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**EFFECTS OF DEEP TILLAGE ON REDISTRIBUTION
OF LEAD SHOT AND CHUFA FLATSEDGE AT
CATAHOULA LAKE, LOUISIANA**

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Ingestion of lead shot by waterfowl has been documented throughout the U.S. and in several other countries and remains a problem in many

areas (Sanderson and Bellrose 1986, Pain 1992). Although lead shot is prohibited for waterfowl hunting in the U.S., shot can remain available to foraging birds for many years because of slow settling rates in some substrates (Wills and Glasgow 1964, Mudge 1984, Anderson 1986, Mauser et al. 1990, Pain 1991). Tillage has been

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recommended as a technique for reducing availability of lead shot to migratory birds (Fredrickson et al. 1977, Wooley 1981). Conventional tillage practices (primarily disking) are effective in reducing shot densities near the soil surface (Lewis and Legler 1968, Fredrickson et al. 1977, Esslinger and Klimstra 1983, Castrale 1989). In certain habitats, however, waterfowl forage on subterranean foods that are located well below the surface (Wetmore 1919, Chabreck et al. 1983), indicating that deeper burial of shot may be needed.

Catahoula Lake provides important winter and migration habitat for waterfowl in the Mississippi Flyway, with peak numbers exceeding 400,000 ducks in recent years (Woolington and Emfinger 1989). Lead poisoning of waterfowl has been a recurring problem at Catahoula Lake (Yancey 1953, Wills and Glasgow 1964, Smith 1981, Zwank et al. 1985, Hohman et al. 1990a, Peters 1992). The density of lead shot in sediments of Catahoula Lake is extremely high, exceeding most other major waterfowl staging areas in the U.S. (reviewed by Hohman et al. 1990a).

Chufa flatsedge (*Cyperus esculentus*) tubers are the primary food of waterfowl at Catahoula Lake (Wills 1971, Hohman et al. 1990b, Peters and Afton 1993). Any adverse effect of deep tillage on chufa tuber production could lower the value of the lake to waterfowl. Our objectives were to assess deep tillage as a technique to reduce availability of lead shot to foraging waterfowl, and examine the effects of tillage on chufa tuber biomass in 2 subsequent growing seasons.

STUDY AREA

Catahoula Lake is a 12,000-ha wetland basin located in the Mississippi River floodplain of central Louisiana (31°30'N, 92°08'W). Historically, the lake basin filled during late fall, and water levels generally remained high through June and then receded in July, exposing about 6,000 ha of mud flats by early August (Wills 1970). This cycle of drying and reflooding stimulated growth of moist-soil plants that attracted large concentrations of wintering waterfowl (Wills 1970). In the

1960's, a navigation project on the Red River necessitated construction of a diversion canal and water-control structure adjacent to the lake to prevent permanent flooding. However, water-control capabilities are limited, and abrupt increases in water level result from heavy rainfall or back-flooding from local rivers (Woolington and Emfinger 1989).

Catahoula Lake has been an intensively hunted waterfowl area since at least the turn of the century (Wills 1965). Wills and Glasgow (1964) estimated that the density of lead shot in Catahoula Lake sediments was 74,000 shot/ha in 1963. Subsequent studies in 1978 and 1987 (along the same transects used earlier) reported 189,000 and 226,000 shot/ha, respectively, with >84% of shot in the top 10 cm of the soil (J. W. Emfinger, La. Dep. Wildl. and Fish. [LDWF], Baton Rouge, unpubl. data). Use of lead shot has been prohibited on the entire lake since 1988.

Water levels presently are managed to provide habitat for wintering waterfowl, allow hunting opportunity, and reduce availability of lead shot to foraging waterfowl (Catahoula Lake Water Level Management Agreement, LDWF, Baton Rouge, unpubl. rep.). The lake is partially drained (~2,000 ha remain flooded) in summer to stimulate growth of waterfowl food plants. In fall, water levels are not intentionally raised until 10 days before the waterfowl hunting season (i.e., mid-late Nov) to prevent birds from feeding in areas with high shot densities. Water levels are raised after the hunting season (i.e., early Jan) to discourage dabbling ducks from feeding on the lake.

METHODS

We selected 2 areas (A and B) of the lake bed and randomly positioned 6 rectangular plots in each area. The 2 areas were 2.1 km apart and differed slightly in elevation and soil type (Peters 1992). All plots were located in plant communities consisting primarily of chufa and bearded sprangletop (*Leptochloa fascicularis*) with scattered patches of spikerush (*Eleocharis* sp.). Each plot consisted of 4 7- × 7-m experimental units (EU's), with adjacent EU's 10 m apart.

The density of spent lead shot in sediments of the lake was too low for a powerful statistical comparison in our experiment. Consequently, we seeded copper-coated lead shot (No. 4 shot) at equal densities in the EU's (18.1 kg/EU [1,763,265 shot/ha]) with a drop-type fertilizer spreader (Ortho model 3000). We used No. 4 shot (3.3 mm diam) because it was the most common shot size in lake sediments. We used copper-coated shot because it is rarely used by hunters there, and thus allowed easy differentiation between our seeded shot and other shot. Given mass differences between lead and nontoxic steel shot, we were concerned that there might be a difference between shot types in redistribution caused by tillage; thus, we used lead shot in our experiment.

Within each plot, treatments were assigned randomly to EU's. Treatments consisted of (1) tilling with a

vegetable plow (VP) (modified moldboard plow with 5 low moldboards and 5 elevated, surface-skimming moldboards [Wilcox Agri-Products, Walnut Grove, Calif., Model 5WB18VP]); (2) disking (\bar{x} depth = 10.5 cm, SE = 0.47, n = 12) followed by plowing with a vegetable plow (DVP); (3) tilling with a large 7-bottom moldboard plow (MP) (Wilcox Agri-Products Model 7WBD18); and (4) untilled control. A Case International 300 horsepower, 4-wheel-drive tractor (Model 4894) pulled the plows. Tillage treatments were applied from 29 October to 4 November 1989. On 5 November 1989, tillage depth was estimated at 2 locations in each tilled EU by placing a ruler in the bottom of the unfilled trench on 1 edge of the EU and measuring (± 1 cm) to the soil surface of adjacent untilled ground.

A 1-m-wide perimeter of each EU was not sampled because of the possibility of soil not seeded with shot being shifted by plows into perimeter areas. Sampling locations were randomly selected from a grid of 25 1- \times 1-m squares in the remaining 5- \times 5-m core area of each EU. Three separate core samples (6.7 cm diam) were taken from each of 4 sampling locations within each EU during each sampling period (i.e., pretreatment, 15–25 Oct 1989; posttreatments, 15–27 Oct 1990 and 15 Oct–13 Nov 1991). Pretreatment core samples were taken to a depth of 30 cm; posttreatment samples were taken to 40 cm because tillage depths were >30 cm in some treatments. Cores were divided into 10-cm strata, and the 3 samples from the same stratum within each sampling location were combined. Samples were sifted through 2.0-mm-mesh sieves to recover shot and chufa tubers. Chufa tubers were oven dried (63 C) to constant mass (± 0.01 g). Pretreatment sampling indicated that 95% of chufa tuber biomass was in the top 20 cm of soil; thus, posttreatment analysis was limited to tuber biomass from the top 20 cm.

We estimated variance components, within and among EU's, for numbers of shot and chufa tuber biomass in pretreatment samples (VARCOMP procedure, SAS Inst. Inc. 1987:967). Tillage depth was analyzed using analysis of variance (ANOVA procedure, SAS Inst. Inc. 1987:125). Numbers of shot (copper-coated only) from posttreatment samples were square-root transformed to stabilize variances. Most samples of chufa tuber biomass were <1 g; thus, 1 was added to each datum and then each was square-root transformed to stabilize variances. Transformed shot and chufa tuber data were analyzed using ANOVA (see Table 1 for description of models). Transformed means were compared using Fisher's least significant difference test (Milliken and Johnson 1984:300–304). Means and 95% confidence intervals were retransformed to their original units for presentation (Sokal and Rohlf 1969:381–382). Chufa tuber biomass also was converted to g/m².

RESULTS

Analysis of pretreatment samples indicated that variances in numbers of shot and tuber

biomass, within and among EU's, were not significantly different from zero ($P > 0.10$ for all tests), indicating that distributions of shot and tuber biomass were uniform.

Tillage Depth

The area-by-treatment interaction was significant (Table 1); treatments VP and DVP were deeper in area A than area B, but treatment MP was deeper in area B than area A (Table 2). In both areas, mean tillage depth was greater for treatments VP and DVP than for treatment MP (Table 2).

Numbers of Shot

Numbers of shot recovered did not differ between years, and all interactions including year were not significant (Table 1). Although the area-by-treatment-by-stratum interaction was significant (Table 1), differences between areas were minor. Therefore, shot data were summarized for areas and years combined (Table 3). Compared to other treatments, controls had more shot in the top 10 cm of soil. Treatment MP had more shot in the 0- to 10-cm stratum than treatment VP, and more in the 10- to 20-cm stratum than treatments VP and DVP. Treatments VP and DVP had more shot in the 20- to 30-cm and 30- to 40-cm strata than did treatment MP. Treatments VP and DVP did not differ in any stratum and were most effective at redistributing shot to lower soil strata, with 97 and 95% of shot below 10 cm, respectively (Fig. 1).

Chufa Tuber Biomass

In pretreatment samples (n = 192 for all strata), mean tuber biomasses (g/m²) from the 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm strata were 42.0 (SE = 0.03), 36.1 (SE = 0.02), and 3.7 (SE = 0.01), respectively. Posttreatment sampling revealed that tuber biomass differed among treatments, but differences were

Table 1. Analyses of variance of numbers of shot, chufa tuber biomass, and tillage depth for tillage experiment, Catahoula Lake, Louisiana, 1989-1991.

Source ^a	Numbers of shot				Chufa tuber biomass				Tillage depth				
	df	MS ^b	F	P	df	MS	F	P	df	MS	F	P	
A	1	0.307	0.44	0.52	1	0.050	0.71	0.42	1	333.422	40.49	0.0001	
P(A)	(error a)	10	0.694		10	0.070			10	8.235			
TRT		3	4.308	3.10	0.0416	3	0.244	5.59	0.0036	2	1,101.095	162.97	0.0001
A × TRT		3	0.536	0.39	0.76	3	0.091	2.08	0.12	2	332.145	49.16	0.0001
P × TRT(A)	(error b)	30	1.390			30	0.044			20	6.756		
YR		1	0.068	0.08	0.78	1	0.239	5.12	0.0472				
YR × A		1	0.158	0.20	0.67	1	0.399	8.54	0.0153				
YR × P(A)	(error c)	10	0.805			10	0.047						
YR × TRT		3	2.087	2.44	0.08	3	0.153	8.51	0.0003				
YR × A × TRT		3	0.252	0.30	0.83	3	0.055	3.06	0.0431				
YR × P(A × TRT)	(error d)	30	0.854			30	0.018						
REP(YR × A × P × TRT)	(error e)	288	0.962										
S		3	52.812	62.67	0.0001								
A × S		3	8.750	10.38	0.0001								
TRT × S		9	126.989	150.70	0.0001								
A × TRT × S		9	2.888	3.43	0.0004								
YR × S		3	0.915	1.09	0.35								
YR × A × S		3	0.561	0.67	0.57								
YR × TRT × S		9	0.778	0.92	0.50								
YR × A × TRT × S		9	0.862	1.02	0.42								
Residual error ^c		1,104	0.843			288	0.021			36	2.195		

^a A = area, P = plot, TRT = treatment, YR = year, REP = replicate, S = stratum.

^b Mean squares.

^c All factors that include stratum were tested with residual error.

Table 2. Mean (95% CI) tillage depth (cm) by area and treatment, Catahoula Lake, Louisiana, 1989–1991. Confidence intervals are valid only within areas.

Area ^a	Treatment		
	Vegetable plow	Disking and vegetable plow	Moldboard plow
A	41.5A (39.9–43.1)	39.5A (37.9–41.0)	22.4B (20.9–24.0)
B	31.5A (30.0–33.1)	32.4A (30.8–33.9)	26.6B (25.0–28.1)

^a Within areas, means with unlike letters differ ($P < 0.05$).

not consistent between areas and years (i.e., yr × area × treatment interaction [Table 1]).

1990—One Year Posttreatment.—In area A, mean tuber biomass was greater for controls than for treatment DVP (Table 4). In area B, mean tuber biomass did not differ among treatments.

1991—Two Years Posttreatment.—In area A, mean tuber biomass was greater for controls and treatment DVP than for treatment MP; however, treatment VP did not differ from controls or treatment DVP (Table 4). In area B, mean tuber biomass did not differ among treatments.

DISCUSSION

Effects of Tillage on Shot

Although equal densities of shot were seeded on each EU, numbers of shot recovered differed among treatments. Total shot recovered

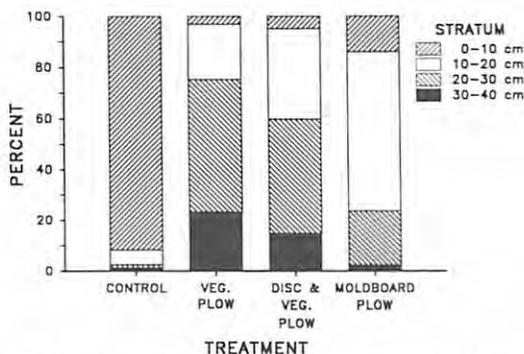


Fig. 1. Percent of seeded shot recovered by soil stratum and treatment at Catahoula Lake, Louisiana, 1989–1991.

(sum of strata means in Table 3) was greater for controls (15.6) than for other treatments (range = 12.2–12.7); thus, tillage apparently redistributed some shot below 40 cm. Consequently, our estimates are conservative with regard to effectiveness of various tillage treatments in redistributing shot to lower strata. Under conditions of sparse vegetation at the time of tillage, redistribution of shot was similar between EU's tilled with a vegetable plow and those disked and tilled with a vegetable plow. However, tall or dense vegetation can impede performance of a vegetable plow; consequently, the manufacturer recommends disking before plowing under such conditions.

The vegetable and large moldboard plows are capable of tillage depths to 45 cm if soil

Table 3. Mean (95% CI) number of shot recovered/sampling locations by stratum and treatment, Catahoula Lake, Louisiana, 1989–1991. Confidence intervals are valid only within strata.

Stratum ^a (cm)	Treatment			
	Control	Vegetable plow	Disking and vegetable plow	Moldboard plow
0–10	14.3A (11.4–17.5)	0.4B (0.1–1.1)	0.6BC (0.1–1.4)	1.8C (0.8–3.0)
10–20	0.9A (0.3–1.9)	2.7B (1.5–4.1)	4.3B (2.8–6.1)	7.9C (5.7–10.3)
20–30	0.2A (0.0–0.7)	6.5B (4.6–8.8)	5.5B (3.7–7.6)	2.7C (1.5–4.2)
30–40	0.2A (0.0–0.8)	2.9B (1.7–4.5)	1.8B (0.9–3.1)	0.3A (0.0–1.0)

^a Within strata, means with unlike letters differ ($P < 0.05$).

Table 4. Mean (95% CI) chufa tuber biomass (g/m^2) from the top 20 cm of soil by area and year for each treatment, Catahoula Lake, Louisiana. Confidence intervals are valid only within an area by year combination. Note that 1990 and 1991 represent 1 and 2 years after treatment, respectively.

Area	Year	Treatment			
		Control	Vegetable plow	Disc and vegetable plow	Moldboard plow
A	1990*	64.2A (38.0–92.8)	40.0AB (16.0–66.4)	25.1B (2.5–50.1)	32.9AB (9.6–58.6)
	1991	87.1A (59.0–117.6)	56.5AB (31.0–84.4)	86.9A (58.8–117.3)	40.8B (16.7–67.3)
B	1990	74.6A (47.5–104.0)	60.6A (34.7–88.8)	65.9A (39.5–94.6)	42.3A (18.1–68.9)
	1991	46.0A (21.4–73.0)	48.8A (23.9–76.0)	83.8A (55.9–114.0)	51.3A (26.2–78.7)

* Within areas and years, means with unlike letters differ ($P < 0.05$).

conditions permit and a powerful tractor is used. We were unable to achieve maximum tillage depths because of dense clay soils on the lake bed and tractor limitations. The large moldboard plow had 7 moldboard blades and probably was difficult for the tractor to pull, thus limiting its tillage depth. We believe that a large crawler tractor would allow greater tillage depth and more effective redistribution of shot for both the large moldboard and vegetable plows.

Our results indicate that deep tillage is more effective than conventional tillage in reducing shot densities near the soil surface. Fredrickson et al. (1977) collected samples down to 25 cm in the soil, and recovered 18% of shot below 10 cm in tilled areas. In contrast, we recovered 97, 95, and 86% of shot below 10 cm for treatments VP, DVP, and MP, respectively. We conclude that deep tillage, especially with vegetable plows, would substantially reduce availability of lead shot to foraging waterfowl at Catahoula Lake and probably other areas.

Effects of Tillage on Chufa Tuber Biomass

Our pretreatment samples indicated that 51% of chufa tuber biomass occurred in the top 10 cm of soil and 95% occurred above 20 cm. The tuber distribution and dense clay soils at Catahoula Lake suggest that most waterfowl

foraging would be limited to the top 10 cm; foraging below 20 cm probably is rare.

Tilling the compacted sediments of Catahoula Lake increased the soil volume, raising the elevation of treated sites. Soil in treatment MP EU's was not elevated as high as in treatment VP and DVP EU's (M. S. Peters, pers. observ.), probably because of shallower tillage depths of treatment MP. One year posttillage, differences in elevation between controls and tilled EU's ranged from 5 to 10 cm, with some settling 2 years after tillage. Differences in elevation affected soil moisture near the surface and the duration that sites were shallowly flooded after heavy rains (M. S. Peters, pers. observ.). Such differences may have contributed to observed treatment differences in chufa tuber biomass. Chufa tuber production is greater if the soil is saturated than if shallow flooding or low soil moisture conditions occur throughout the growing season (Merrell 1975). Kelley and Fredrickson (1991) suggested that maintaining moist soil conditions after disking is important for subsequent production of chufa tubers. Area A was much drier than area B throughout the 1990 and 1991 growing seasons (M. S. Peters, pers. observ.). Thus, tillage likely enhanced tuber production on area B by limiting flooding, but may have inhibited tuber production on area A because of reduced soil moisture.

One year after treatment, most tubers in tilled EU's probably resulted from within-sea-

son production. However, tubers in controls probably were produced during several seasons because tubers can remain dormant for 3.5 years (Kelley and Fredrickson 1991). Deep tillage probably redistributed many tubers from the top 20 cm to lower soil strata, perhaps too deep for subsequent sprouting. Chufa tubers planted 7.6–15 cm below the surface germinate readily, but tubers planted below 15 cm have low germination rates (Bundy et al. 1960). Tubers also may have been killed by desiccation following tillage (Tumbleson and Kommedahl 1961, Thomas 1969).

Shading from other plants reduces chufa tuber production (Bell et al. 1962, Jordan-Molero and Stoller 1978, Keeley and Thullen 1978) and may have contributed to the reduction of tuber biomass on some tilled EU's. One year posttreatment, bearded sprangletop seemed to increase on all tilled EU's in area B and on treatment MP EU's in area A, as compared to controls (M. S. Peters, pers. observ.). Bearded sprangletop matures before chufa and shades young chufa plants. Cocklebur (*Xanthium* sp.) invaded some tilled sites in area A 1 year after tillage, particularly on treatment VP EU's, and seemed to increase 2 years after treatment (M. S. Peters, pers. observ.). On 1 side of tilled EU's, plows moved tilled soil onto untilled soil, creating an elevated edge. Cocklebur was particularly common on these edges, suggesting that higher ground enhanced conditions for establishment of cocklebur on tilled sites in area A. If cocklebur eventually outcompeted chufa on tilled sites, it could severely impact chufa tuber production. Cocklebur did not invade tilled sites in area B, probably because it was wetter there.

RESEARCH AND MANAGEMENT RECOMMENDATIONS

Deep tillage is a viable management option to reduce availability of lead shot to foraging birds on Catahoula Lake and probably on other areas with high lead-shot densities. Deep tillage could be used on seasonally dry wetlands,

exposed lake beds, and upland fields. Deep tillage would be particularly suited for moist-soil units because they can be drained easily and plant responses after tillage can be controlled through water level management.

At Catahoula Lake, soil moisture and duration of shallow flooding in subsequent growing seasons seem to influence the ability of chufa and other plants to repopulate tilled sites. On lower portions of the lake bed that stay wetter throughout the growing season, tillage may eventually enhance chufa production. On higher portions of the lake bed, tillage may make sites drier and encourage bearded sprangletop or invasion of cocklebur. Further research is needed to examine plant responses to tillage on different elevations of the lake bed and with varying soil moisture regimes.

SUMMARY

We examined the effects of deep tillage on redistribution of artificially seeded lead shot and chufa tuber biomass at Catahoula Lake, Louisiana. All deep tillage techniques resulted in redistribution of shot from the top 10 cm of soil to lower strata as compared to controls. In control sites, 92% of shot was recovered above 10 cm. For sites tilled with a vegetable plow, 97% of shot was recovered below 10 cm and 75% below 20 cm. For sites disked and then tilled with a vegetable plow, 95% of shot was recovered below 10 cm and 60% below 20 cm. Chufa tuber biomass did not differ among treatments on wetter sites 1 and 2 years following treatment. After 1 year on drier sites, controls had more tuber biomass than sites that were disked and then tilled with a vegetable plow. After 2 years following treatment on drier sites, tuber biomass did not differ among experimental units that were tilled with a vegetable plow, those that were disked and tilled with a vegetable plow, and controls. Deep tillage is a viable management option for reducing availability of lead shot to foraging waterfowl on Catahoula Lake and probably on other areas.

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