Lead distribution on a public shotgun range

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Abstract A detailed study has been made of the distribution of lead on a public shotgun range in the George Washington – Jefferson National Forests in southwestern Virginia. Sampling of more than 100 sites has yielded data on the distribution pattern of the lead shot. Since opening in 1993 through 2000, 11.1 metric tons (t) of lead have been accumulated over an area 220×300 m (66,000 m^2) with an average rate of accumulation of 1.4 t/year. More than 85% of the total dispersed lead lies scattered in the forest that surrounds the approximately 60×60-m cleared shooting surface. Lead is irregularly distributed because of the use of stationary targets and the general trajectory of launched clay targets. Maximum concentrations occur at distances of ~28, ~80, and ~180 m, and reach a maximum value of more than 5,000 g/m^2. Significant amounts of fine particulate lead, generated during shooting and as a result of impact occur close to the shooting box, but are absent at distances beyond 50 m.

Keywords Lead · Shooting range · Shot · Shotgun

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Introduction

Recreational shooting is becoming increasingly popular with the American public and there is a growing need for facilities to accommodate this activity. Local, state, and federal organizations and agencies continue to develop shooting facilities, sometimes in isolated forest areas so that the discharge of weapons can be carried out safely. Shooting ranges vary from sites that are rigidly structured with high backstops to simple open clearings with or without a constructed backstop. Some are completely supervised whereas others are unsupervised and self-policed. In most cases, the sites are chosen and oriented such that they offer little or no direct threat to human habitation or normal activities. In large forested areas open to the public, such as the National Forests in Virginia, the establishment of formal shooting ranges has greatly decreased the incidence of random shooting in the forest and along roads. As a result, the safety of all of the recreating public on the forest is improved, and the potential for shot impacting on neighboring lands is reduced.

At the same time that formal ranges provide a clear benefit to the public, there is a growing concern among the public about the dispersal and fate of heavy metals such as lead in the environment. It is clear that the establishment of formal shooting ranges results in the accumulation of significant amounts of lead and other metals used in the manufacture of bullets and shot. The effects of lead on waterfowl in fluvial, lacustrine, and marine environments are well documented (Feierabend 1983; Sanderson and Bellrose 1986; Pain 1990), but much less attention has been given to the ecological and environmental effects of lead on birds and other organisms in upland environments (Kendall and others 1996).

This study was initiated as part of Forest Service monitoring of an active shooting range that is operated in the George Washington and Jefferson National Forests of the USDA Forest Service. It is about 5 km west of Blacksburg, Montgomery County, in southwestern Virginia (37°18′N; 80°26′30″W; Fig. 1). The range contains two shooting areas (Fig. 2), a rifle range and a shotgun range, and lies on the southeast flank of Sinking Creek Mountain approximately 0.4 km north of Route 460. The shooting range lies at an elevation of about 685 m in a second growth mixed hardwood forest on the Devonian Brallier Formation, which is composed primarily of a deeply weathered black shale. The ridge top is composed of Silurian sandstone, the

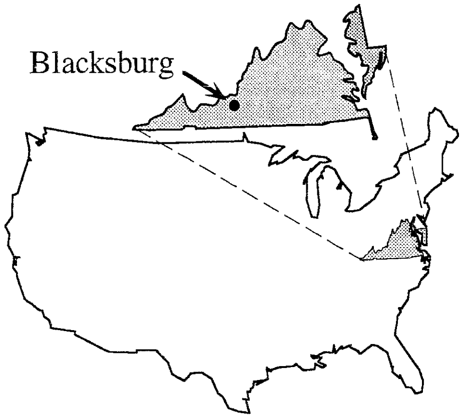

Fig. 1
General location map of the shooting range, which is located in the George Washington and Jefferson National Forests in Montgomery County in southwestern Virginia, approximately 5 km west of Blacksburg

Fig. 3
Recreational shooters are shooting out across the shotgun range from the shooting box. The closest trees at the back margin of the cleared area are 60–65 m from the shooting box and the width of the cleared area is approximately 60 m

Fig. 2
Oblique aerial photograph of the Blacksburg shooting range showing the rifle range (*elongate area in the foreground*) and shotgun range (*more equant area behind the rifle range*). The photograph was taken in January 2001, and the small white zones are residual snow accumulations. Photograph by J.R. Craig

float from which is scattered across the forested mountainside. The rifle range was cut into the slope such that there is a 4–5-m-high backstop behind the 100-m-long shooting lanes. The shotgun range occupies a cleared 60 m long by 60 m wide slightly sloping surface now covered with grass (Fig. 3). The shooting ranges are completely surrounded by second growth forest, last cut over in the 1930s, dominated by red and white oaks that are up to 31 cm in diameter and contain as many as 60 growth rings; some pine up to 33 cm in diameter contain up to 90 growth rings. The shooting range was established in 1993, has been in continuous use since that time, and appears to be receiving increasing amounts of use. Actual attendance data and the numbers of rounds fired are not known with accuracy, but the US Department of Agriculture (USDA) Forest Service made a rough estimate of 1 million rounds per year for both the rifle and shotgun areas (W. Compton 1993, personal communication). Limited range attendance data taken from a vehicle counter on the entrance road are: 1998 – 17,620; 1999 – 13,071; 2000 – 18,258; 2001 through 5 March – 7,052 vehicles. The counter has not been operative at all times, so these are conservative figures. Assuming estimates of 1.3 occupants per vehicle and the discharge of 50 rounds by each occupant on each visit, the numbers of rounds fired per year would be 1997 – 1.15 million rounds; 1999 – 0.85 million rounds; 2000 – 1.19 million rounds. These data all support the estimate of at least 1 million rounds being fired per year. Observations by the authors suggest that 90% of the total range usage is on the rifle range.

The Blacksburg range offers an excellent site for the study of metal distribution and accumulation because it is well defined geographically, has no encroachment by other metal-distributing activities, has remained in continuous operation, and is expected to remain open for the foreseeable future. The range appears to be typical in terms of simple construction and typical in terms of clientele served (target shooters, sports shooters, and hunters). The attendance is probably somewhat higher than that of many of the more remote shooting ranges in the National Forest, but is probably less than on ranges near greater population centers. It is important to note that this is an unsupervised range, so there are a wide variety of shooting activities and a very wide variety of firearms used at the site. Hence, samples from nearly any part of the range areas can contain bullets and shot of many types because shooters use munitions designed for target shooting as well as those designed for hunting. The discussions in this paper will refer to lead because it is the overwhelmingly dominant (probably 97% or more) metal present on the range. Other metals present are as jackets and firing caps (copper), pellets (steel), hardening agents (arsenic and antimony), casings (brass, aluminum, steel), and targets (all types of metals), but all of these together are estimated to total no more than 2 or 3% of the total metal present. The USDA does carry out periodic range cleaning, which clears the heaviest of the target debris on the shotgun range and many of the casings from the shooting box areas; little or none of the bullets and shot have been removed by cleaning. The authors believe that this range has similar characteristics with many outside ranges in the United States and, therefore, can serve as a representative model from which many useful conclusions may be drawn.

Shotgun range usage

The Blacksburg shooting range is generally open for public usage from dawn to dusk more than 350 days each year; it is closed periodically for maintenance and general cleaning. Although the two shooting areas are designated as a rifle range and a shotgun range, the ranges are not continuously supervised and there is some cross over of range usage as evidenced by the presence of bullets on shotgun range and shotgun casings on the rifle range. Most shooting on the shotgun range is conducted with 12-gauge shotguns using number 6 to 8 shot as evidenced by the discarded shells, boxes, and recovered pellets. There is also limited usage of 10-, 20-, and 410-gauge shotguns. The shotgun range has a centrally located shooting box that apparently is used by most shooters. A clay target launching site is located approximately 7 m to the right of the shooting box. Shooters may use mechanical launching devices or may have colleagues hand-throw the clay targets. No firm data exist on the numbers of shells discharged by individual shooters, but random observations of, and discussions with, typical shooters indicate that trips to the shooting range usually result in the discharge of a minimum of 30 shells and probably an average of 50 shells. Assuming that the average 12-gauge shotgun shells contains 30–45 g of lead, the typical shooter would discharge 1,500–2,250 g of lead shot per trip to the range. In general, bullets constitute only a few percent of the total lead recovered from any sampling site on the shotgun range. However, along the center line where targets are placed, bullets are more abundant. The greatest concentration of bullets was observed at a distance of 28 m on the center line where they constituted 874 g (or 17%) of the total 5,048 g Pb/m^2.

Scope of the present study

This paper presents data and discusses the lead distribution and loading on the area impacted by shooting activities on the shotgun range. This range (Fig. 3) consists of an open gently sloping surface, approximately 62 m in length by about 65 m in width, which was cleared in the forest. It is bounded on all sides by mixed hardwood second growth forest dominated by oak trees. The surface slopes slightly from left to right (from the shooters perspective) and rises away from the shooter at about a 5–6% slope. The ultimate area of study for which data are reported is approximately 220 m across by approximately 300 m in length. The study area as shown on the diagrams in this article is bounded by the shooting box (set as the 0 coordinate) and extends 100 m to the left of the shooter and 120 m to the right of the shooter. This slight asymmetry results from the positioning of the rifle range, which lies at about 100 m to the left of the shooting box. Hence, any measurements farther to the left than 100 m would be influenced more by the rifle range than by the shotgun range. The right side limit of 120 m and the maximum range limit were determined by the concentrations of shot recovered.

This study is part of a larger project examining the entire shooting range (rifle range and shotgun range) to determine (1) the area of impact of the shot, (2) the nature and uniformity (or lack thereof) of the lead distribution, (3) the loading (concentration) of the lead on the range, (4) the impacts of shooting on the vegetation immediately adjacent to the range surface, (5) any evidence of lead transport from the range or surrounding surfaces, (6) the nature of the corrosion phases on the lead, and (7) whether lead is present in ground and surface waters. A study of lead in surface water has been published (Craig and others 1999) and preliminary results on the corrosion of the lead shot have been presented (Rimstidt and Craig 2000).

Approach and methods

Sampling methods and patterns

Two of the major objectives of this study of the shotgun range were to determine (1) the area impacted by lead shot, and (2) the uniformity (or lack of uniformity) of lead distribution. The first estimate at the Blacksburg shotgun range was that much of the shot would occur on the approximately 60×60-m surface that had been cleared in front of the shooting box. Accordingly, the initial sampling was carried out at 5-m intervals along a line extending directly outward from the center of the shooting box towards the center of the far edge of the cleared area. Progression of sampling to the outer limit of the cleared area indicated that much shot must have carried beyond that area; hence, sampling was carried out at 10- or 20-m intervals to a distance of 320 m from the shooting box. It was apparent from the outset that shooting distributes shot in arc-like patterns because much of the shooting is at targets that have been launched or thrown (generally right to left) at varying heights. Observation of shooters revealed that shots ranged over a wide angle and at highly variable trajectories that would carry shot from far to the right of the open area, across the center, and far to the left of the open area. Accordingly, sampling was also carried out on a series of traverses at right angles to the center line. Most intensively, samples were taken along traverses at 50, 100, 150, and 200 m out from the shooting box. The full sampling included more than 100 sites as indicated on Fig. 4 and are given in Table 1.

Sampling was conducted as much as 100 m to the left of the center line and as much as 120 m to the right. Beyond 100 m to the left lies the rifle shooting area of the Blacksburg shooting range and this area contains considerable amounts of lead from the rifle shooting activities. The lead concentrations from the shotgun range activities have dropped to 20–25 g/m^2 at 100 m to the left; thus the impact of the shotgun range activity becomes small

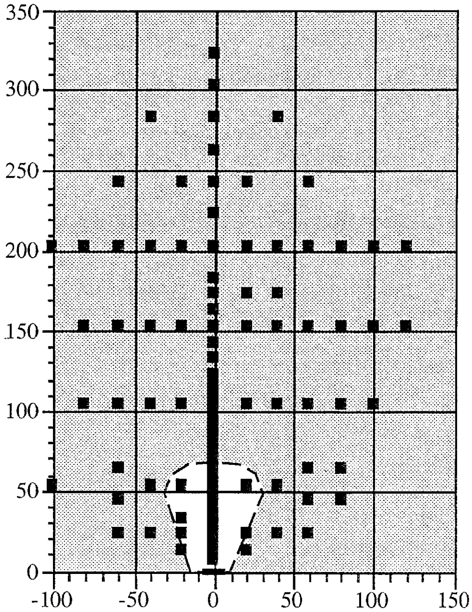

Fig. 4
Distribution of sample sites (marked by *squares*) used in the present study. The location of the shooting box is marked by the *heavy line at the bottom* and the margin of the cleared area is marked by the *dashed line*. A total of more than 100 sample sites were used in the model calculations presented in this paper

beyond that distance. Sampling was conducted farther to the right side of the range because there was no influence from a rifle shooting area that would contaminate the data and because there appears to be a slight right-hand bias to the shot distribution. That is, there are higher lead values at 80 and 100 m to the right than to the left; this probably results from some bias to shoot at aerial targets, launched from the right-hand side, before they reach the center of the range.

Initially the authors did not know the depth to which shot might have penetrated or been worked by subsequent activity. After testing several areas of various dimensions, it was found that sampling of areas 50×50 cm provided a significant areal coverage and when sampled to depths of 3 to 10 cm, provided 1–8 kg of total sample (soil, spent shot, pieces of clay targets, shot cups, various target materials, and wood or grass fragments). Thus, 50×50-cm^2 areas (Fig. 5) were located and sampled to a depth where it became apparent that there had not been deeper penetration by the shot and that there had not been reworking of material on the surface. Usually this occurred at the base of the A-soil zone, which was relatively darker and organic-rich; the underlying lead-free soil was a yellow-orange clay-rich zone. All material within the 50×50 cm^2 was extracted and sieved through a 6-mm metal sieve. Clods of soil and masses of root or organic material were disaggregated and worked until it was clear that there could not be shot left adhering to them. The coarser material primarily included shards of clay targets, pebbles, leaves, roots, shotgun shells and cups, and miscellaneous target materials (boxes, milk jugs, glass bottles, electronic devices, etc.; Fig. 6).

The progression of sampling revealed that most of the lead shot are dispersed in the surrounding forest; hence, most samples were taken from that area where the soil is cov-

Table 1
Lead concentration data from Blacksburg shotgun range. Samples were taken on 0.25-m^2 areas and then multiplied by four to give the data here, which represent concentrations per square meter. The data cover an area as shown in Fig. 3 and are assigned the same *x* and *y* coordinates as are shown on that figure. Data are rounded to the nearest full gram

x	*y*	Pb, g	*x*	*y*	Pb, g	*x*	*y*	Pb, g	*x*	*y*	Pb, g
–100	50	20	0	4	191	0	95	861	20	240	60
–100	200	35	0	5	216	0	100	778	40	20	18
–80	100	14	0	8	195	0	105	616	40	50	298
–80	150	50	0	10	552	0	110	585	40	100	113
–80	200	64	0	12	852	0	115	674	40	150	290
–60	20	4	0	15	1,973	0	120	527	40	170	428
–60	40	19	0	16	1,122	0	130	371	40	200	153
–60	60	29	0	20	1,425	0	140	413	40	280	4
–60	100	74	0	25	2,642	0	150	337	60	20	9
–60	150	72	0	28	5,048	0	160	243	60	40	42
–60	200	103	0	30	2,600	0	170	390	60	60	96
–60	240	25	0	32	2,072	0	180	766	60	100	66
–40	20	16	0	35	1,669	0	200	624	60	150	109
–40	50	124	0	36	2,416	0	220	223	60	200	208
–40	100	313	0	40	1,047	0	240	89	60	240	57
–40	150	206	0	44	629	0	260	30	80	40	12
–40	200	248	0	45	824	0	280	12	80	60	38
–40	280	1	0	50	1,526	0	300	1	80	100	32
–20	10	17	0	55	1,336	0	320	1	80	150	172
–20	20	75	0	60	1,752	20	10	18	80	200	236
–20	30	392	0	65	1,188	20	20	62	100	100	5
–20	50	517	0	70	1,478	20	50	952	100	150	164
–20	100	660	0	75	1,650	20	100	886	100	200	101
–20	150	292	0	80	3,065	20	150	361	120	150	70
–20	200	236	0	85	1,673	20	170	525	120	200	78
–20	240	49	0	90	2,618	20	200	283			

Fig. 5
Typical 50×50-cm sampling sites on the cleared range. The surface materials were removed and all shot and/or bullets recovered. Sampling was carried out to a depth to where no additional shot was found and to where there was no evidence of disturbance. The sampling depth thus varied from as little as 3 cm on parts of the cleared area to as much as 10 cm in portions of the forest where shot and leaves continually accumulate

Fig. 6
An example of the variety and density of debris that accumulates on the range as a result of normal recreational shooting. Sampling of areas at approximately 35 m out from the shooting box have yielded as much as 25 kg of debris per m^2 (not including lead shot). The most abundant materials are broken clay targets, shotgun shells, packing for pellets, and miscellaneous target materials (glass, plastics, wood, etc.)

ered by 5- to 10-cm-thick mass of flattened, overlapping, and decomposing leaves with penetrating roots (commonly referred to as "duff"). Recently fired shotgun shot pellets could be seen lying on or between the most recently fallen leaves whereas older shot were found dispersed throughout the mulch- to peat-like mass. These samples were carefully extracted so that pellets did not drop out before being collected and were then thoroughly disaggregated to release the shot. The investigators attempted to take samples that were unbiased, but did recognize that large trees clearly act as backstops and it is common to observe high concentrations of lead shot directly in front of the large tree trunks; many shot bounce off or just drop and accumulate in front of the trees. Conversely, behind the large trees, there were shadow zones where there were few or no shot because they were shielded by the tree trunk. Accordingly, samples were not taken directly in front of, or directly behind large trees because of the bias resulting from the backstop or shielding effects. Where such sites fell in the sampling patterns, the sample site was adjusted approximately one-quarter of a meter, left or right or front or back. This avoided the bias, but kept the sample in the same square meter area being represented. During sample processing, all material retained on the top of the sieve was examined before being discarded and all bullets and casings were extracted and retained to be added to the shot. Numerous samples also contained bullets of a variety of caliber; these were added to the recovered shot as they represent metals contributed to the range by the recreational shooting activities. The material that passed through the 0.25-inch sieve were collected in plastic bags, labeled, and returned to the laboratory for processing.

The disaggregated samples were dumped into 20-l plastic buckets. The buckets were filled with tap water and the mass of the material was stirred and agitated until the heavier fractions (the lead and related metals) had settled to the bottom. The floating organic material and much suspended fine clay and target waste were decanted off several times. Samples were then transferred to a 36-cm Garrett Gravity Trap gold pan, which was used to separate the lead and related metals from the much lower-density soil, sand, target fragments, and glass particles. When properly used, the gold pan is extremely efficient in separating the heavier from the lighter materials and it is relatively easy to monitor the presence and movement of lead shot or fragments in the pan. The lead shot, bullets, and shot and bullet fragments were separated and dried (Fig. 7). Once dried, the recovered metal materials were examined under a binocular microscope and all remaining extraneous materials were removed; the samples were then weighed on a top-loading balance with an accuracy of ~0.1 g. The separation procedure was tested for reliability by adding 100 g of typical lead shot to a lead-free mass of soil and organic matter, which weighed several kilograms and was typical of the organic debris in the forest. This test sample was processed in the same manner as the regular samples; the result was recovery of 99.5 g of lead shot. It is recognized that some material could be lost during the recovery efforts at any site; however, the test indicated a very high rate of recovery – one that the principal investigators believe is typical. Nevertheless, it is proper to note that the potential for small losses means that the results given below are conservative; there was no opportunity for the introduction of lead into samples, but there was the possibility of small losses. Shot samples recovered from most of the range surface and the surrounding forest area consisted of intact shotgun pellets that appear to have fallen undamaged to the ground after travelling on a normal arc from the shooting box outward. However,

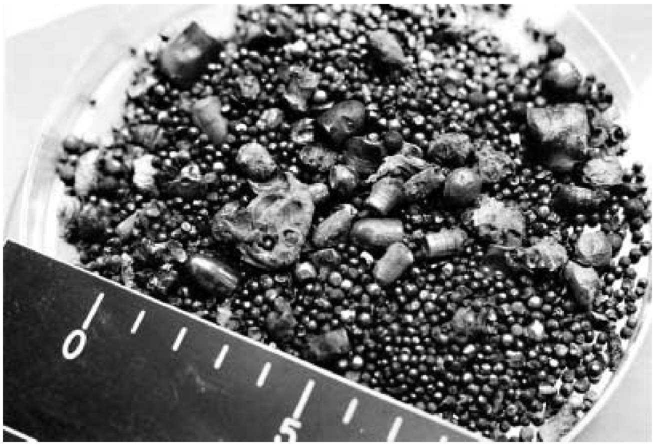

Fig. 7
An example of the typical materials recovered during the processing of samples in the present study. The majority of the lead and related metals occurs as lead shot of many different sizes, but significant amounts of metal may also occur as bullets and buckshot at some areas on the range surface. This sample was taken at 28 m out from the shooting box along the center line and contains several bullets apparently used for target practice

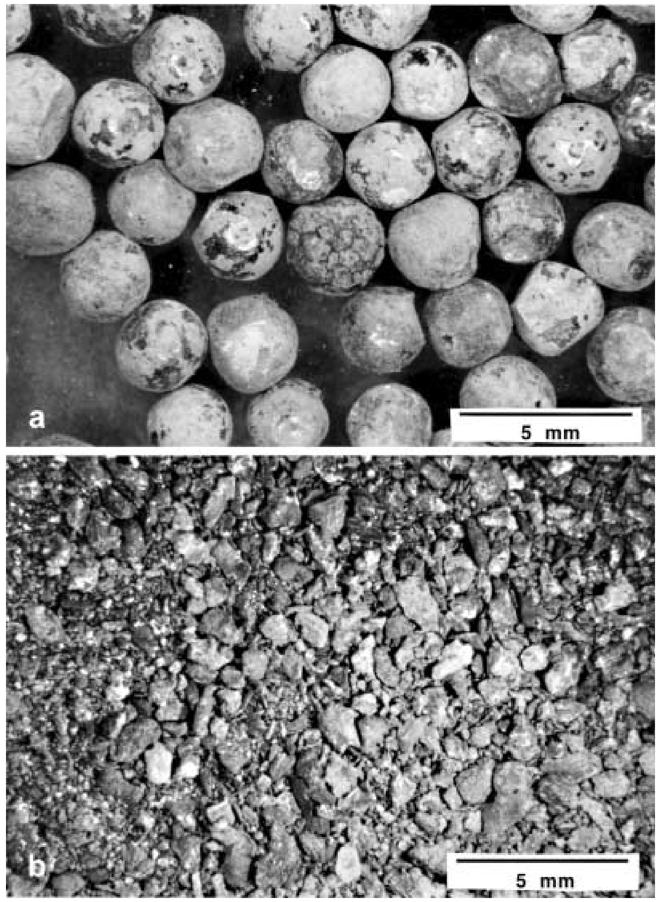

Fig. 8
a Shot recovered from a sample site at 180 m are typical of samples found on most of the impacted area. **b** Much finer material (photographed at the same scale) occurs near the shooting box along with typical shot (sample from 8 m). The finer irregular fragments are released upon firing, but do not travel very far because of their smaller mass and irregular shapes and hence accumulate close to the shooting box. All these materials passed through a 1-mm sieve, but particles range downward in size to 0.01 mm or smaller. The photographs were shot at the same camera settings and the *scale bar* is 5 mm in length

careful examination of samples taken close to the shooting box revealed that they contained significant amounts of finer and very irregular fragments of lead (and minor amounts of brass or other metals) as shown in Fig. 8. These fragments are apparently generated by the abrasion of the shot against one another, or against the choke at the mouth of the gun barrel as they exit the shotgun barrel. Because they do not possess so much mass as the larger pellets and are not very aerodynamic, they do not travel very far before falling to the ground. The particles range in size from 1 mm downwards to 0.01 mm or less. This fine size makes their recovery more difficult and required very careful panning (and in some cases, re-panning of the finest debris) to effect their recovery. No doubt, some of the finest material was lost, but the high specific gravity of the lead and other metals still allows for very high recovery rates. The presence of these particles is potentially very important as discussed below.

Statistical methods

The evolving sampling procedure resulted in non-uniform sampling of the shotgun range. In particular, it resulted in much more intense sampling along the center axis of the range (x=100 in Table 1) than on other parts of the affected area. Consequently, it was not appropriate to weight all samples equally and simply average the data from all sites. The higher lead concentrations along the center axis would have biased the total and would have given a gross over estimate of the lead. For example, the average lead concentration of all samples was 572 g/m^2; extrapolation onto the entire 220 by 300 m area would have yielded an estimate of 37.7 metric tons (t). Any similar statistical analysis based on simple summary statistics such as sample means will fail to produce a good match between the predicted lead profile (Fig. 9) and actual measurements because it does not take into account the spatial autocorrelation in lead distribution. In other words, having found high (or low) amounts of lead at a given site, it is reasonable to expect high (or low) concentrations in nearby sites.

To obtain a profile of the actual (not average) amount of lead on the range that allows unbiased estimation in the presence of a systematic and non-representative sampling design, geostatistical principles were applied. In this case, universal kriging (Cressie 1993; Chilès and Delfiner 1999; Schabenberger and Pierce 2001) was used. This best linear unbiased prediction method combines information about the spatial autocorrelation with a mean trend across the shooting range to reconstruct the profile of lead shot concentrations. This analysis was performed on the log-transformed data for four reasons. The spatial autocorrelation structure for these data is more easily discernible on the logarithmic scale, back-transformed predictions of lead are guaranteed to be non-negative, the back-transformed values will not overestimate the actual amount,

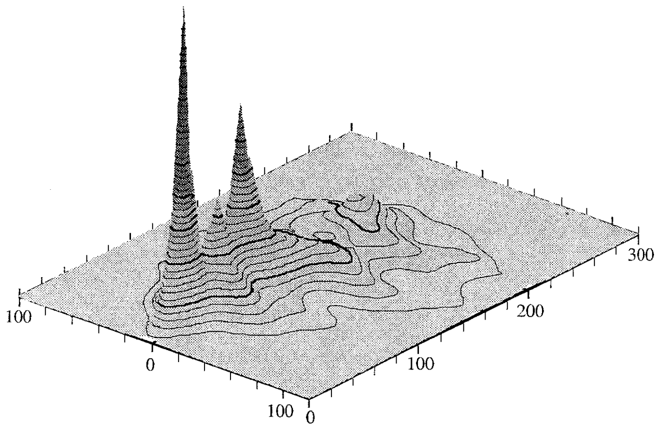

Fig. 9
Three-dimensional surface prepared by using kriging to analyze the data set given in Table 1. The contours on the surface are at 100-g intervals. This clearly shows the presence of the two major anomalies at approximately 30 and 80 m and the minor anomaly at about 180 m. It also shows a slight right-hand bias to the lead distribution; that is, there is a slightly higher concentration of lead to the right of the center line than to the left. This bias probably results from the release of flying targets from the right-hand-side of the shooting box and a slight tendency to shoot before they have reached the center axis of the range

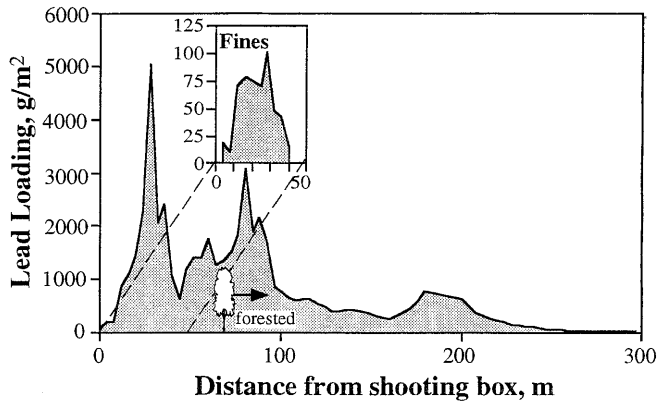

Fig. 10
A profile of the distribution of lead, in grams per square meter, along the center axis of the shotgun range from the shooting box to a distance of 320 m. This is a profile along the x=0 line in Fig. 9. It is apparent that there are two major maxima at ~30 and at ~80 m, and a smaller maximum at ~180 m. See discussion in text. The *insert* shows the concentration of fine lead particles (<0.1 mm and ash shown in Fig. 8b) along the center axis of the shotgun range. These particles have much larger surface areas per gram of lead and thus have much greater potential for surface reaction or dissolution than do the normal shotgun pellets

and the average lead amount can be modeled as a standard response surface on that scale. The result of the universal kriging takes into account the higher concentration along the center axis (Fig. 10) and permits development of a three-dimensional surface as shown in Fig. 9. This accurately shows the areas of maximum concentration and the much lower concentrations over most of the area and yields an estimate of 11.1 t of lead for the entire area affected.

Results and discussion

Lead densities

In more than 100 samples taken on and around the shotgun shooting range, the amounts of dispersed shotgun pellets and bullets ranged from zero to more than 5,000 g/m^2. Lead shot constituted more than 95% of all of the metal recovered in most samples except those taken at the sites where ad hoc stationary targets were set. Actually, the only sample ever taken that had no pellets was a sample taken 20 m behind and 20 m to the right of the shooting box. Every other sample (including one 20 m behind and 20 m to the left of the shooting box) had at least one pellet present. The greatest densities of lead shot lay along the center axis (the profile shown in Fig. 10 and the line where x=0 in Fig. 9), where the lead loading rises to more than 5,000 g/m^2 at a distance of 28 m. The lead concentration then drops to about 1,100 g/m^2 at a distance of 40–65 m and then rises to more than 3,000 g/m^2 at a distance of ~80 m. Beyond that maximum, the concentration of lead drops to a value of less than 400 g/m^2 at 130 m before rising to a third maximum of more than 750 g/m^2 at about 180 m.

To relate the lead concentrations to the numbers of shotgun pellets that occur in various areas, representative samples of the lead shot were examined and it was found that there were approximately 12.5 shot pellets per g. Thus, concentrations of 100 g/m^2 are equivalent to approximately 1,250 shotgun pellets per m^2. Given that typical 12 gauge shotgun shells contain 30–45 g of shot, the 100 g/m^2 areas are equivalent to about three shotgun shell loads per square meter. The most lead-rich sample (at 28 m along the center line) contained 4174 g of shot per m^2 (and 874 g of bullets). The 4,174 g of shot per m^2 are equivalent to approximately 115 shotgun shell loads per m^2. Assuming that 95% of the 11.1 t of total lead on the shotgun range is present as shot, there are approximately 132,000,000 individual pellets dispersed over the affected area. This is roughly equivalent to approximately 285,000 shotgun shells discharged there since the range opened in 1993.

Shot distribution

The primary objective of the study was to determine the distribution of the lead and related metals that have accumulated on the shooting range since it was opened in 1993. This information would provide a real measure of the total area of impact from activities on the shooting range, provide an estimate of the total amount of lead dispersed at the range, reveal areas of anomalous accumulation of lead, and provide background information that might prove valuable in the planning of other similar shooting ranges. The recovery and analysis of lead and related metals from more than 100 samples distributed across the shotgun shooting area of the Blacksburg shooting range revealed that the lead is not distributed in a regular pattern, but rather that there are distinct areas of high concentration. The scope of these anomalies is evident in a perusal of the data set in Table 1; Fig. 10 shows a profile outward along the center axis of the range, and Fig. 9 shows a three-dimensional model of the lead distribution.

Universal kriging predictions of the shot distribution profile based on a second-order response model for the average lead amount and a spherical autocorrelation model without nugget effect are shown in Fig. 9 after back-transformation onto the original scale. The total amount of lead under this profile gives an estimate of the total lead amount on the range, which equals 11.1 t or an average of 168 g of lead per square meter.

At the outset of the study, the investigators did not know the distance to which shot would be distributed into the forest beyond or beside the approximately 60×60-m cleared area. No data existed on the types of shot being used, the trajectories of the shooting, or the degree to which the forest trees (up to 12–15 m in height) might effectively reduce the travel distance of the shot. During the study, it was found that the National Shooting Sports Foundation (1997) had presented some diagrams of idealized shot distribution for skeet ranges where shooting was carried out under supervised conditions using approved shot and targets. Their diagrams indicated flight trajectories of up to ~225 m. Hence, the investigators anticipated that some samples of lead shot might be found 150 m or so beyond the cleared area. The Blacksburg shot gun range is, of course, significantly different than the NSSF ranges because of unsupervised general use of many types of weapons and detailed study revealed that more than 100 g Pb/m^2 existed in samples at distances of 260 and 280 m out from the shooting box. The farthest sample taken, 320 m from the shooting box along the center line, still contained two lead pellets (0.8 g/m^2). Thus, it was apparent that the area affected by the shotgun pellets extended outward as much as 300 m and laterally from –100 m on the left to +120 m on the right side. This is equivalent to 66,000 m^2.

The distribution of the lead shot on the shotgun range reflects the patterns of firearm use on the range. Hence, it is clear that the two principal anomalies result from two different shooting modes. The close anomaly at 25 to 30 m results from users mounting targets at this distance as shown in Fig. 11. The investigators have observed numerous range users firing at targets that have been set in the center of the cleared area at 25–30 m. Figure 11 shows targets set against a small log and the pattern of cleared vegetation resulting from shooting along the center line is clearly evident. Common targets include clay targets, golf balls, plastic milk jugs, glass bottles, small cardboard boxes, fruits, and vegetables. The investigators have also observed shooting at sofas. Numerous small pieces of wire and resisters, and even a small piece of a gold contact, apparently derived from electronic devices such as digital phones have been recovered (Fig. 12a). The investigators have been told of shooters using computers as targets; although the reports are anecdotal, confirmation appears to exist in the discovery of numerous damaged computer keyboard keys (Fig. 12b). The placement of the targets at

Fig. 11
Targets are commonly placed at 25–30 m, especially in the center of the cleared surface area, as shown in this photograph. The targets are most commonly clay pigeons, golf balls, bottles, boxes, and assorted fruit, but may range widely as shown in Fig. 12

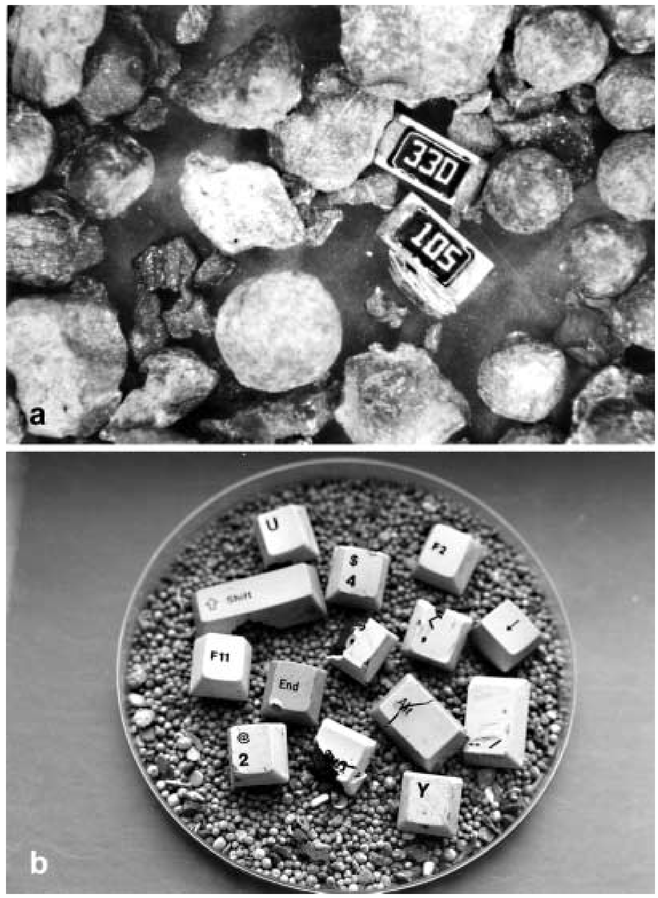

Fig. 12a,b
At approximately 30 m, the targets used vary widely in nature and the firearms employed range from shotguns to pistols and rifles. **a** Parts of small electronic devices intermixed with the shot evidence that shooters employ a wide variety of targets including cellular phones and computers. **b** The presence of numerous damaged computer keyboard keys appears to verify reports of computers being used as targets

25–30 m results in the accumulation of large amounts of lead at this distance, especially because there is a slight rise in the range surface at this distance that would tend to retain much of the shot. Samples taken from 20 to 40 m, and especially at 25–30 m, commonly contain rifle and pistol bullets as well as shot (Fig. 12c); this indicates that some shooters use the shotgun range for target practice with other types of firearms. The peak of lead concentration is quite narrow because targets are generally set in or very close to the center of the range. The breadth results from some spacing of targets, ricochet, and use of shotguns that spread the shot over some width. The total amount of lead dispersed on the cleared area of the shooting range (approximately 3,600 m^2) is estimated to be 1.72 t, which is equivalent to approximately 15.5% of the total lead dispersed at the shotgun range.

The high lead concentration at ~80 m apparently results from the accumulation of lead fired at elevated trajectories in attempts to hit clay targets that have been launched or thrown. Because the launching pad is approximately 7 m to the right of the shooting box, most pigeons are moving from right to left in front of the shooter. They are, however, moving in a very wide range of trajectories – from nearly straight up over the shooter to very low across in front of the shooter. Even when shooters are successful in hitting the flying targets, most of the shot do not strike the target, but rather travel well beyond it. The 80-m anomaly is wider than the closer one because of the spread of the shot at a greater distance and because shooters are tracking a moving target across the range as they are firing. The peak at approximately 80 m apparently results from the combined effect of the normal low trajectory of much of the shot and from the slowing of some of the shot by leaves and branches of trees at the edge of the cleared area. There is a slight right-hand bias to the peak of concentration, probably resulting from the tendency of the shooters to fire early in the flight of the flying targets.

The cause of the third, and much smaller anomaly, at approximately 180 m out from the shooting box is not so clear as the two nearer and larger anomalies. The tree trunks precluded any of the shot in a low trajectory from reaching the site, so it must result from a higher trajectory that arcs up over the first line of trees and falls at that distance. There is no clear explanation why there is a minimum between the second large anomaly at about 80 m and the third anomaly, but the data clearly define these features.

Shot sizes and distribution of fine lead particles

Throughout most of the cleared surface and surrounding forested area, more than 90% of the shot is number 6 to 8 pellets; this is consistent with information on the large number of discarded shot boxes and shot gun casings. These pellets are generally 2–3 mm in diameter, as shown in Fig. 8a. Occasionally there are smaller birdshot and larger 4–5-mm buckshot. More than 95% of the pellets appear as standard lead pellets; only about 5% are copper jacketed shot and the number or steel shot is trivially small. Sectioning and examining many shot reveals that at least some contain hardening agents such as copper, arsenic, and antimony; data in hand are insufficient to determine the quantities of those metals presently on the range.

Careful examination of the shot recovered from the range surface near the shooting box revealed that those samples contained significant quantities of fine particulate lead as shown in Fig. 8b. These samples were carefully panned to insure a high recovery of these fine materials. The "fine" materials shown in Fig. 8b have passed through a 1-mm sieve and range in size down to less than 0.01 mm. They are apparently formed either as the result of lead shot colliding with other as they exited the gun, or as the result of abrasion on the choke of the guns as they were fired. A series of samples were taken at 4-m intervals along the center axis (Fig. 9) to specifically determine the quantity of the fine lead particles. These data are shown in the insert in Fig. 10 and reveal that the amount of fine particulate lead rises until about 30 m and then declines rapidly. The importance of these particles is that they have a much larger surface area per gram of lead than do the complete lead shot and, hence, could leach more lead per gram than intact shot. An additional consideration is that some recovery methods that sieve shot and bullets out of soils as a means of recovery or cleaning will probably not recover the fine particulate lead present near the shooting box.

Effects on the trees

The cleared surface of the shotgun range has been cut out of a 60-year-old second growth mixed hardwood forest (see Fig. 2) and is bounded by forest on all sides. The trees along the forest margin of the cleared area at approximately 65 m from the shooting box and along the sides of the cleared area range from 1 to 35 cm in diameter and are primarily oaks. There are, however, scattered pine, maple, gum, dogwood, and minor amounts of other hardwoods. When the trees are leafed out, it is apparent that some of the trees along the back margin of the open area are distressed as evidenced by fewer live branches and leaves than are present on the trees along the sides. Examination of the trees in the first 5 m beyond the back margin of the developed area reveals that much of the lead shot has sufficient velocity to penetrate the smooth bark of 1- to 10-cm diameter maples and to penetrate the somewhat cork-like bark of the pines. Leaves of trees and shrubs along the back margin have numerous holes from shotgun pellets. At distances of ≥70 m from the shooting box (that is more than about 5 m into the forest beyond the margin of the cleared area), there is no visible evidence of shotgun pellet damage to the hardwoods, although a few scattered trees have bullets stuck in them. Out to distances of more than 100 m from the shooting box, the softer cork-like bark of the pines does contain numerous embedded shotgun pellets (Fig. 13a). The number of pellets embedded and the small impressions left by shot that bounced off the pine trees declines with distance (Fig. 13b) until about 130 m, beyond which there is no longer any visible effect on the trees.

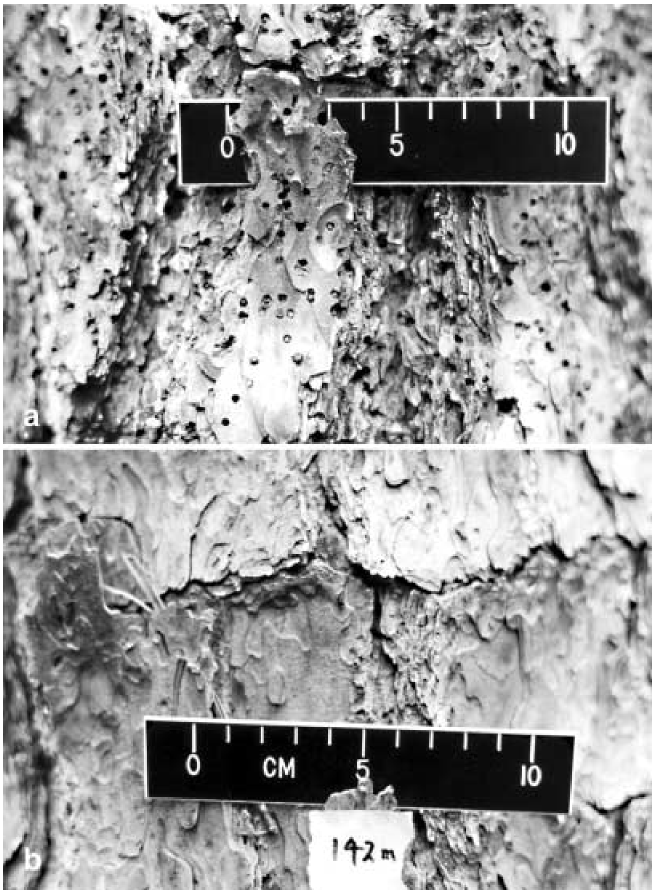

Fig. 13a,b
Trees in the forest beyond the cleared area of the shotgun range contain embedded shotgun pellets and small impressions from the pellets out to a distance of approximately 130 m from the shooting box. The intensity of the visible impacts declines with distance as evidenced by photographs of the bark of Virginia pines at **a** 91 m, and **b** 142 m

Summary and conclusions

The Blacksburg Shooting Range in the George Washington and Jefferson National Forests is a typical public recreational shooting area with a rifle range and a shotgun range. It has similar characteristics with many outdoor ranges in the United States. More than 100 separate 50×50cm sites have been sampled on the shotgun range area to determine the area impacted by lead shot dispersal, the patterns of lead dispersal, and quantity of lead present. Lead has been dispersed over an area approximately 220 m wide by 300 m in length. The total quantity of lead in the shotgun range area is estimated as 11.1 t. The highest concentrations of lead occur along the center axis of the range at a distances of approximately 30 and 80 m; a lesser concentration occurs along this axis at about 180 m. These concentrations result from shooting patterns at stationary targets and at air-borne targets.

The geostatistical analysis yielded an estimate of total lead on the range surface of 11.1 t, which is considerably less than a biased overestimate obtained from extrapolating the sample mean to the reference area of 220×300 m^2. This estimate is a conservative assessment for several reasons. Lead can only be lost from a sample during sampling, not added to it. Great care has been exercised in the collection and processing of the samples to minimize losses, but some small losses can not be ruled out. Shot lodged in the vegetation, such as pine bark, was not been collected and collection areas in front of tree trunks in the forested area were avoided. Shooting has continued since the sample collection and shot continues to accumulate on the range. Finally, the statistical analysis of the lead concentration on the logarithmic scale followed by back transformation (exponentiation) to the original scale is likely to yield slight underestimates of the actual amount. Only in certain special cases, such as normally distributed data, can precise bias corrections be applied. Because the log-lead concentrations were clearly non-normally distributed, these corrections were not applied here. Fortunately, (universal) kriging remains a best linear prediction method, even if the data are not normally distributed (Schabenberger and Pierce 2001).

The average rate of lead accumulation on the shot gun range is approximately 1.4 t/year based upon the total estimated lead and the time since the range was opened in 1993 through to the end of 2000. Periodic range cleaning by Forest Service personnel or volunteers removes much of the larger debris, such as targets and shells, but does not recover much if any of the dispersed shot. Accordingly, it is reasonable to extrapolate that lead will continue to build up on the range area at a rate of at least 1.4 t per year. More than 80% of the lead is dispersed in the forest beyond and adjacent to the ~60×60-m cleared range surface.

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