maumelle River, both 303(D) listed impaired waters, with impairments caused by dioxins and metals.

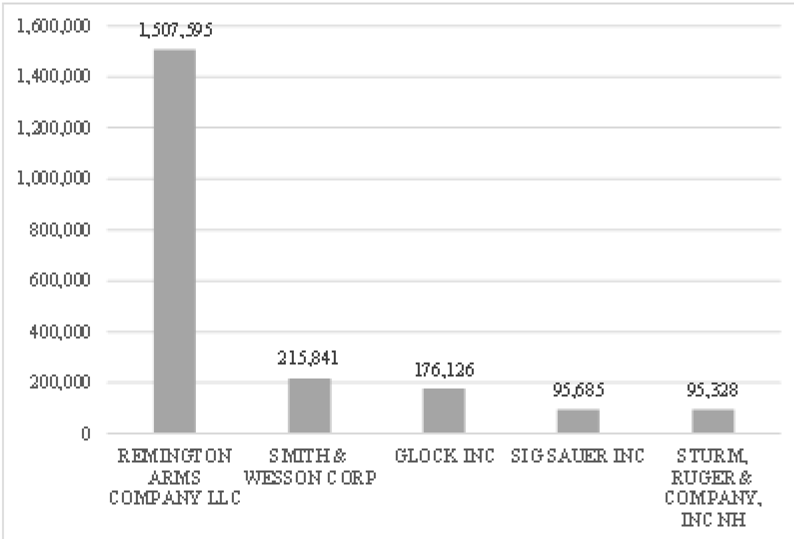

Figure 3. Top Five Manufacturers by Total Releases of Lead and Lead Compounds in 2017. Summarized from the ECHO Detailed Facility Reports, United States Environmental Protection Agency.

The stacked graph in Figure 4 displays the emissions data we were able to collect from the 2017 EPA report concerning the toxic emissions of the top 20 firearms manufacturers in America. The total emissions (in pounds) are displayed at the top of each bar. Eleven of the facilities reported their emissions in 2017, while nine of them failed to report any data. Remington Arms is a significant contributor to the copper and lead compounds emitted.

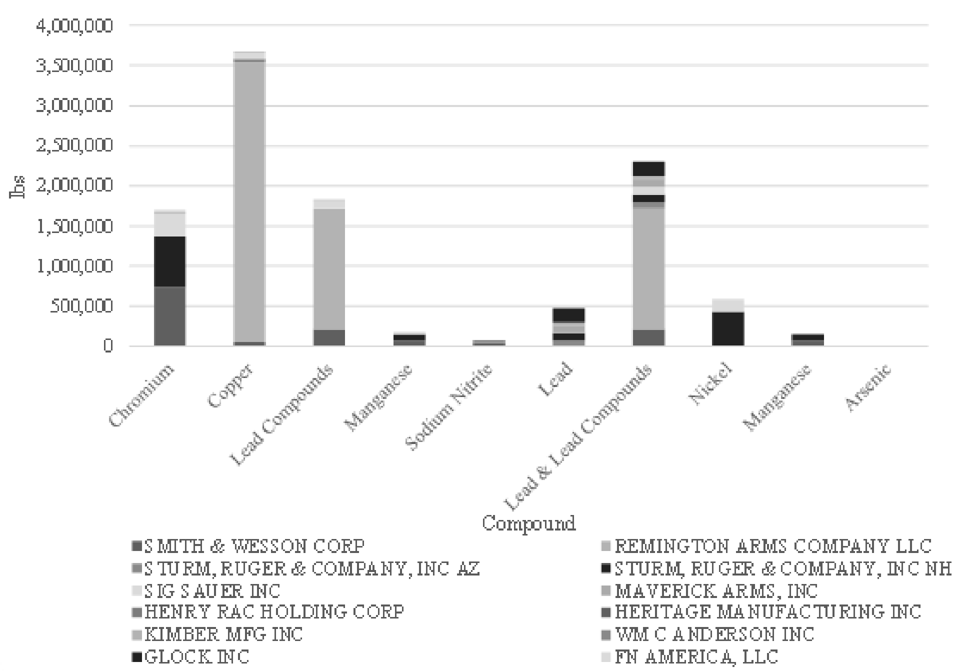

Figure 4. Total Pounds of Toxic Emissions Released by Top 20 Firearm Manufacturing Facilities in 2017.

The Environmental Justice (EJ) Report Percentiles provided by the EPA were collected for each of the companies investigated. The percentile defines what percent of the defined area/population (state, regional, or national) has an equal or lower risk/potential for exposure to the parameter the percentile is referring to. For example, the ozone levels in a three mile radius surrounding Glock's largest factory are in the 85th percentile when compared to the larger surrounding region.[21] The EPA regional percentile is used in this investigation in order to analyze smaller areas than national data allows while considering an area larger than the immediate perimeter of each factory examined.

There are 11 different percentiles available for comparison, but we chose to focus on only six due to their relevance to the emissions/manufacturers studied: Particulate Matter, Ozone, National Air Toxics Assessment (NATA) Air Toxics Cancer Risk, NATA Respiratory Hazard Index, Hazardous Waste Proximity, and the Wastewater Discharge Indicator. The five other percentiles were not investigated because of their lack of relevance to firearms manufacturing and their emissions. Figure 5 shows EJ report percentiles that are relevant to the environmental conditions surrounding firearm manufacturers. Four of the six EJReport Percentiles were higher than 50%, and the two others were both greater that 40%. This demonstrates that there is an unequal burden of exposure to environmental hazards attributable to firearms manufacturing.

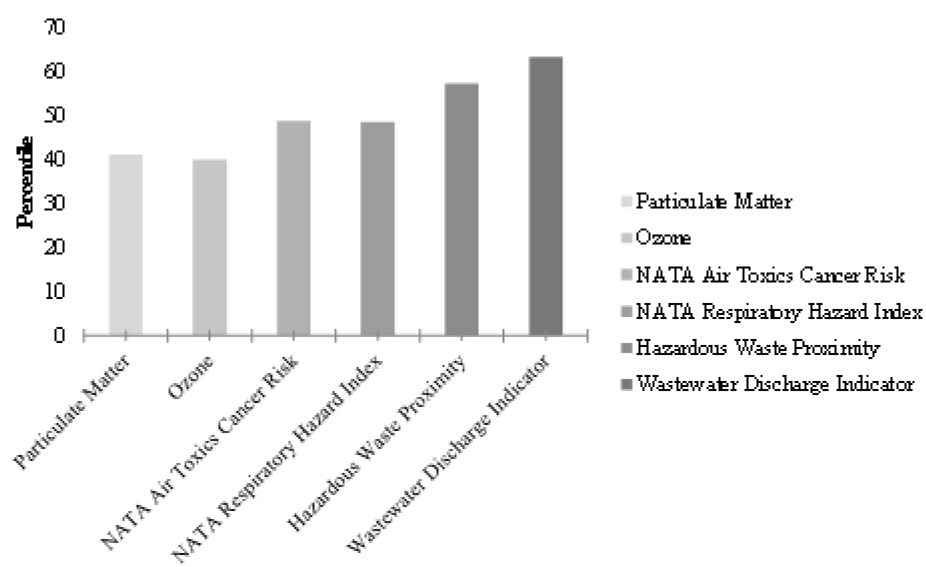

Figure 5. Average Regional EJReport Percentiles for Manufacturers Investigated. Gathered from EPA ECHO Database Reports, 2019.

Overall, we found that firearms manufacturers emitted a multitude of toxic materials into the surrounding environment (Fig. 6). The EJReports and percentiles from 2017 highlighted the magnitude of this impact with the quantities of toxic compounds released in one year for each factory. The number of TRI Releases and penalties for noncompliance from firearms and ammunition manufacturers were concentrated in the New England and Missouri/Arkansas areas.

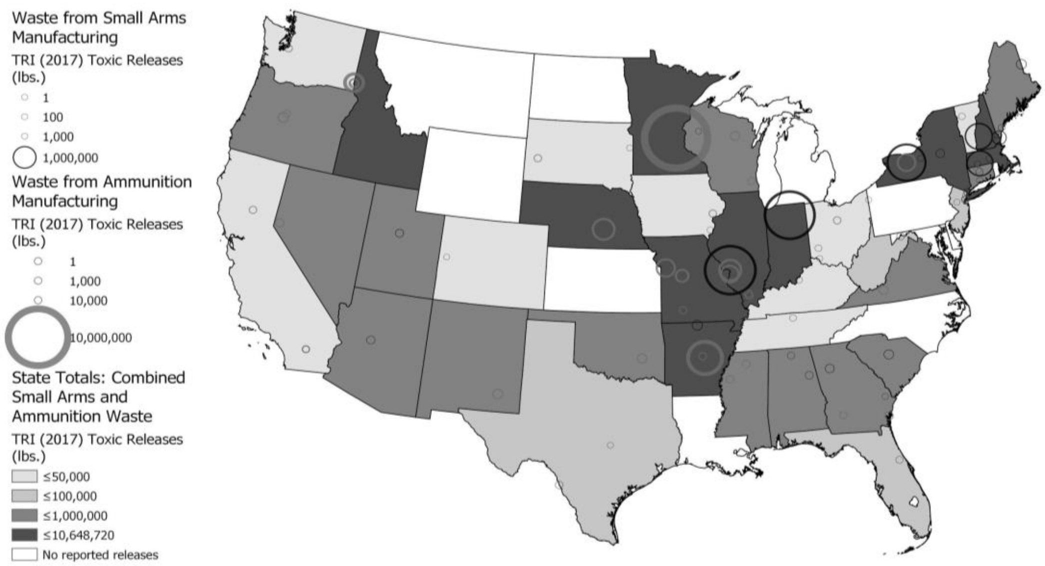

Figure 6. Summary of Total Toxic Releases from Firearms and Ammunition Manufacturing, by Site and State, 2017

Several of the factories released considerable amounts of toxic emissions, including multiple substances that are proven to have both environmental and human health consequences. Lead has been linked to many different health defects, including various cancers and brain damage.[22] However, lead's useful properties including malleability, the ability to block high levels of radiation, availability/low cost, and high density make it a desirable material to use in manufacturing and have thus kept it from being banned from consumer products. As a whole, the top 20 firearm manufacturing companies released 1,821,470 lbs of lead compounds, in addition to 475,211 lbs of lead. Releasing these high quantities of lead can have many detrimental effects on human health and the environment.

Another significant waste product produced by the top producing firearms companies is chromium. Chromium waste, if released as an air pollutant in manufacturing, can pose a serious risk to human health. It is linked to skin rashes, respiratory problems, and lung cancer among other health problems.[23] Compared to other emissions, chromium can have a more harmful effect on plants and animals in the environment. The 1,702,516 lbs. of chromium released is easily enough to cause environmental damage. Overall, the vast quantities of copper, lead, chromium, sodium nitrite, and other toxic compounds released by munitions factories have the potential to pose a serious threat to human health, the environment, and the economy in the areas surrounding them.

After a piece of land has been contaminated by toxic materials, the materials will continue to persist and leach into the environment for decades. Some toxins, such as mercury and lead, persist in the environment for many years and accumulate over time. Humans or wildlife can easily and unknowingly ingest these toxins through their water, food, or airborne contact.[24] Not only will the land remain contaminated for many years, but clean up and containment processes can take millions of dollars out of the federal Superfund program.

Occupational Health

The firearm manufacturing and firing range industries are quite expansive, with thousands of employees.[2] These people work with and around firearms regularly and are exposed to dangerous levels of lead. In order to evaluate the severity of occupational health hazards in the firearms manufacturing and firing range industries, data concerning the occupational conditions of the industries was collected by sorting through the OSHA database[11] on firearms manufacturers and firing ranges' violations. After data analysis, it is clear that the firearms industry is severely under-inspected, violations pertaining to lead levels are the most common, and the prominence of these violations has not improved in the past 15 years.

Some recent studies have observed state-based legislation that protects shooting ranges from liability for environmental and occupational health hazards.[25] As a result, many ranges are able to establish and maintain very unhealthy work environments, which negatively impact the health of those working there. The *Best Management Practice for Lead at Outdoor Shooting Ranges* report, compiled 20 years ago by the US EPA in collaboration with the National Rifle Association (NRA) and National Shooting Sports Foundation (NSSF), estimates that in the latter half of the 1990s, about four percent of all lead produced in the United states was made into bullets and shot; quite a bit of this eventually ended up in the environment at shooting ranges.[26] Another report by the National Institute for Occupational Safety and Health estimated that 16,000-18,000 firing ranges were in operation in the US.[27] Medical studies have identified elevated blood lead levels among employees, families and customers of indoor firing ranges.[28,29] Two Norweigan studies of soldiers identified respiratory hazards from indoor firing practice, finding declines in forced expiratory volume and reported respiratory symptoms similar to metal fume fever.[30,31] Voie, et al. explains that there are no bullets available that do not have any toxins; subsequently, those who work with firearms regularly, such as soldiers, are exposed to these harmful substances, including CO emissions, particulate matter, copper, zinc and tin, among others, on a daily basis.[31] Not only are soldiers and firing range employees exposed to all these unhealthy conditions, but so are the employees of the firearm manufacturing industry. Among them, lead poisoning is a significant problem. The firearms manufacturing industry is responsible for 17,393 employees, with a payroll of $1.1 billion, but also for the multitude of hardships many face due to lead poisoning from working in the industry.[32] This section quantifies and explores the trends and extent of the unhealthy occupational conditions within the firearm manufacturing and recreational industries.

This research originally focused on the occupational health of the workers of the firearm manufacturing industry; however, since little to no primary literature particularly addressing that topic was found, we created our own database using the list of violations found on the OSHA online database.[11] OSHA regulations are intended to outline safe working conditions in order to preserve the health of individual workers. These regulations include limiting the amount of lead allowed to be released by a specific work site in order to avoid adverse effects (namely lead poisoning) on the people working in that facility. The dataset included all of the manufacturers with and without violations. The data collecting process began by locating a complete list of firearm manufacturers throughout the entire United States on the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) database.[10] Once located, the process continued by searching the OSHA database using NAICS code 332994 which specifically targets inspections within firearms manufacturers. Through this data set, information about the number and type of a company's OSHA violation from 2014 to 2019 was collected. Once consolidated, the data was used to create a map depicting the locations of the arms manufacturers as well as the locations of the manufacturers with OSHA violations (see Fig. 7).

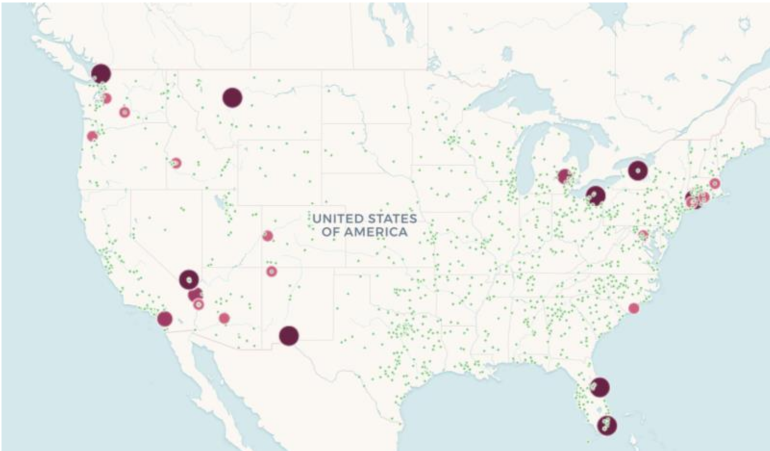

Figure 7. Map of All US Firearms Manufacturers and the Accompanying OSHA Violations from 2014-2019. Green dots represent individual arms manufacturers. Red dots represent manufacturers with OSHA violations.

Figure 7 shows the 2,184 firearms manufacturers in the United States, and those that have violations. The map also summarizes trends seen among firearms manufacturers' OSHA violations as well as the severity of these violations, illustrating the risk of harm to employees of these manufacturers. The green dots represent manufacturers without violations, and the red dots represent the manufacturers with violations. Red dots are shown as proportional symbols, with larger and darker red dots indicating more violations received by the manufacturer. There are more violations in the manufacturers located on the coast, whereas there is a lack of manufacturers with violations in the midwest.

This analysis also includes data concerning the occupational health risks of those who work with firearms on shooting ranges. While searching for literature on the occupational health and risks of those who work with firearms, a dataset of violations among firearm ranges for 2004-2013 was found. Additionally, a separate dataset of firing range violations from 2014 through 2019 was also compiled. Since firing ranges fall under the NAICS code for recreational facilities (713990) all the data for recreational facility OSHA violation was sorted and firing range violation data was extracted. This data set was then matched with a list of all of the firing ranges in the United States.[13]

Figure 8 displays 4,048 firing ranges (indoor and outdoor) and 517 OSHA violations from 2014-2019 as dots. The small, green dots represent the ranges free of OSHA violations, while the red dots represent ranges with one or more OSHA violation(s). The larger and darker the red dot is, the more violations that range has received. Many of the large red dots are on both the east and west coasts, with a lack of ranges with violations in the west.

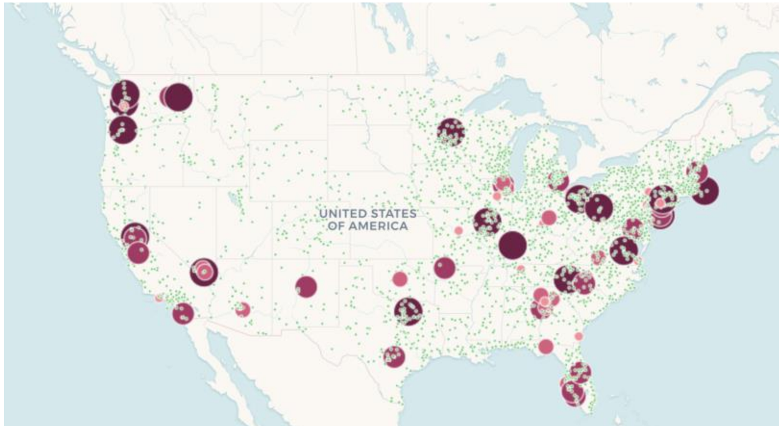

Figure 8. Map of US Firing Ranges (Indoor and Outdoor) and the Accompanying OSHA Violations from 2014-2019. Green dots represent individual arms manufacturers. Red dots represent manufacturers with OSHA violations.

OSHA violations related to lead are the most common form of violation for both firearms manufacturers and shooting ranges. From 2004-2013 there were 1,931 violations for shooting ranges, of which 1,512, or 78.30% were lead related. From 2014-2015, there were 517 violations issued that of which 417, or 80.70% of the total violations were lead related. Though the overall number of annual violations has been halved, a large majority of violations that continue are related to lead exposures.

The total number of searchable inspections from 2014-2019 on the OSHA database is 134. This equates to a mere 6.1% of manufacturers inspected in this time period. A multi-part investigative report by the *Seattle Times*, several years ago, explored occupational health conditions among workers at shooting ranges.[33] They identified the total number of firing ranges in the US as 6,000. The total number of searchable inspections from 2004-2014 on the OSHA database was 201: this equates to only 3.3% of all firing ranges receiving inspection during this time period. Even though inspections have risen significantly, the proportion of inspections is still very low. There is no comprehensive data that shows the total number of firing ranges from 2014-2019 in the US or their violations. As of now, we can estimate that there is somewhere between 4,000-10,000 ranges and of those ranges 680 is the maximum number of inspections that could have taken place from 2014-2019. Thus, the percentage of inspected ranges could only be somewhere from 6 - 18%. As figures 7 and 8 both indicate, there are also significant geographic variations in OSHA inspections by state, some states receiving no inspections of manufacturing or shooting facilities. Future research should explore the geographic disparity in OSHA inspections, related to firearms, and the inequality in protections for works on an interstate level.

Both firearms manufacturers and firing ranges throughout the US pose major threats to the employees who work in them. The most prominent of these threats being lead related poisoning. Lead has devastating effects on the body notably, its ability to reproduce. These dangerous levels of lead can accumulate through a number of range and factory deficiencies ranging from incorrect airflow direction to filter degradation.[28] Additionally, the only reason these deficiencies prosper may indeed be caused by the lack of inspection of both firearms factories and firing ranges. Our data analysis shows the minimal amount of inspections that took place from 2014-2019 in the 2,184 firearms manufacturers across the United States. Of these 2,184 manufacturers only 134 inspections took place, and of these 134 inspections, 214 violations were issued. The fact that only 6.4% of the manufacturers in the US had record of being inspected, truly shows how insufficiently regulated this industry is. Furthermore, this neglect is not only in the manufacturing industry, it continues into firing ranges as well. Though inspection rates have improved from 2004-2013, data from 2014-2019 estimates only a 6 - 18% inspection rate among firing ranges. This is an increase in percentage compared to the firearms manufacturers, and this may be due to the public access of firing ranges, but the percentage is still not nearly as high as it should be. The inadequacy of reporting on inspections for both firing ranges and firearms manufacturers, our data suggests, is a major reason for which these occupations are not safe for employees.

In addition, of the violations documented, a majority of them, especially in firing ranges, were lead related. For both the 2004-2013 and 2014-2019 time periods, the percentage of lead violations in firing ranges was close to 80%. This demonstrates that lead exposure remains one of the most pressing occupational health concerns in the operation of shooting ranges. The lack of inspection throughout firearms-related workplaces in combination with the prominence of elevated lead levels is the main reason for which firearms occupational establishments are not safe for the people who work in them. A good suggestion of a plausible solution to this life-threatening problem is to increase the number of inspections across the country in these facilities. The more inspections that occur, the less likely facilities whom continually violate the OSHA regulations are able to stay open and harm their employees.

Firearm Injury Prevention & Control

In this section, we analyze whether or not the strictness of state gun laws has an impact on the crude suicide, homicide, and overall death rates due to firearms in each state. To determine the relationships between state gun laws and homicides and suicides, we used various databases to gather the crude rates for firearm deaths and the number of gun laws in each state and compared them using statistical techniques. The results show that there was a negative association between the number of gun laws a state has and its firearm death crude rate and suicide by firearm crude rate; however, there is no correlation between a state's number of gun laws in 2015 and its homicide by firearm crude rate, between 2013-2017. It should be noted, however, that a significant body of literature connects specific gun laws with reductions in firearm homicide;[1] however, the total number of laws alone did not appear to be a significant predictor, during this time period. Our results could have significant effects in the public health realm, as our research supports the idea that passing more restrictive state gun laws could help to prevent gun deaths, specifically due to suicide.

Figure 9 shows the number of gun laws per state with a range of 2 to 102 gun laws, with Mississippi having the lowest and California having the highest. The coasts seem to have a higher number of laws compared to states in the midwest and central America. Additionally, there are only a few outliers such as California, Massachusetts, and New York.

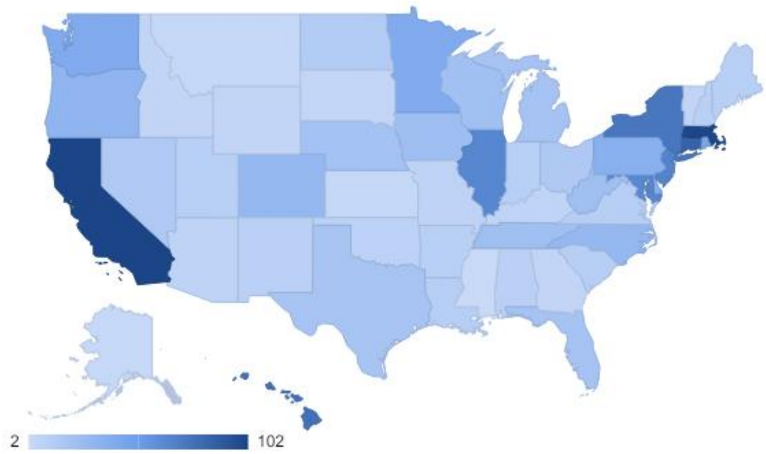

Figure 9. Number of gun laws per state. The number of gun laws are depicted based on the shading of the state with lighter shades corresponding to fewer gun laws.

Table 1 summarizes the correlation coefficient between state gun laws and crude death rates where firearms were the injury mechanism. States with more gun laws tended to have lower crude rates of firearm deaths. States with a greater number of gun laws did not show a statistically significant negative trend in relation to the number of homicide deaths by firearm (p-value = 0.126). States with more gun laws showed lower rates of suicide by firearm (p-value < 0.001).

Table 1. Correlation Coefficient Values for Total State Gun Laws

Crude Suicide Rate	Crude Homicide Rate	Crude Firearm Death Rate
-0.796	-0.219	-0.740

A residual is the difference between the observed value of the dependent variable and the value predicted by the linear regression model. In this study, the residuals correspond to the differences between the actual crude suicide and homicide rates for each state from the state's crude suicide and homicide rates predicted by the two models generated from the bivariate regressions above. A positive residual means the linear regression model underestimated the crude death rate for that particular state, while a negative residual means the model overestimated the crude death rate. The map of residual values from Figure 10 shows that the crude firearm suicide death rates were generally overpredicted for states in the midwest and northeast based on the number of restrictive gun laws issued in each. This is with the exception of West Virginia which has a high residual indicating a relatively large underprediction of crude suicide death rate. Many of the states in the West have positive residuals showing a general underprediction of crude suicide rates in this region.

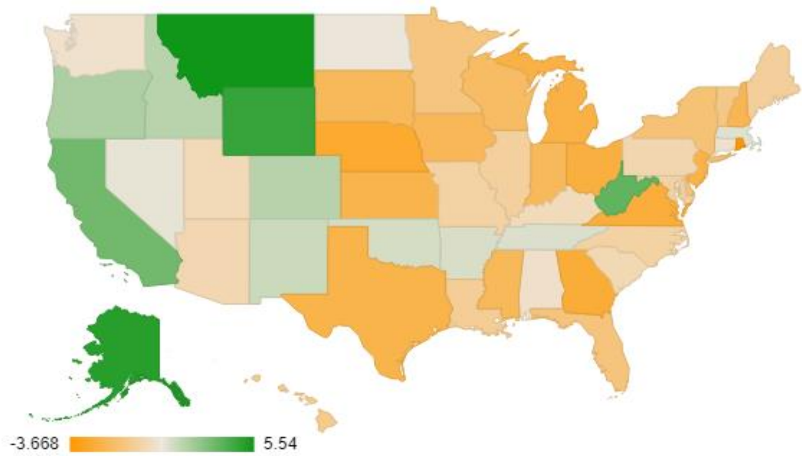

Figure 10. Residual values for the number firearm suicide deaths per state. The residuals are depicted based on the shading of the state with dark orange corresponding to lower negative values and dark green corresponding to higher positive values.

Figure 11 shows the residuals for homicide rates. Alaska has a higher residual as compared to many other states. In the southeastern US, there is a cluster of states, namely Louisiana, Mississippi, and Alabama, that had more firearm deaths than predicted by the linear regression model. Opposingly, many northern states have negative residuals, meaning that there were fewer homicides due to firearms that was predicted based on the number of laws.

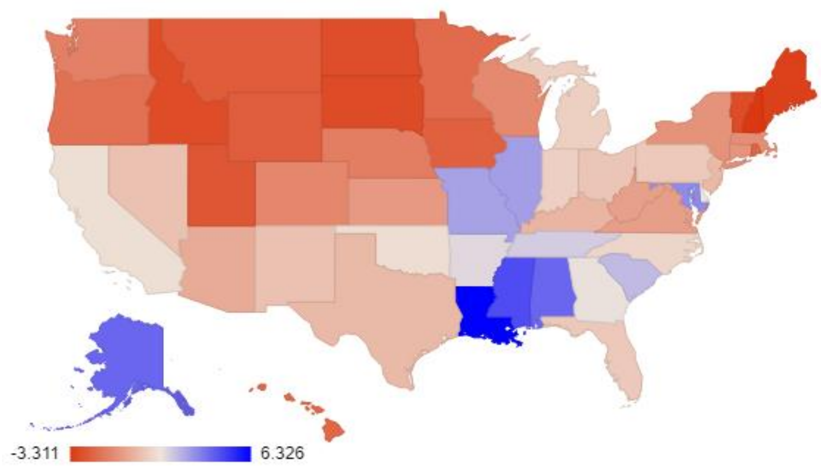

Figure 11. Residual values for the number firearm homicide deaths per state. The residuals are depicted based on the shading of the state with dark red corresponding to lower negative values and dark blue corresponding to higher positive values.

A decrease in the total crude death by firearm rate and the suicide crude rate by firearm crude rate but not the homicide by firearm crude rate was associated with an increase in the number of gun laws. We saw a similar negative relationship between a state's suicide rates and the number of gun laws, revealing that increased firearm laws were correlated with a decrease in suicide rate by firearms and all other suicide methods combined.

Our primary independent variable, the total number of laws according to the State Firearm Laws database, might not truly reflect the restrictiveness of a state's laws, since a state with fewer laws may have stricter legislation than it appears to have if each of the state's laws are extremely severe. Future studies could create a system for rating the severity of laws and find their correlation with violent deaths. While our study does not provide evidence on the impact or lack of impact of specific laws, our study provides evidence that a general increase in the number of restrictive state gun laws prevent gun violence. Our study supports much of the public health literature on firearms, which reveals that firearm regulation likely prevents gun violence. While deciding whether to issue more gun legislation could be impacted by much more than public health factors, our study provides evidence that an increase in restrictive state gun legislation prevents gun deaths, one of many important factors for policy makers to weigh.

Impact of Stand Your Ground Policy on Firearm Homicides

Expanding upon traditional self-defense doctrine, Stand Your Ground (SYG) policies eliminates the duty to retreat, justifying the use of violence in any place — public or private — when in perceived danger. These laws first garnered national attention when neighborhood watch captain George Zimmerman evoked Florida's SYG legislation to defend his fatal shooting of unarmed Trayvon Martin in 2012.[34] Despite its controversy, these laws have proliferated across the country since 2005, when Florida first passed SYG policies. To this day, 27 states have implemented SYG in varying capacities.[35,36]

Critics denounce these "shoot first" laws, claiming that it permits gratuitous violence in situations that can be safely deescalated by retreating. On the other hand, advocates argue that SYG laws would deter crime since the threat of retaliation causes criminals to reconsider assaulting an individual. As firearms continue to comprise a substantial portion of injuries and deaths across the nation, the adoption of SYG policies by a majority of states has generated considerable public discourse over their implications with regard to public health and criminal justice.[37]

Since SYG laws remove the "duty to retreat" from danger in public, they may increase firearm homicides by increasing the likelihood of violent encounters. Several studies have empirically verified this hypothesis, such as in Florida.[38] In this study, we examine whether this trend would also hold true on a national scale.

Figure 12 depicts the range of SYG laws, which have now been implemented by a majority of states. Nevada, Tennessee, North Carolina, Florida, and Kansas are the most lenient in their SYG policies. These states presume that deadly force is presumed lawful, even if the homicide is done by the aggressor.

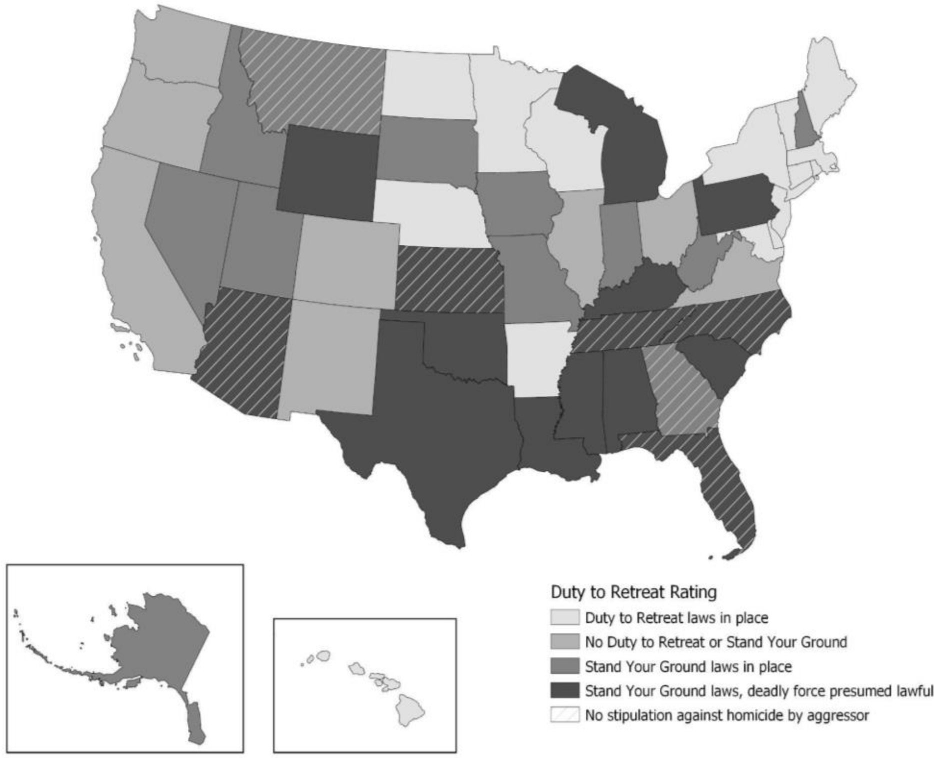

Figure 12. The varying degrees of SYG laws across the United States. The two lightest shades represent states without SYG policies. The lightest shade refers to states that legislate a duty to retreat, while the darker shade denotes states that do not have a duty to retreat. The two darkest shades refer to states with SYG laws currently in place, with the darkest shade signifying that any claim of justifiable homicide is presumed to be valid. Most states have a stipulation that SYG laws cannot be invoked when the shooter provoked the conflict; the states lacking this are displayed with hash lines.

As shown in Figure 13, SYG states followed a similar trend as the rest of the United States. The spikes in the SYG crude death rates are marginally higher and longer. For instance, from 2014 to 2017, the firearm homicide mortality crude rate of SYG states increased by 1.4 while that of non-SYG states increased only by 0.7. However, holistically, SYG states do not deviate significantly from the national trend in firearm homicides.

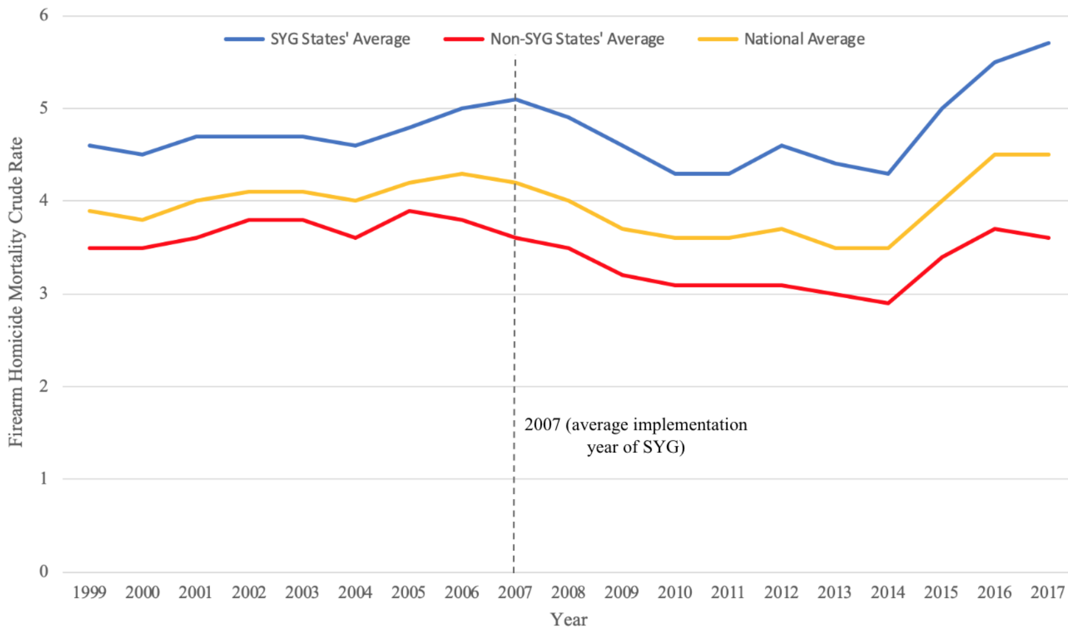

Figure 13. Firearm homicide mortality crude death rates from 1999 to 2017.

Figure 14 depicts the change from before implementation of SYG laws in 2007 to after their adoption. 2007 represents the average year of adoption of SYG legislation and can therefore act as a reasonable demarcation date for the purposes of our study. While SYG states experienced a slight increase in crude death rates, non-SYG states experienced a decrease. This suggests that SYG legislation is correlated with higher firearm homicide mortality.

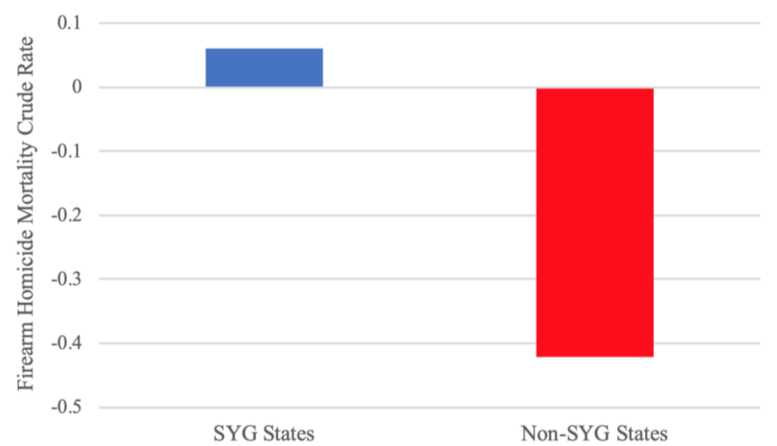

Figure 14. Changes in firearm homicide mortality crude death rates from 1999-2006 period to 2008-2017 period.

There is an association between SYG laws and increased firearm homicide mortalities. SYG states witnessed slower declines in firearm homicide rates compared to the rest of the nation, and the implementation of SYG widened the firearm homicide rate gap between SYG and non-SYG states. However, our analyses were not conclusive to prove causation between SYG and firearm homicide mortalities. There were confounding factors that may have influenced our results, especially since SYG laws are passed part and parcel with other gun legislation such as concealed carrying policies and the rise in firearm possession. Our data could not appropriately separate the impact of SYG policies and other related laws.

Ultimately, SYG laws do represent a meaningful factor out of many that are correlated with the rise in total firearm homicide deaths across the country. Additionally, data suggests that SYG laws are correlated to volatility in homicide rates. A public health approach would advise caution in the implementation of SYG laws. Moreover, SYG laws may have disproportionate impacts on certain demographics, which would be a meaningful avenue to explore. Finally, we recommend that the Dickey Amendment, which precludes the CDC from using its funds to advocate for gun control, and the Tiahrt Amendment, which prevents firearms trace data of the National Tracing Center from being used in gun violence research, be repealed as they limit the scope and extent of firearm research.

CONCLUSION

As the results from the subtopics demonstrate, the life cycle assessment approach is an effective mechanism for opening up public health research on firearms to a variety of upstream and downstream interventions. LCA extends the interpretation of public health and firearms beyond the realm of injury prevention and control to environmental and occupational health and public health jurisprudence. One consequence of this expansion is that policy attempting to minimize the health impact of firearms may consider the toxic emissions in the manufacturing of firearms and ammunition, improving OSHA surveillance of both small arms manufacturers and firing ranges, particularly in areas where no inspections are conducted, emphasizing the importance of gun policy to reduce suicide by firearms, and exercising caution against current efforts to expand "Stand Your Ground" policy.

Though these four areas of focus are a start toward developing a research agenda that takes advantage of the LCA approach to firearms and ammunition, much still remains to be done. For purposes of comparison, our work focused on the US. Though the majority of guns produced in the US are for the private, civilian US market,[39,40] we do not know the environmental health impact of the sizable market for firearm imports to the US. This information could be identified and studied, because the US EPA has worked to expand Toxic Release Inventory practices to many other countries,[41] and data are collected in Canada, Europe, and Japan, which produce high volumes of firearms imported to the US.[42]

Though the life cycle of ammunition has received more scrutiny, particularly in efforts to encourage adoption of non-leaded or reduced lead ammunition, environmental and occupational health work done here highlights the significance of ammunition as a "single use disposable" product, leading to lead contamination that affects humans and wildlife. The environmental and occupational health harms are amplified by what public health scholars have emphasized: the widespread acquisition and use of firearms is harmful to human health, particularly in the elevated levels of suicide, homicide and accidental deaths and injuries that are a result of a largely unregulated civilian firearm market, when held in comparison to all other industrialized countries.

REFERENCES

1. Hemenway, David. Private Guns Public Health. Ann Arbor: University of Michigan Press; 2004.
2. Runyan C. Using the Haddon matrix: introducing the third dimension. Injury Prevention. 1998;4(4):302–307.
3. Egede P, Dettmer T, Herrmann C, Kara S. Life Cycle Assessment of Electric Vehicles – A Framework to Consider Influencing Factors. Procedia CIRP. 2015;29:233–238. (The 22nd CIRP Conference on Life Cycle Engineering). doi:10.1016/j.procir.2015.02.185
4. Amienyo D, Azapagic A. Life cycle environmental impacts and costs of beer production and consumption in the UK. The International Journal of Life Cycle Assessment. 2016;21(4):492–509. doi:10.1007/s11367-016-1028-6
5. World Health Organization. Tobacco and its environmental impact: an overview. 2017. http://apps.who.int/iris/bitstream/10665/255574/1/9789241512497-eng.pdf?ua=1
6. Ferreira C, Ribeiro J, Almada S, Rotariu T, Freire F. Reducing impacts from ammunitions: A comparative life-cycle assessment of four types of 9mm ammunition. The Science of the Total Environment. 2016;566–567:34–40. doi:10.1016/j.scitotenv.2016.05.005
7. Carapic J, Deschambault EJ, Holtom P, King B, Small Arms Survey. A practical guide to life-cycle management of ammunition. 2018. http://www.smallarmssurvey.org/fileadmin/docs/Q-Handbooks/HB-05-LCMA/SAS-HB05-LCMA.pdf
8. Hemenway D, Azrael D, Miller M. Gun use in the United States: results from two national surveys. Injury Prevention. 2000;6(4):263–267. doi:10.1136/ip.6.4.263
9. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Annual Firearms Manufacturing and Export Report. Washington, DC: Bureau of Alcohol, Tobacco, Firearms and Explosives; 2017.
10. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Firearms Commerce in the United States: Annual Statistical Update 2018. Washington, DC: Bureau of Alcohol, Tobacco, Firearms and Explosives; 2018.
11. U.S. Department of Labor, Occupational Safety and Health Association (OSHA). Inspections within Industry | Occupational Safety and Health Administration. Integrated Management Information Systems (IMIS). 2019 [accessed 2019 Jul 31]. https://www.osha.gov/pls/imis/industry.html
12. CARTO. The World's Leading Location Intelligence Platform — CARTO. 2019 [accessed 2019 Jul 31]. https://carto.com/
13. Granroth D. About this site - Range Listings. Range Listings. 2019 [accessed 2019 Jul 31]. https://rangelistings.com/about.php
14. Centers for Disease Control and Prevention, National Center for Health Statistics. Underlying Cause of Death, 1999-2017 Results Form. Underlying Cause of Death 1999-2017 on CDC WONDER Online Database, released December, 2018. Data are from the Multiple Cause of Death Files, 1999-2017, as compiled from data provided by the 57 vital statistics jurisdictions through the Vital Statistics Cooperative Program. 2018 Dec [accessed 2019 Jun 10]. http://wonder.cdc.gov/ucd-icd10.html
15. McClenathan J, Pahn M, Siegel M. The Changing Landscape of U.S. Gun Policy: State Firearm Laws, 1991-2016. Boston, MA: Department of Community Health Sciences, Boston University School of Public Health; 2018. http://www.statefirearmlaws.org/
16. Cherney S, Morral AR, Schell TL. RAND State Firearm Law Database. 2018 [accessed 2019 Jul 31]. https://www.rand.org/pubs/tools/TL283.html
17. U.S. Environmental Protection Agency (EPA). Enforcement and Compliance History Online. 2019 [accessed 2019 Jul 31]. https://echo.epa.gov/
18. US EPA O. Toxics Release Inventory (TRI) Program. US EPA. 2013 Jan 31 [accessed 2019 Jul 31]. https://www.epa.gov/toxics-release-inventory-tri-program
19. US EPA O. Pollution Prevention (P2). US EPA. 2013 May 28 [accessed 2019 Jul 31]. https://www.epa.gov/p2
20. U.S. Environmental Protection Agency (EPA). EasyRSEI Dashboard v237. EPA EasyRSEI Dashboard Version 2.3.7. 2019 [accessed 2019 Jul 31].

https://edap.epa.gov/public/extensions/EasyRSEI/EasyRSEI.html
21. US EPA O. How to Interpret a Standard Report in EJSCREEN. US EPA. 2014 Oct 23 [accessed 2019 Jul 31]. https://www.epa.gov/ejscreen/how-interpret-standard-report-ejscreen
22. National Toxicology Program, U.S. Department of Health and Human Services. Health Effects of Low-level Lead Evaluation. Washington, DC: Office of Health Assessment and Translation (OHAT), Division of the National Toxicology Program (DNTP); 2012. https://ntp.niehs.nih.gov/pubhealth/hat/noms/lead/index.html
23. Pellerin C, Booker SM. Reflections on hexavalent chromium: health hazards of an industrial heavyweight. Environmental Health Perspectives. 2000;108(9):A402–A407.
24. Kuppusamy S, Venkateswarlu K, Megharaj M, Mayilswami S, Lee YB. Risk-based remediation of polluted sites: A critical perspective. Chemosphere. 2017;186:607–615. doi:10.1016/j.chemosphere.2017.08.043
25. Deming R. The Second Amendment v. The Environment: Florida's Transformation of Gun Range Environmental Liability. Colorado Natural Resources, Energy & Environmental Law Review. 2018;29:81–114.
26. Environmental Protection Agency (EPA). Best Management Practices for Lead at Outdoor Shooting Ranges. New York: Division of Enforcement and Compliance Assistance: RCRA Compliance Branch; 2005. p. 103. Report No.: EPA-902-B-01-001.
27. National Institute for Occupational Safety and Health (NIOSH). NIOSH Alert: Preventing Occupational Exposures to Lead and Noise at Indoor Firing Ranges. Department of Health and Human Services, Centers for Disease Control and Prevention; 2009. p. 32. Report No.: DHHS (NIOSH) 2009-136.
28. Beaucham C, Page E, Alacron WA, Calvert GM, Methner M, Schoonover TM. Indoor Firing Ranges and Elevated Blood Lead Levels — United States, 2002–2013. MMWR. Morbidity and Mortality Weekly Report. 2014;63(16):347–351.
29. Laidlaw MAS, Filippelli G, Mielke H, Gulson B, Ball AS. Lead exposure at firing ranges—a review. Environmental Health. 2017;16(1):34. doi:10.1186/s12940-017-0246-0
30. Borander AK, Voie ØA, Longva K, Danielsen TE, Grahnstedt S, Sandvik L, Kongerud J, Sikkeland LIB. Military small arms fire in association with acute decrements in lung function. Occupational and Environmental Medicine. 2017;74(9):639–644. doi:10.1136/oemed-2016-104207
31. Voie Ø, Borander A-K, Sikkeland LIB, Grahnstedt S, Johnsen A, Danielsen TE, Longva K, Kongerud J. Health effects after firing small arms comparing leaded and unleaded ammunition. Inhalation Toxicology. 2014;26(14):873–879. doi:10.3109/08958378.2014.970783
32. U.S. Census Bureau. Annual Survey of Manufactures: General Statistics: Statistics for Industry Groups and Industries: 2016 and 2015. Washington, DC: U.S. Census Bureau. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk#
33. Willmsen C, Kamb L, Mayo J. Loaded with lead: How gun ranges poison workers and shooters. The Seattle Times. 2014 Oct 17 [accessed 2019 Jul 31]. http://projects.seattletimes.com/2014/loaded-with-lead/1/
34. CNN. Trayvon Martin Shooting Fast Facts. CNN. 2019 Feb 28 [accessed 2019 Jul 31]. https://www.cnn.com/2013/06/05/us/trayvon-martin-shooting-fast-facts/index.html
35. Giffords Law Center. "Stand Your Ground" Laws. Giffords Law Center to Prevent Gun Violence. [accessed 2019 Jul 31]. https://lawcenter.giffords.org/gun-laws/policy-areas/guns-in-public/stand-your-ground-laws/
36. Giffords Law Center. Stand Your Ground. 2018. https://lawcenter.giffords.org/wp-content/uploads/2018/05/Stand-Your-Ground-Factsheet-Giffords-Law-Center.pdf
37. Fowler KA, Dahlberg LL, Haileyesus T, Annest JL. Firearm injuries in the United States. Preventive Medicine. 2015;79:5–14. doi:10.1016/j.ypmed.2015.06.002
38. Humphreys DK, Gasparrini A, Wiebe DJ. Evaluating the Impact of Florida's "Stand Your Ground" Self-defense Law on Homicide and Suicide by Firearm: An Interrupted Time Series Study. JAMA internal medicine. 2017;177(1):44–50. doi:10.1001/jamainternmed.2016.6811

39. Diaz T. Making a Killing. New York: The New Press; 1999.
40. Diaz T. The Last Gun: How Changes in the Gun Industry Are Killing Americans and What It Will Take to Stop It. New York, UNITED STATES: The New Press; 2013. http://ebookcentral.proquest.com/lib/drew-ebooks/detail.action?docID=1023025
41. US EPA O. TRI Around the World. US EPA. 2013 Mar 3 [accessed 2019 Jul 31]. https://www.epa.gov/toxics-release-inventory-tri-program/tri-around-world
42. Mosendz P, Barrett P, Rojanasakul M. How Foreign Guns Invaded the U.S. 2018 [accessed 2019 May 15]. https://www.bloomberg.com/graphics/2018-us-gun-imports/

Supplementary Table 1. Summary of Data and Methods for Life Cycle Assessment Subtopics

Area	Data	Methods
Upstream		
Environmental Health: Firearms and Ammunition Manufacturing	Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Environmental Protection Agency (EPA): ECHO: data set on compliance (CAA, CWA, RCRA) Toxic Release Inventory (TRI) Risk Screening Environmental Indicators (RSEI)	Statistical Summaries and Comparisons Geocoding Geographical analysis and visualization using ArcGIS Online and ArcGIS Pro
Occupational Health: Firearms Manufacturing and Recreational Shooting Ranges	Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Occupational Safety and Health Association (OSHA) Shooting Ranges, NSSF *Seattle Times*	Statistical Summaries and Comparisons Geocoding Geographical analysis and visualization using CARTO
Downstream		
Injury Prevention & Control: Firearms as injury mechanism: total deaths, homicides and suicides, by state (2013-2017)	Centers for Disease Control (CDC) Detailed Mortality Records: WONDER State Firearm Laws compiled by Boston University School of Public Health	Statistical Summaries and Comparisons Bivariate Regression and Correlation Analysis Visualization using Google Sheets
Stand Your Ground Policy: Firearms as injury mechanism: homicides	Centers for Disease Control (CDC) Detailed Mortality Records: WONDER RAND State Firearms Database	Statistical Summaries and Comparisons Visualization using Google Sheets and ArcGIS Pro