Wheat Grain and Soil Changes Following Termination of Sewage Biosolids Application[†]

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ABSTRACT

One question about utilizing sewage biosolids for beneficial use is how long it may take a site to "recover" from continuously excessive applications. We wanted to determine the resilience of a dryland wheat agroecosystem that has received biosolids additions for several years at rates that were six to nine times greater than the agronomic rate. We utilized 17 years of field-study information from biosolids addition to dryland hard-red winter wheat (*Triticum aestivum* L. 'Vona' or 'TAM107'). We found that the agronomic rate for continuous application of biosolids from the cities of Littleton and Englewood, CO is 2 to 3 dry tons acre^{-1}. We compared plant and soil responses to a treatment of 18 dry tons biosolids acre^{-1} (six to nine times larger than the recommended rate) that we discontinued after 12 years of application to a control (0 tons acre^{-1}) and continuous application of 3, 6, and 12 tons acre^{-1}. We applied biosolids from the cities of Littleton and Englewood, CO to a Platner loam (Aridic Paleustoll) at our West Bennett site A, which is approximately 25 miles northeast of Bennett, CO and to a Weld loam (Aridic Paleustoll) at site B, which is about 3 miles east of site A. Wheat-grain yields, protein content, and P, Zn, Cd, Cu, Ni, and Pb concentrations approached the levels in the control (0 tons acre^{-1}) or the 3 tons acre^{-1} treatment within three croppings after discontinuation of the 18 tons acre^{-1} application rate. Soil parameters did not recover to the same extent as the plant responses. The soil parameters that recovered to levels of the control or 3 tons acre^{-1} treatments within three croppings at both sites were soil NH_4HCO_3-diethylenetriaminepentaacetic acid (AB-DTPA)-extractable P, Zn, Ni, and Pb, soil NO_3-N and NH_4-N in the 0-8-inch depth, and soil NH_4-N in the 8-24-inch depth. The pH and electrical conductivity of saturated-soil-paste extracts and AB-DTPA-extractable Cd and Cu in the 0-8-inch depth, and soil NO_3-N in the 8-24-inch depth did not recover to levels of the control or 3 tons acre^{-1} treatments within three croppings at both sites. These results suggest that the dryland wheat agroecosystem is very resilient once excessive biosolids applications are halted; however, soil levels of Cd, Cu, and NO_3-N may not return to the levels associated with the agronomic rate as quickly as other soil parameters.

INTRODUCTION

If applied at an agronomic rate (a rate that supplies the N needs of a crop), sewage biosolids can supply nutrients such as N, P, and Zn to dryland wheat while not posing any environmental or health threats (Barbarick et al., 1992, 1995, 1996, 1997, 1998; Barbarick and Ippolito, 2000). We have determined that 2 to 3 dry tons $acre^{-1}$ is the agronomic rate for continuous application of biosolids from the cities of Littleton and Englewood, CO. An unresolved question, however, is the time required for land that has received biosolids to "recover" regarding plant and soil concentrations of various constituents from multiple, long-term applications or overapplications. For example, Barbarick and Ippolito (2000) have shown that N availability from biosolids application to soils in a greenhouse study provided non-significant N carryover after two wheat croppings following biosolids addition.

Our overall goal is to determine changes in wheat grain and soil nutrient and trace-metal concentrations following the termination of a biosolids application rate that is six to nine times larger than the agronomic rate (18 dry tons $acre^{-1}$ per cropping) compared with a control (0 dry tons $acre^{-1}$) and continuous application of 3, 6, or 12 dry tons $acre^{-1}$ per cropping. Our hypotheses were:

Within three harvests following cessation of application of the 18 dry tons biosolids $acre^{-1}$ treatment,

1. Wheat grain yield and protein concentration will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

2. Wheat grain P, Cd, Cu, Ni, Pb, and Zn concentrations will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

3. The pH and electrical conductivity of saturated soil pastes for the 0-8-inch depth will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

4. Soil ABDTPA-extractable P, Cd, Cu, Ni, Pb, and Zn concentrations in the 0-8-inch depth will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

5. Soil NO_3-N and NH_4-N concentrations in the 0-8-inch depth will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

6. Soil NO_3-N and NH_4-N concentrations in the 8-24-inch depth will not be significantly different at the 0.10 probability level than the 3 dry tons $acre^{-1}$ rate per cropping.

We did not expect the "recovery" of the 18 tons acre^{-1} rate to be equivalent to the control (0 tons acre^{-1}) since we have added significant amounts of biosolids-borne plant nutrients and trace elements. Given more recovery time, the 18-ton acre^{-1} treatment could provide plant and soil responses more like those in the control.

MATERIALS AND METHODS

Our long-term field study was initiated in August 1982 on a location near Bennett, CO (labeled as West Bennett) in Adams County (Barbarick et al., 1992). Two sets of plots (A for those established in 1982; B for those established in 1983) were used since hard red winter wheat (*Triticum aestivum* L. "Vona' from 1982-1990, 'TAM 107' from 1990-1998) was grown in a dryland summer-fallow rotation system. Table 1 indicates the rotation used for sites A and B. Alternate-year (to allow fallowing) biosolids application rates were 0, 3, 6, 12, and 18 dry tons acre^{-1} from 1982 up to 1990. Beginning in 1990 at site A and 1991 at site B, we discontinued the 18 dry tons acre^{-1} rate with the overall goal of determining how long these high-application plots would "recover" to the levels of our lowest rate plots (3 tons acre^{-1}).

Table 1. Crop rotation and sewage biosolids application history at each site.

Crop Year	Site A	Site B
1982-83	0, 3, 6,12, 18 tons acre^{-1}	Fallow
1983-84	Fallow	0, 3, 6,12, 18 tons acre^{-1}
1984-85	0, 3, 6,12, 18 tons acre^{-1}	Fallow
1985-86	Fallow	3, 6,12, 18 tons acre^{-1}
1986-87	0, 3, 6,12, 18 tons acre^{-1}	Fallow
1987-88	Fallow	0, 3, 6,12, 18 tons acre^{-1}
1988-89	0, 3, 6,12, 18 tons acre^{-1}	Fallow
1989-90	Fallow	0, 3, 6,12, 18 tons acre^{-1}
1990-91†	*0, 3, 6,12 tons acre*$^{-1}$	*Fallow*
1991-92†	*Fallow*	*0, 3, 6,12 tons acre*$^{-1}$
1992-93	*0, 3, 6,12 tons acre*$^{-1}$	*Fallow*
1993-94	*Fallow*	*0, 3, 6,12 tons acre*$^{-1}$
1994-95	*0, 3, 6,12 tons acre*$^{-1}$	*Fallow*
1995-96	*Fallow*	*0, 3, 6,12 tons acre*$^{-1}$
1996-97	*0, 3, 6,12 tons acre*$^{-1}$	*Fallow*
1997-98	*Fallow*	*0, 3, 6,12 tons acre*$^{-1}$

† We discontinued the 18 dry tons biosolids acre^{-1} rate at site A in 1990-91 and at site B in 1991-92.

We established the West Bennett site A, which is approximately 25 miles northeast of Bennett, CO, on a Platner loam soil (fine, montmorillonitic, mesic Abruptic Aridic Paleustoll), and we developed site B, which is about 3 miles east of site A, on a Weld loam soil (fine, montmorillonitic, mesic Aridic Paleustoll). Selected properties for baseline soils taken in 0-6, 6-12, and 12-24-inch increments are listed in Table 2.

Table 2. Selected baseline soil chemical characteristics.

Property	Depth cm	Site A, 1982	Site B, 1983
pH	0-6	6.5	7.5
	6-12	6.6	7.3
	12-24	7.5	7.5
E.C., ds m^{-1}	0-6	0.1	0.4
	6-12	0.2	0.4
	12-24	0.3	0.4
Organic matter, g kg^{-1}	0-6	10	10
	6-12	9	11
	12-24	8	10
NO_3-N, mg kg^{-1}	0-6	2	4
	6-12	7	2
	12-24	1	4
AB-DTPA-extractable, mg kg^{-1}			
P	0-6	9	18
	6-12	4	17
	12-24	1	18
K	0-6	462	343
	6-12	438	316
	12-24	356	335
Zn	0-6	1.6	0.7
	6-12	0.6	0.6
	12-24	0.3	0.8
Fe	0-6	18	7
	6-12	14	9
	12-24	9	10
Mn	0-6	11	13
	6-12	4	10
	12-24	2	14
Cu	0-6	2.5	2.7
	6-12	2.5	2.6
	12-24	3.0	2.4

We applied sewage biosolids (see Table 3 for biosolids properties) to plots of 12 by 56 feet in 1982, 1984, 1986, 1988, 1990, 1992, 1994, and 1996 at site A. The application rates were equivalent to 3, 6, 12, and 18 dry tons biosolids acre^{-1} from 1984-1990 and 3, 6, and 12 dry tons biosolids acre^{-1} from 1992-1996. In 1983, 1985, 1987, 1989, 1991, 1993, and 1997, we applied the same rates of biosolids used at site A to plots of 9 by 56 feet at site B. We inadvertently missed the biosolids applications in 1995. Also, in the inaugural year, 1982, we used the 18 dry tons acre^{-1} plots as part of a time of incorporation study (Utschig, 1985) where we applied 6 dry tons biosolids acre^{-1}. We present the cumulative biosolids application rates and the cumulative amounts of P, Zn, Cd, Cu, Ni and Pb added with the biosolids by years and site in Tables 4 through 10. We used four replications of all treatments at both experimental sites. In 1982 and 1983, we applied a more liquid biosolids (35 to 42 g solids kg^{-1}) to our bermed plots by transfer from semi-tanker trucks through fire hose. Our farmer cooperators disked the biosolids after the liquid biosolids had infiltrated into the soil and dried on the surface. All other years we weighed air-dried biosolids (528 to 880 g solids kg^{-1}), evenly spread the material over the plots using a front-end loader on a small tractor, and then hand raked the biosolids to improve the uniformity of distribution. In the years that we used air-dried biosolids, we rototilled all plots with the small tractor to a depth of about 8 inches.

Grain yields were determined by harvesting a 6- by 50-foot area with a small-plot combine and weighing the grain in the field. Grain elemental concentrations of Cd, Cu, Ni, P, Pb, and Zn were measured in concentrated HNO_3 digests (Ippolito and Barbarick, 2000) by the inductively coupled plasma-atomic emission spectrophotometer (ICP-AES; Soltanpour et al., 1979). We obtained subsamples from the harvested grain and determined protein concentrations found with a Dickey John GACC III® near infra-red analyzer.

Immediately following each wheat harvest, we collected composite soil samples (two to three cores per plot) from the 0-8-inch (plow layer) and 8-24-inch depths near the center of each plot. Samples were taken near the center of each plot to avoid the biosolids redistribution problem that can occur with tillage operations (Yingming and Corey, 1993). We immediately air-dried the soil samples, then crushed them to pass a 2-mm sieve. The concentrations of soil P, Cd, Cu, Ni, Pb, and Zn were determined in an AB-DTPA extract utilizing ICP-AES. We used this extraction method since Barbarick and Workman (1987) indicate that AB-DTPA concentrations correlate well with the total amount of metal added to biosolids-amended soils and Lindsay and Norvell (1978) showed that soil-DTPA concentrations correlate to plant availability of Zn and Cu.

Since our objective was to determine when some soil parameters associated with the discontinued 18-ton acre^{-1} rate approached those of the lower biosolids rates, we conducted F-tests and then used least significant differences at the 0.10 probability level ($LSD_{0.10}$) to discuss differences between treatments (0, 3, 6, 12 and discontinued 18 tons acre^{-1}) for each year. We constructed bar graphs to illustrate trends between treatments and over time. We will focus only on the comparison of the 18 tons acre^{-1} rate with all other rates.

Table 3. Littleton/Englewood sewage biosolids used at the West Bennett sites from 1982 through 1997.

Parameter†	1982	1984	1986	1988 Site A	1990	1992	1994	1996	1983	1985	1987	1989 Site B	1991	1993	1997	mean ± sd
Total solids, g kg^{-1}	35	528	850	780	720	760	880	530	42	680	850	760	560	880	680	636 ± 260
Org. N, g kg^{-1}	75	21	10	9	25	34	27	34	16	20	10	9	39	31	11	25 ± 17
NO_3-N, g kg^{-1}	3	<1	<1	<1	<1	<1	<1	<1	2	1	2	<1	<1	<1	<1	<1
NH_4-N, g kg^{-1}	50	8	2	<1	6	12	6	1	57	<1	3	6	11	5	4	11 ± 17
P, g kg^{-1}	28	11	8	16	34	37	17	36	21	27	13	21	33	27	12	23 ± 9
Cu, mg kg^{-1}	1040	462	359	917	865	863	493	459	877	1160	422	884	807	558	236	693 ± 270
Zn, mg kg^{-1}	1980	751	618	1050	1300	1300	816	422	1300	2540	681	1260	1320	942	301	1080 ± 564
Ni, mg kg^{-1}	70	56	47	66	93	177	65	35	94	91	50	78	91	85	15	74 ± 35
Pb, mg kg^{-1}	270	531	206	228	134	20	81	39	161	322	204	134	129	45	31	169 ± 131
Cd, mg kg^{-1}	<30 ‡	8	10	12	9	7	7	3	15	11	9	9	7	6	3	9 ± 3
Mo, mg kg^{-1}	59	12	7	20	32	22	22	8	20	38	9	36	45	26	6	24 ± 15

† Total solids content is based on a wet mass basis; all other concentrations are based on an oven dry mass basis.
‡ We did not include this concentration in the mean calculation.

Table 4. Cumulative biosolids application at the West Bennett sites from 1982 through 1997.

Site	Year	Cumulative Biosolids Applied in tons $acre^{-1}$				Site	Year	Cumulative Biosolids Applied in tons $acre^{-1}$			
		3 tons $acre^{-1}$	6 tons $acre^{-1}$	12 tons $acre^{-1}$	18 tons $acre^{-1}$			3 tons $acre^{-1}$	6 tons $acre^{-1}$	12 tons $acre^{-1}$	18 tons $acre^{-1}$
A	1982	3	6	12	6†	B	1983	3	6	12	18
	1984	6	12	24	24		1985	6	12	24	36
	1986	9	18	36	42		1987	9	18	36	54
	1988	12	24	48	60		1989	12	24	48	72
	1990	15	30	60	78		1991	15	30	60	90
	1992	18	36	72	78‡		1993	18	36	72	90‡
	1994	21	42	84	78		1995	18§	36§	72§	90
	1996	24	48	96	78		1997	21	42	84	90

† We used the 1982 18 dry tons biosolids $acre^{-1}$ plots for a time of incorporation study, which received only 6 dry tons biosolids $acre^{-1}$.

‡ We discontinued the 18 dry tons biosolids $acre^{-1}$ treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 5. Cumulative biosolids-P application at the West Bennett sites from 1982 through 1997.

		Cumulative P Applied in lbs acre^{-1}						Cumulative P Applied in lbs acre^{-1}			
Site	Year	3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}	Site	Year	3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}
A	1982	168	336	672	336†	B	1983	126	252	504	756
	1984	234	468	936	732		1985	288	576	1152	1728
	1986	282	564	1128	1020		1987	366	732	1464	2196
	1988	378	756	1512	1596		1989	492	984	1968	2952
	1990	582	1164	1164	2820		1991	690	1380	2760	4140
	1992	804	1608	3216	2820‡		1993	852	1704	3408	4140‡
	1994	906	1812	3624	2820		1995	852§	1704§	3408§	4140
	1996	1122	2244	4488	2820		1997	924	1848	3696	4140

† We used the 1982 18 dry tons biosolids acre^{-1} plots for a time of incorporation study, which received only 6 dry tons biosolids acre^{-1}.

‡ We discontinued the 18 dry tons biosolids acre^{-1} treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 6. Cumulative biosolids-Zn application at the West Bennett sites from 1982 through 1997.

Site	Year	Cumulative Zn Applied in lbs acre^{-1} 3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}	Site	Year	Cumulative Zn Applied in lbs acre^{-1} 3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}
A	1982	12	24	48	24†	B	1983	8	16	31	47
	1984	16	33	66	51		1985	23	46	92	138
	1986	20	40	80	73		1987	27	54	109	163
	1988	26	53	106	111		1989	35	69	139	208
	1990	34	68	137	158		1991	43	85	170	256
	1992	42	84	168	158‡		1993	48	97	193	256‡
	1994	47	94	188	158		1995	48§	97§	193§	256
	1996	49	99	198	158		1997	50	100	200	256

† We used the 1982 18 dry tons biosolids acre^{-1} plots for a time of incorporation study, which received only 6 dry tons biosolids acre^{-1}.

‡ We discontinued the 18 dry tons biosolids acre^{-1} treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 7. Cumulative biosolids-Cd application at the West Bennett sites from 1982 through 1997.

Site	Year	Cumulative Cd Applied in lbs acre^{-1}				Site	Year	Cumulative Cd Applied in lbs acre^{-1}			
		3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}			3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}
A	1982	0.09	0.18	0.36	0.18†	B	1983	0.09	0.18	0.36	0.54
	1984	0.14	0.28	0.55	0.47		1985	0.16	0.31	0.62	0.83
	1986	0.20	0.40	0.79	0.83		1987	0.21	0.42	0.84	1.26
	1988	0.27	0.54	1.08	1.26		1989	0.26	0.53	1.06	1.58
	1990	0.32	0.65	1.30	1.58		1991	0.31	0.61	1.22	1.84
	1992	0.37	0.73	1.46	1.58‡		1993	0.34	0.68	1.37	1.84‡
	1994	0.41	0.82	1.63	1.58		1995	0.34§	0.68§	1.37§	1.84
	1996	0.43	0.85	1.70	1.58		1997	0.36	0.72	1.44	1.84

† We used the 1982 18 dry tons biosolids acre^{-1} plots for a time of incorporation study, which received only 6 dry tons biosolids acre^{-1}.

‡ We discontinued the 18 dry tons biosolids acre^{-1} treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 8. Cumulative biosolids-Cu application at the West Bennett sites from 1982 through 1997.

Site	Year	Cumulative Cu Applied in lbs $acre^{-1}$				Site	Year	Cumulative Cu Applied in lbs $acre^{-1}$			
		3 tons $acre^{-1}$	6 tons $acre^{-1}$	12 tons $acre^{-1}$	18 tons $acre^{-1}$			3 tons $acre^{-1}$	6 tons $acre^{-1}$	12 tons $acre^{-1}$	18 tons $acre^{-1}$
A	1982	6	12	25	12[†]	B	1983	5	11	21	32
	1984	9	18	36	29		1985	12	24	49	73
	1986	11	22	45	42		1987	15	30	59	89
	1988	17	33	67	75		1989	20	40	80	120
	1990	22	44	87	106		1991	25	50	100	149
	1992	27	54	108	106[‡]		1993	28	56	113	149[‡]
	1994	30	60	120	106		1995	28[§]	56[§]	113[§]	149
	1996	33	65	131	106		1997	30	59	119	149

† We used the 1982 18 dry tons biosolids $acre^{-1}$ plots for a time of incorporation study, which received only 6 dry tons biosolids $acre^{-1}$.

‡ We discontinued the 18 dry tons biosolids $acre^{-1}$ treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 9. Cumulative biosolids-Ni application at the West Bennett sites from 1982 through 1997.

		Cumulative Ni Applied in lbs acre^{-1}						Cumulative Ni Applied in lbs acre^{-1}			
Site	Year	3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}	Site	Year	3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}
A	1982	0.42	0.84	1.68	0.84†	B	1983	0.56	1.13	2.26	3.38
	1984	0.76	1.51	3.02	2.86		1985	1.11	2.22	4.44	6.66
	1986	1.04	2.08	4.16	4.55		1987	1.41	2.82	5.64	8.46
	1988	1.43	2.87	5.74	6.92		1989	1.88	3.76	7.51	11.27
	1990	1.99	3.98	7.97	10.27		1991	2.42	4.85	9.70	14.54
	1992	3.05	6.11	12.22	10.27‡		1993	2.93	5.87	11.74	14.54‡
	1994	3.44	6.89	13.78	10.27		1995	2.93§	5.87§	11.74§	14.54
	1996	3.65	7.31	14.62	10.27		1997	3.02	6.05	12.10	14.54

† We used the 1982 18 dry tons biosolids acre^{-1} plots for a time of incorporation study, which received only 6 dry tons biosolids acre^{-1}.

‡ We discontinued the 18 dry tons biosolids acre^{-1} treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

Table 10. Cumulative biosolids-Pb application at the West Bennett sites from 1982 through 1997.

Site	Year	Cumulative Pb Applied in lbs acre^{-1} 3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}	Site	Year	Cumulative Pb Applied in lbs acre^{-1} 3 tons acre^{-1}	6 tons acre^{-1}	12 tons acre^{-1}	18 tons acre^{-1}
A	1982	1.6	3.2	6.5	3.2†	B	1983	1.0	1.9	3.9	5.8
	1984	4.8	9.6	19.2	22.4		1985	2.9	5.8	11.6	17.4
	1986	6.0	12.1	24.2	29.8		1987	4.1	8.2	16.5	24.7
	1988	7.4	14.8	29.6	38.0		1989	4.9	9.9	19.7	29.6
	1990	8.2	16.4	32.9	42.8		1991	5.7	11.4	22.8	34.2
	1992	8.3	16.7	33.3	42.8‡		1993	6.0	11.9	23.9	34.2‡
	1994	8.8	17.6	35.3	42.8		1995	6.0§	11.9§	23.9§	34.2
	1996	9.1	18.1	36.2	42.8		1997	6.2	12.3	24.6	34.2

† We used the 1982 18 dry tons biosolids acre^{-1} plots for a time of incorporation study, which received only 6 dry tons biosolids acre^{-1}.

‡ We discontinued the 18 dry tons biosolids acre^{-1} treatment in 1992 at site A and in 1993 at site B.

§ We inadvertently missed the 1995 biosolids application on all plots.

RESULTS AND DISCUSSION

Plant Responses

We present the wheat-grain yields and protein content in Figs. 1 and 2. Basically, the yields were the same for all treatments from 1993 through 1998 (Fig. 1) and the protein contents were equivalent to at least the 3 dry tons acre^{-1} per cropping treatments after discontinuation of the 18 tons acre^{-1} rate in 1992 (Fig.2). These results indicate a rapid recovery of overall wheat production once we discontinued the highest rate of biosolids and indicates that we would accept Hypothesis 1.

The grain-P concentrations were equivalent to at least the 3 dry tons acre^{-1} per cropping treatments within one growing season after discontinuation of the 18 tons acre^{-1} rate in1992 at both sites (Fig. 3). The Zn contents approached those of the control (0 tons acre^{-1}) or 3 tons acre^{-1} treatments by the 1993-94 growing season (Fig. 4). Grain Cd (Fig. 5) followed the same pattern as grain P. Not until after the 1994-95 season were grain Cu levels (Fig. 6) essentially the same as those of the control (0 tons acre^{-1}) or 3 tons acre^{-1} plots. Grain Ni (Fig. 7) followed the same pattern as grain Zn. Most Pb concentrations were below detectable limits so that we have no data or comparisons available. These results indicate a rapid recovery of overall wheat-grain elemental concentrations once we discontinued the highest rate of biosolids and indicates that we would accept Hypothesis 2.

The plant responses indicate recovery of the 18 tons acre^{-1} treatments to the levels of the control (0 tons acre^{-1}) or the 3 tons acre^{-1} plots within three croppings following the cessation of the 18 tons acre^{-1} biosolids application. Barbarick and Ippolito (2000) found that the availability of biosolids-borne N essentially disappeared within two continuous greenhouse-croppings of spring wheat. The recovery in our West-Bennett field plots occurred even though the 18 tons biosolids acre^{-1} treatment had added 2.5, 3.2, 3.7, 3.2, and 2.8 times more P, Zn, Cd, Cu, Ni, and Pb, respectively, at site A by 1996 and 4.5, 5.1, 5.1, 5.0, 4.8, 5.5 times more P, Zn, Cd, Cu, Ni, and Pb, respectively, at site B by 1997 as compared to the quantities of each of these elements added with the recommended rate of 3 tons acre^{-1}. Also, grain Cu and Zn concentrations recovered more slowly than the other plant parameters. The amount of biosolids-borne Cu and Zn exceeded Cd, Ni, and Pb additions but were less than the P added. Apparently, soil reactions transformed all elements studied to less plant-available forms while the change in P availability occurred to a larger extent than those of Zn, Cd, Cu, Ni and Pb.

Soil Responses

Soil pH (Fig. 8) at site A was the same for all treatments in 1994-95 but was significantly lower than the control and the 3 and 6 tons biosolids acre^{-1} treatment in 1996-97. At site B, there were no differences in soil pH after discontinuation of the 18 tons acre^{-1} application rate. The electrical conductivity of the saturated soil paste (measure of soluble salt content in the soil) of the 18 tons acre^{-1} application rate were statistically the same as the 6 tons acre^{-1} additions in 1996-97 and 1997-98 (Fig. 9). These results show that soil pH and electrical conductivity did not recover to the levels of the control or the 3 tons acre^{-1} rates so that we cannot accept Hypothesis 3.

Soil AB-DTPA P concentrations (Fig. 10) for the discontinued 18 tons acre^{-1} treatment were statistically the same as the control or the 3 tons acre^{-1} rate by 1994-95, two croppings after cessation of the 18 tons acre^{-1} application rate. The AB-DTPA Zn levels (Fig. 11) in the 18 tons acre^{-1} treatment did not decline to those of the control or the 3 tons acre^{-1} rate until 1996-97 (site A) and 1997-98 (site B). The soil Cd concentrations (Fig. 12) in the 18 tons acre^{-1} rates were statistically similar to the control or the 3 tons acre^{-1} rate in 1994-95, 1995-96, and 1996-97 but was significantly larger than these two lowest rates in 1997-98. The AB-DTPA Cu concentrations (Fig. 13) were greater than the 3 tons acre^{-1} rates in all years except 1995-96, indicating poor recovery following discontinuation of the highest biosolids rate. The soil Ni concentrations (Fig. 14) in the 18 tons acre^{-1} treatment were statistically similar to the control or the 3 tons acre^{-1} rate by 1995-96. Soil AB-DTPA Pb levels recovered to the Pb levels in the control or 3 tons acre^{-1} immediately (1992-93 at site A and 1993-94 at site B) following termination of the 18 tons acre^{-1} rate. These data suggest that AB-DTPA P, Zn, Ni, and Pb concentrations following cessation of the 18 tons acre^{-1} rate did recover within three croppings to the levels of the control or the 3 tons acre^{-1}, while AB-DTPA Cd and Cu levels did not recover. Consequently, we cannot accept Hypothesis 4.

As we stated in the discussion on plant responses, soil transformations to less soluble forms of P, Zn, Ni, and Pb allowed soil concentrations in the discontinued 18 tons acre^{-1} to recover within three croppings to essentially the same concentrations as the control or 3 tons acre^{-1} rate. By 1997-98, the AB-DTPA Cd and Cu levels were statistically the same as the 6 tons acre^{-1} treatments, indicating a slower recovery than we found with AB-DTPA P, Zn, Ni, and Pb.

For soil NO_3-N and NH_4-N in the 0-8-inch depth (Figs. 16 and 17), the concentrations in the discontinued 18 tons acre^{-1} treatment were statistically similar to the control or 3 tons acre^{-1} immediately following the cessation of biosolids application. This shows that the plant available N in the surface soil layer recovered in the highest rate plots within three croppings following termination of application and we accept Hypothesis 5.

While the soil NO_3-N levels (Fig. 18) in the 8-24-inch depth in the discontinued 18 tons acre^{-1} plots reached those in the 3 tons acre^{-1} treatments by 1997-98 at site B, the NO_3-N in the highest-rate plots never did recover to the same level as the 3 tons acre^{-1} plots at site A. The soil NH_4-N in the 8-24-inch depth (Fig. 19) recovered by 1995-96 at site B and by 1996-97 at site A. Consequently, we can expect NO_3-N carryover in the 8-24-inch depth for at least three croppings and NH_4-N carryover for up to three croppings following termination of the 18 tons acre^{-1} treatment. We cannot, therefore, accept Hypothesis 6.

CONCLUSIONS

Once we discontinued the highest biosolids rate of 18 tons acre^{-1} at our two West Bennett sites, wheat-grain yields, grain protein content, and grain P, Zn, Cd, Cu, Ni, and Pb concentrations became statistically the same as the control (0 tons acre^{-1}) or the 3 tons acre^{-1} treatment within three croppings. Plant responses, therefore, showed recovery to that of the control or the commonly recommended continuous biosolids application rate of 3 tons acre^{-1}.

Soil parameters did not show as widespread recovery as we noted with the plant responses. The soil parameters that recovered to levels of the control or 3 tons acre^{-1} treatments within three croppings at both sites were AB-DTPA P, Zn, Ni, and Pb, soil NO_3-N and NH_4-N in the 0-8-inch depth, and soil NH_4-N in the 8-24-inch depth. The pH and electrical conductivity of saturated-soil-paste extracts and AB-DTPA Cd and Cu in the 0-8-inch depth, and soil NO_3-N in the 8-24-inch depth did not recover to levels of the control or 3 tons acre^{-1} treatments within three croppings at both sites.

Apparently, soil transformations of the above plant nutrients and trace metals to less soluble forms reduced their plant availability. Soil NO_3-N, however, accumulated in the 8-24-inch depth and did not recover to the levels of the control or 3 tons acre^{-1}, our recommended rate for continuous biosolids application. While these results increase our concerns about NO_3-N carryover with overapplication of biosolids, successive croppings following stoppage of the 18 tons acre^{-1} rate will allow further plant removal of the residual NO_3-N.

We conclude that our dryland wheat agroecosystem demonstrated remarkable resilience. Recovery in our West Bennett field plots occurred within three croppings for most parameters we measured even though the 18 tons biosolids acre^{-1} treatment had added 1698, 109, 1.15, 73, 6.62, and 33.7 lbs acre^{-1} more P, Zn, Cd, Cu, Ni, and Pb, respectively, at site A by 1996 and 3216, 206, 1.48, 119, 11.52, 28.0 lbs acre^{-1} more P, Zn, Cd, Cu, Ni, and Pb, respectively, at site B by 1997 as compared to the recommended rate of 3 tons acre^{-1}. These data will help land applicators predict how long they can expect recuperation of a dryland wheat agroecosystem following application of excessive amounts (e.g., above the agronomic rate) of sewage biosolids.

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Figure 1: Yearly average wheat grain yields at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

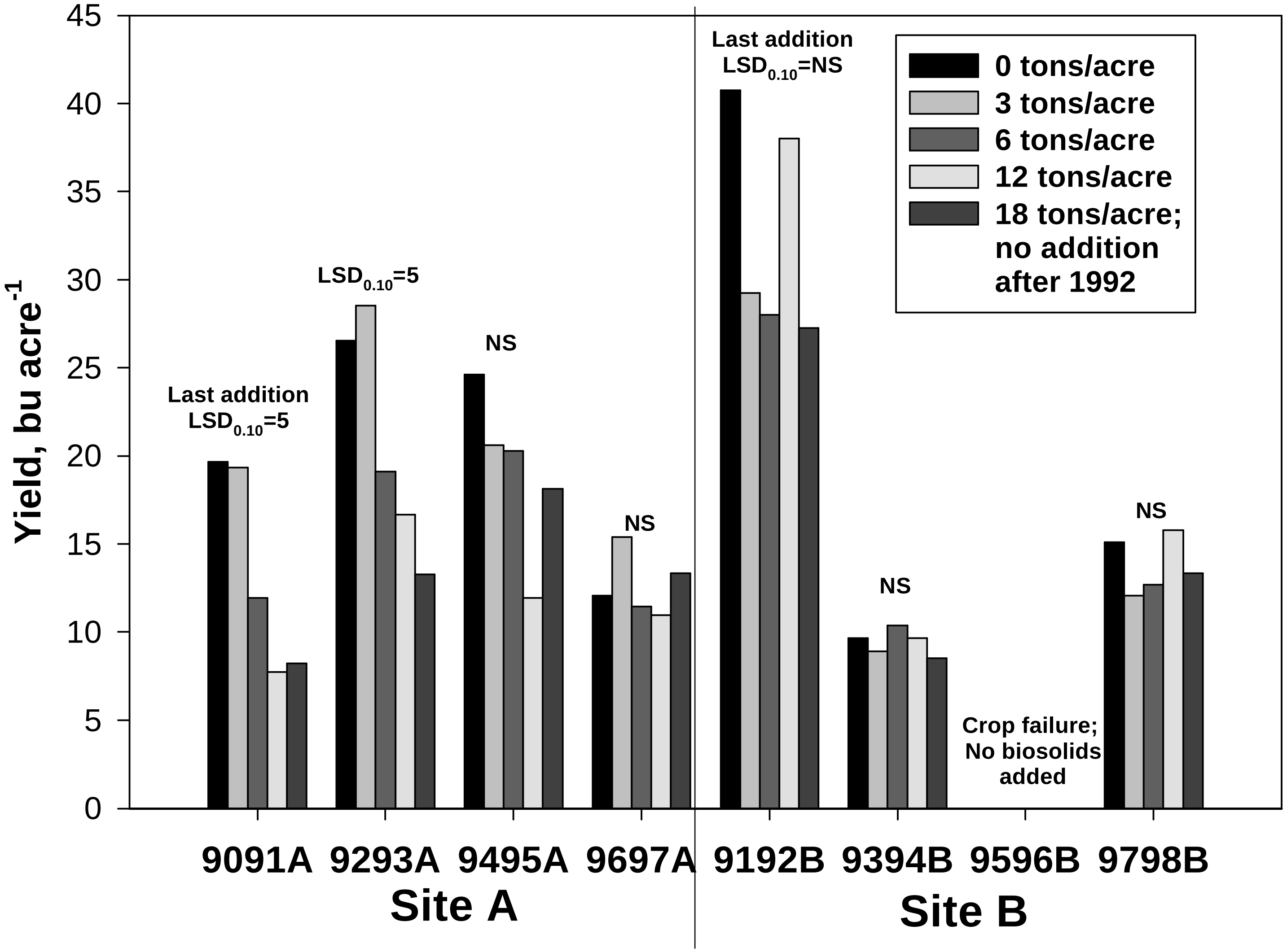


Figure 2: Yearly average wheat protein at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

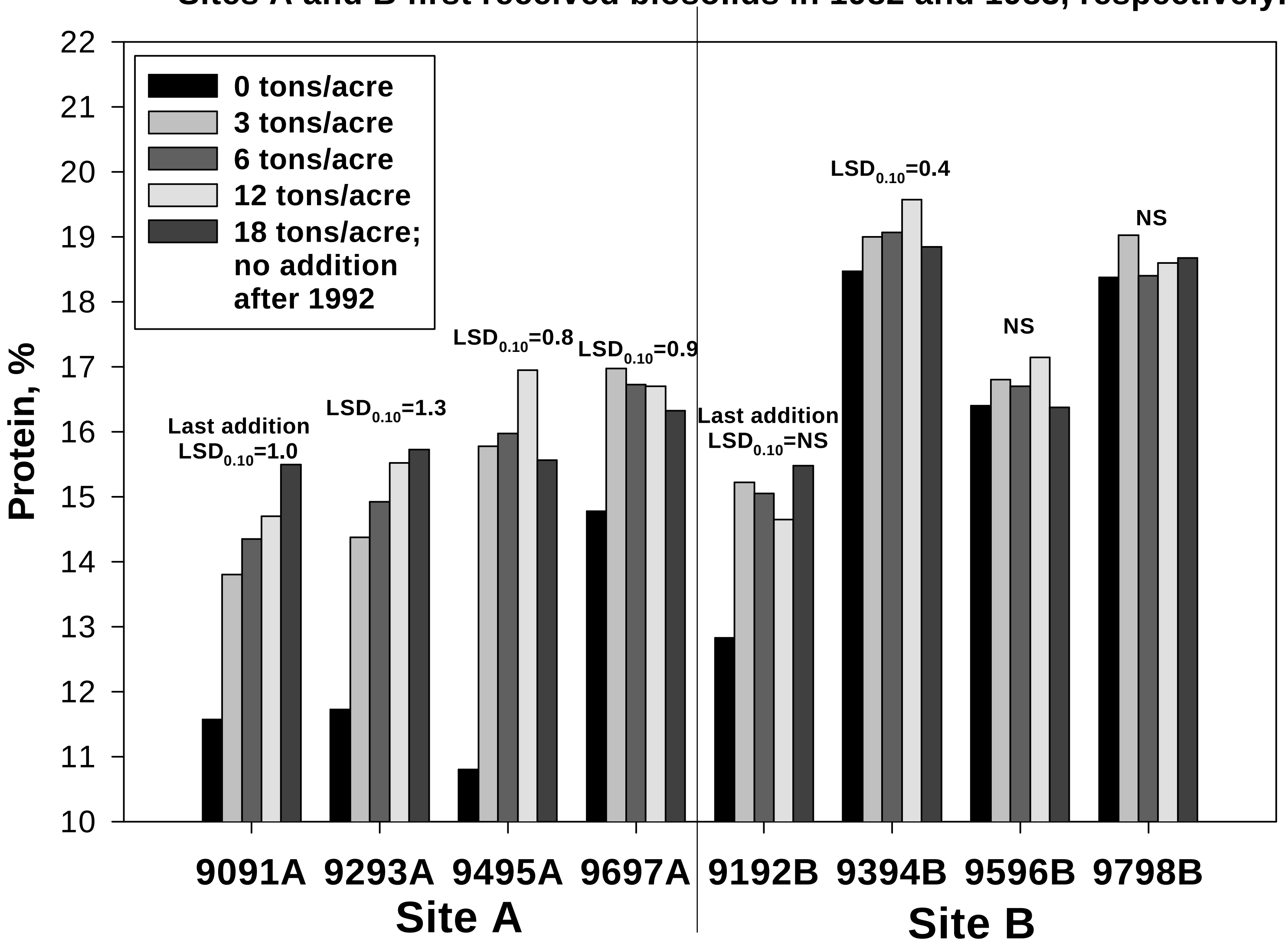


Figure 3: Yearly average grain P concentration at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

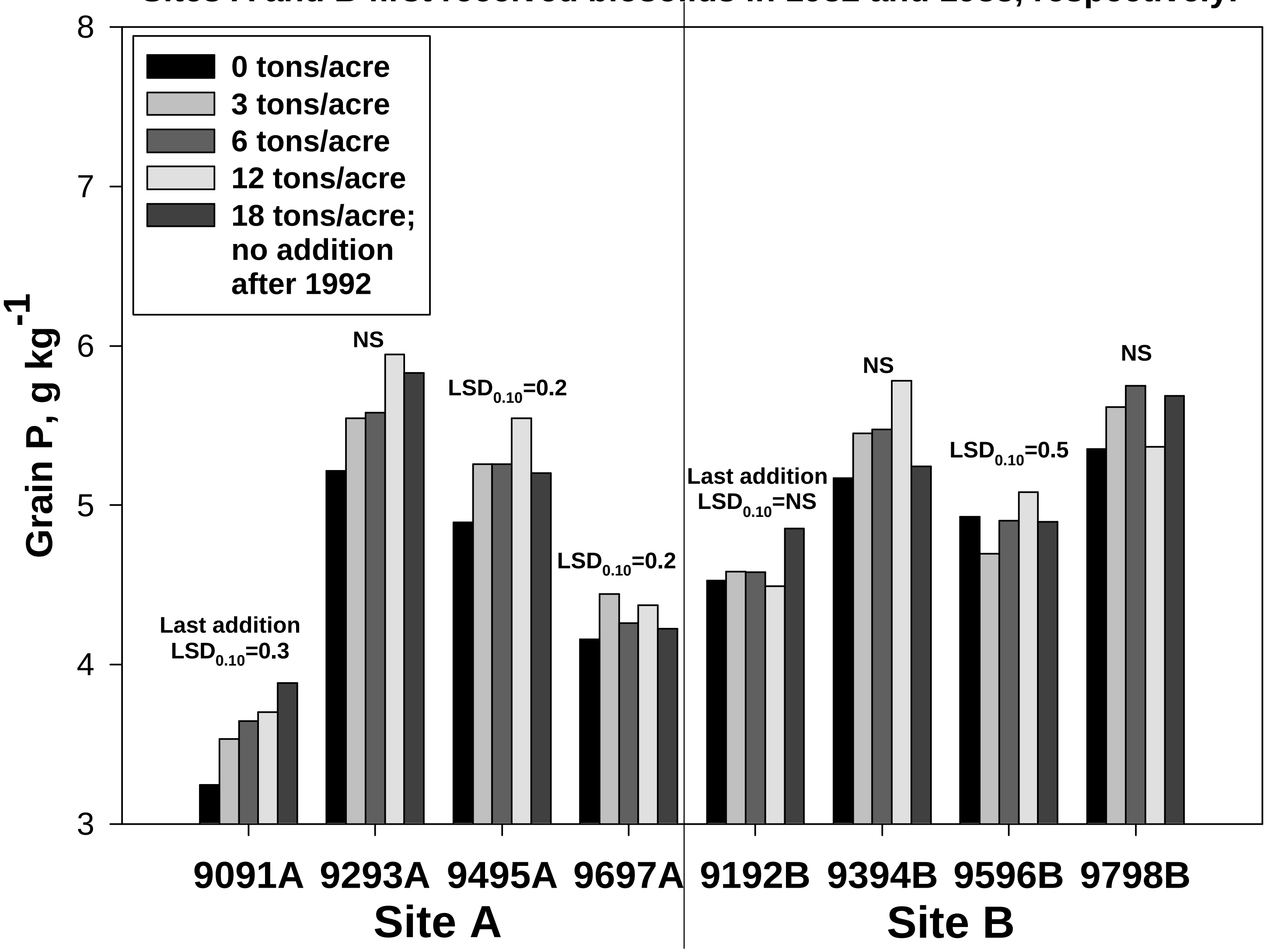


Figure 4: Yearly average grain Zn concentration at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

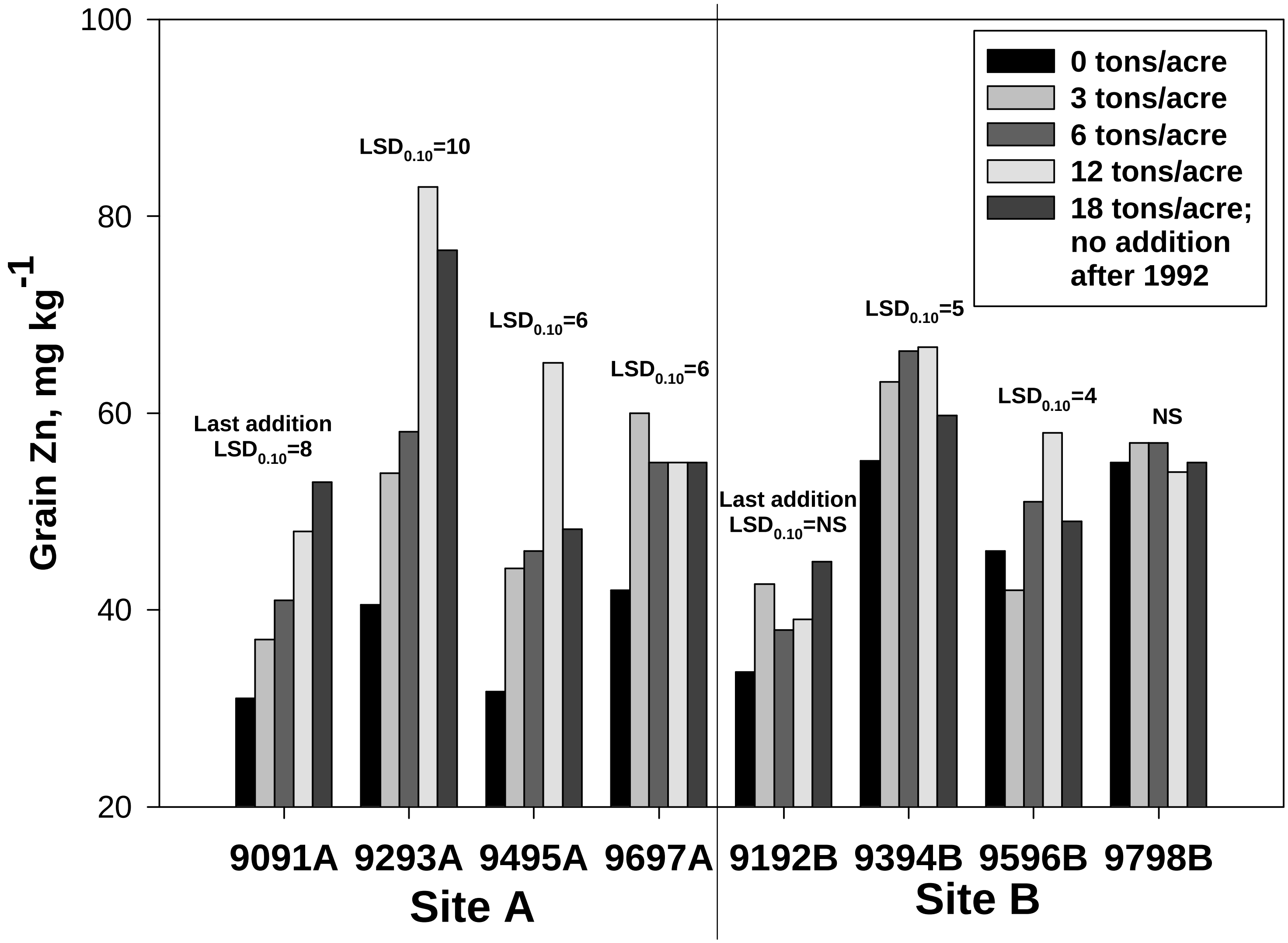


Figure 5: Yearly average grain Cd concentration at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

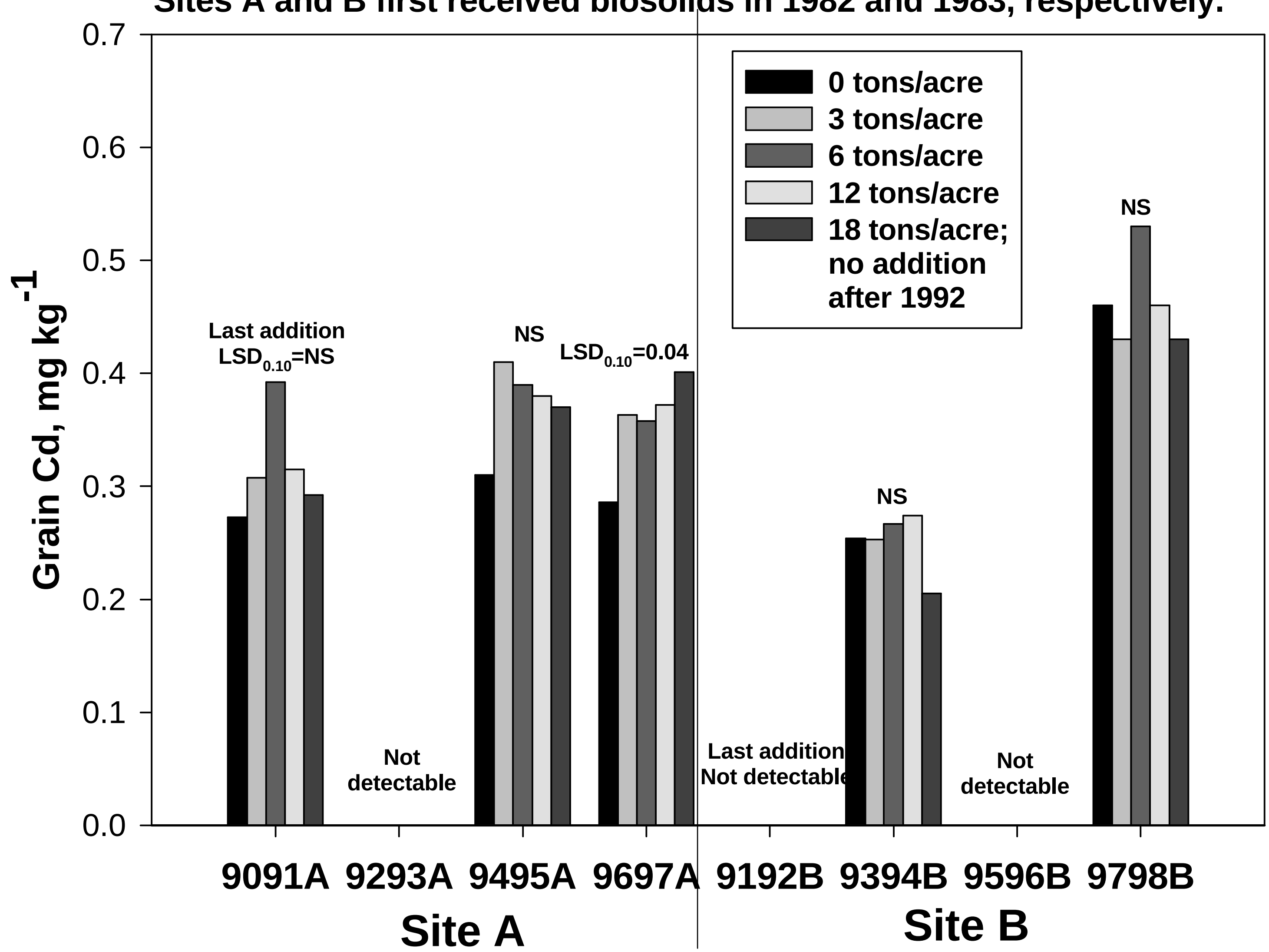


Figure 6: Yearly average grain Cu concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

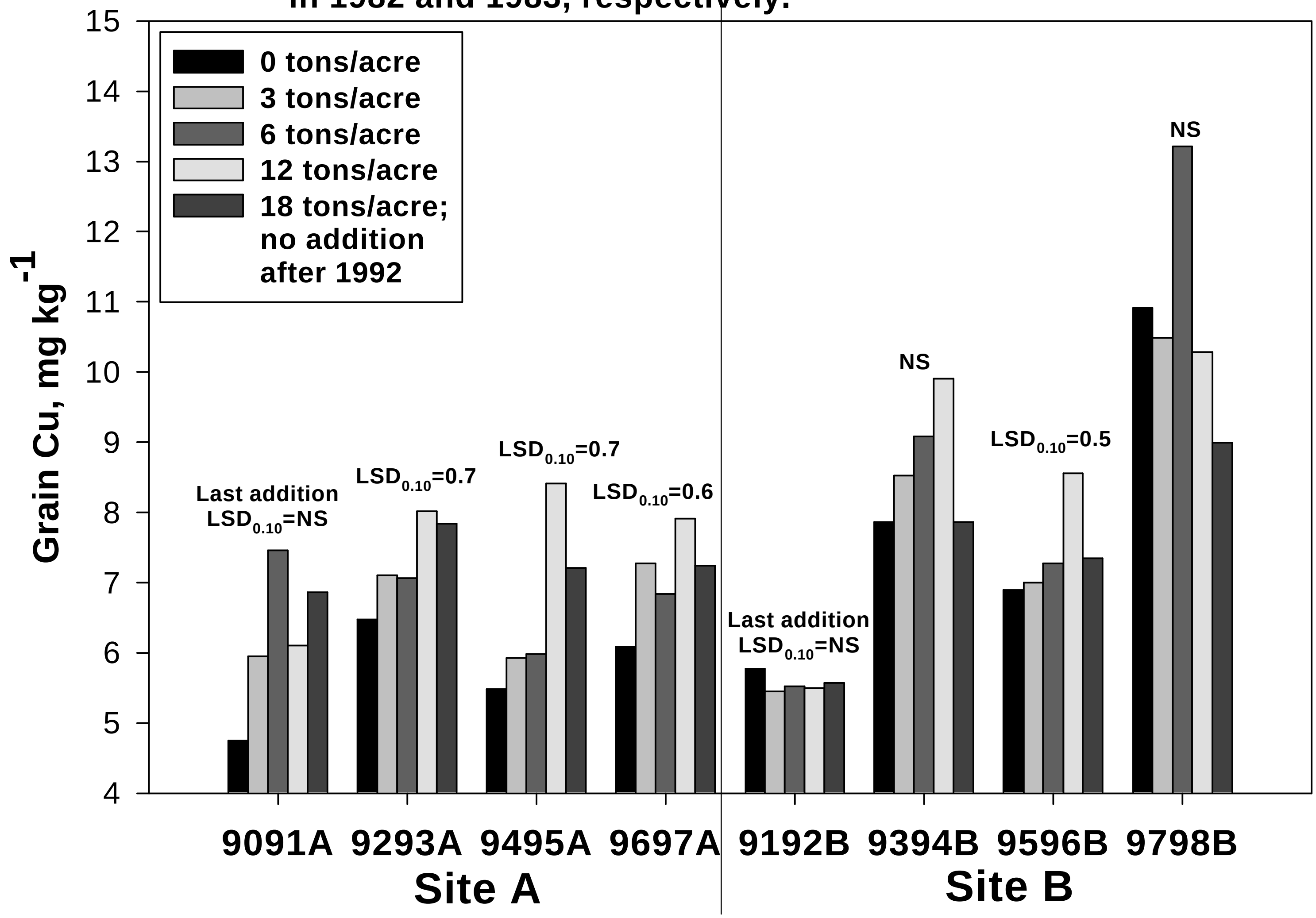
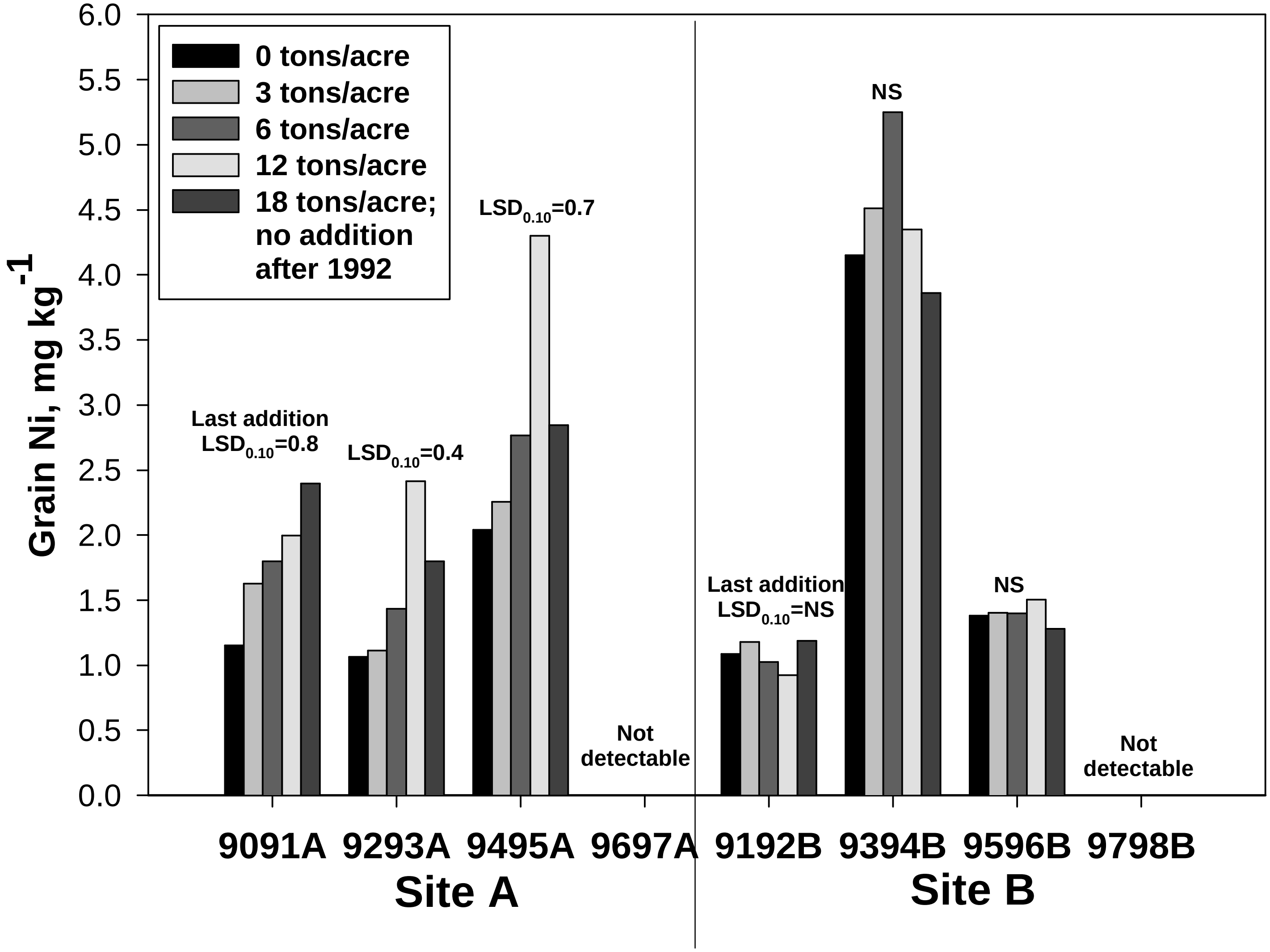


Figure 7: Yearly average grain Ni concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.



We did not construct a figure for the grain Pb concentrations since most of the levels were not detectable.

Figure 8: Yearly average soil pH at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

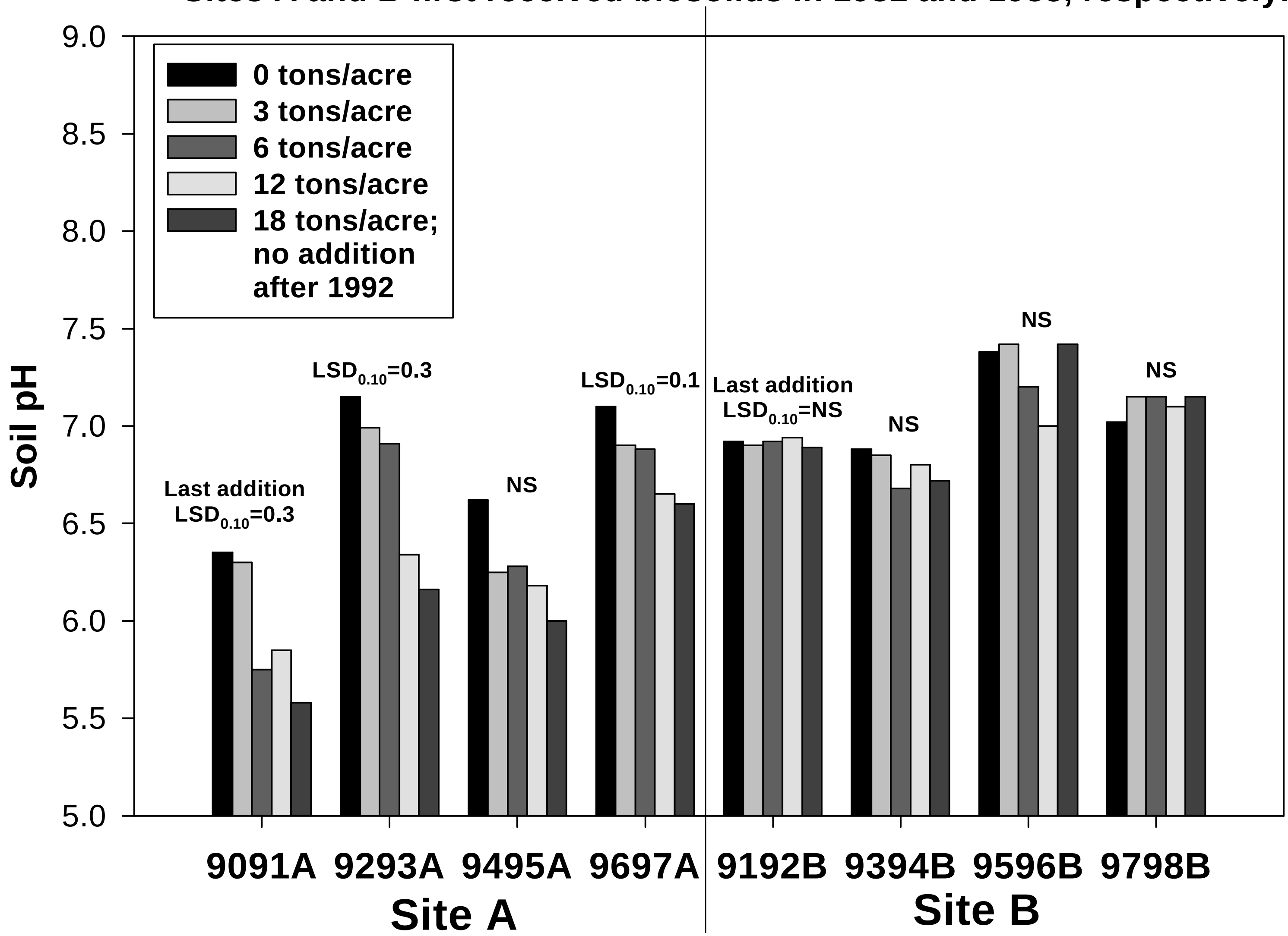


Figure 9: Yearly average soil electrical conductivity (EC) of saturated soil paste at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

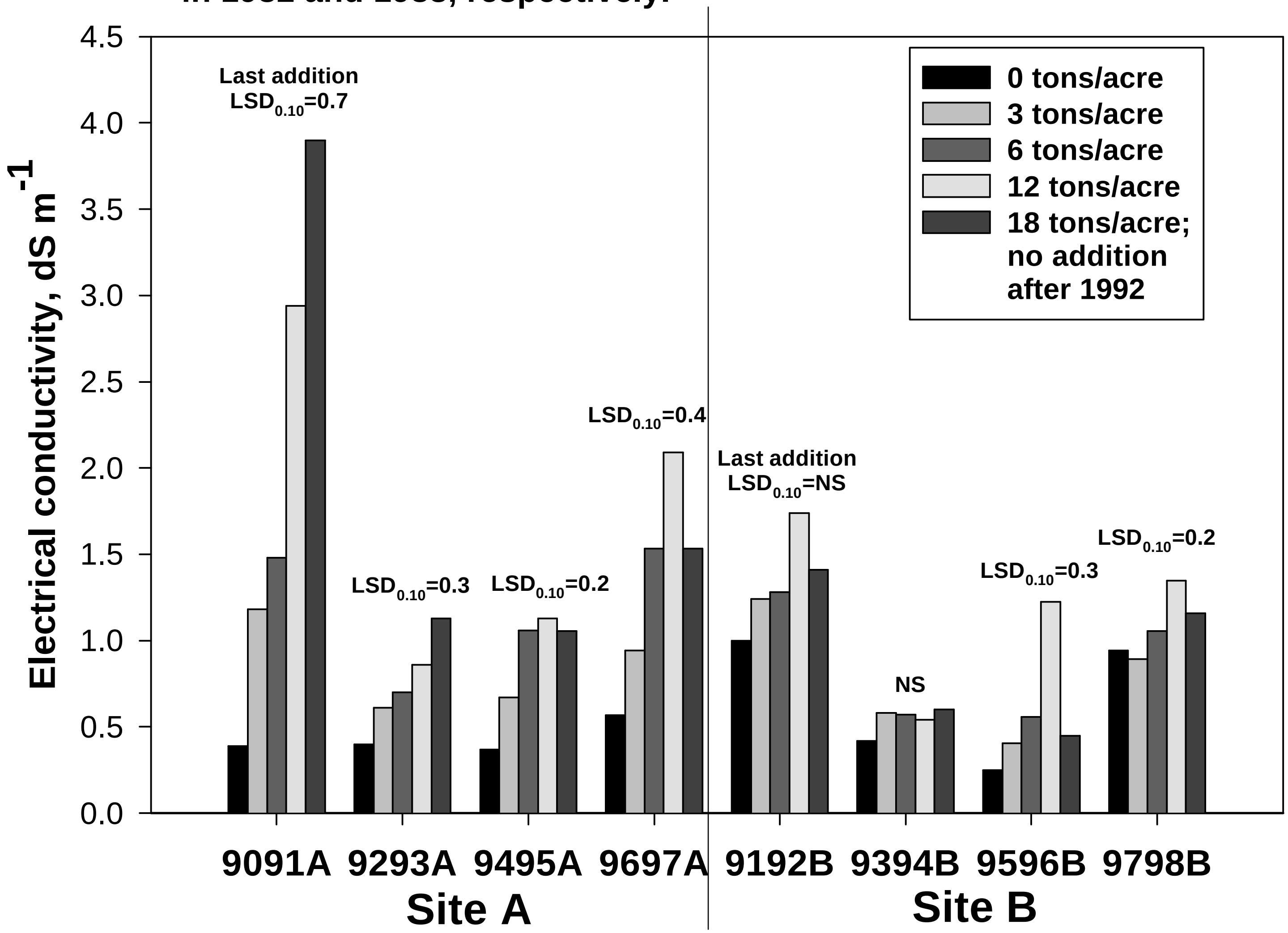


Figure 10: Yearly average soil ABDTPA-P concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

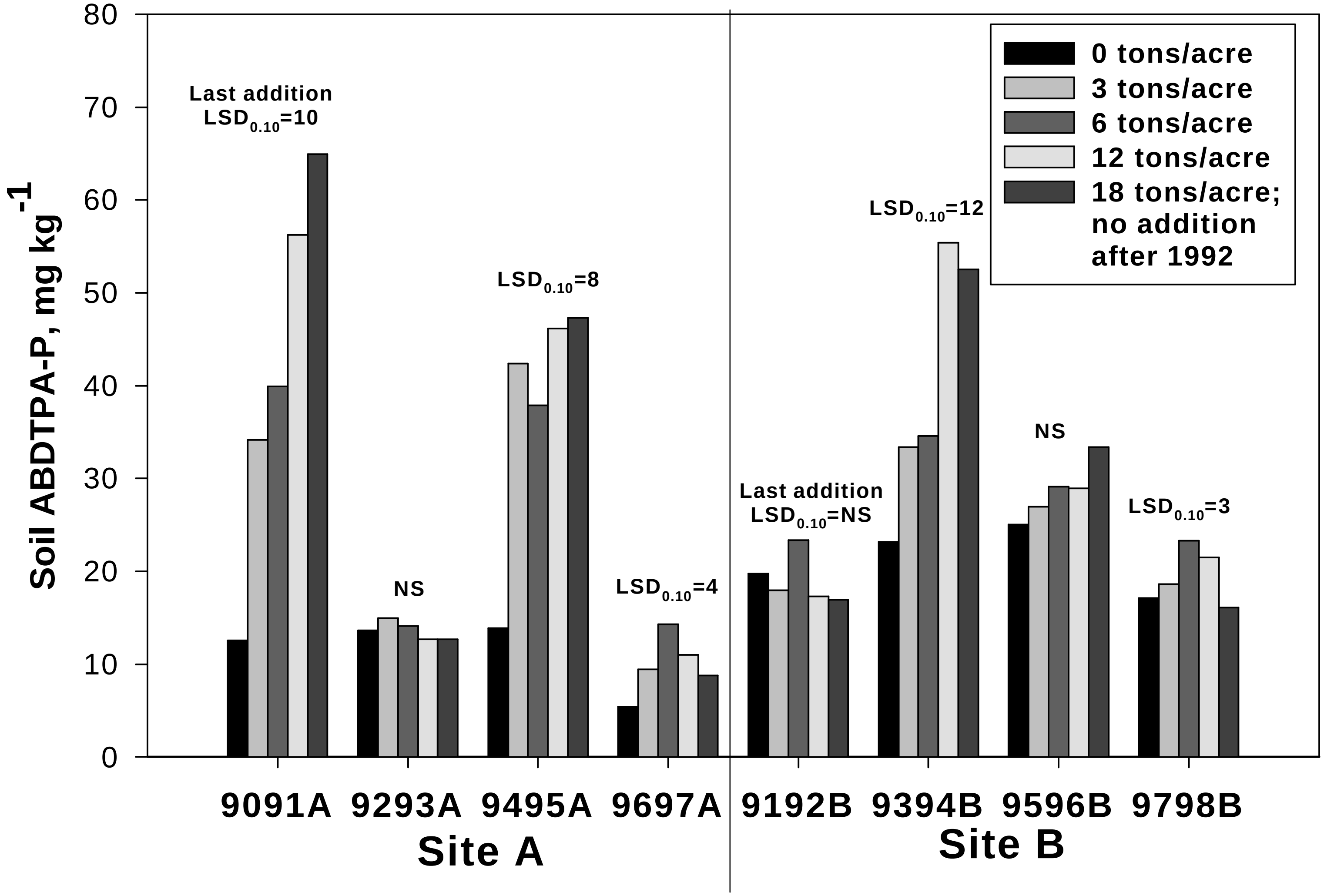


Figure 11: Yearly average soil ABDTPA-Zn concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

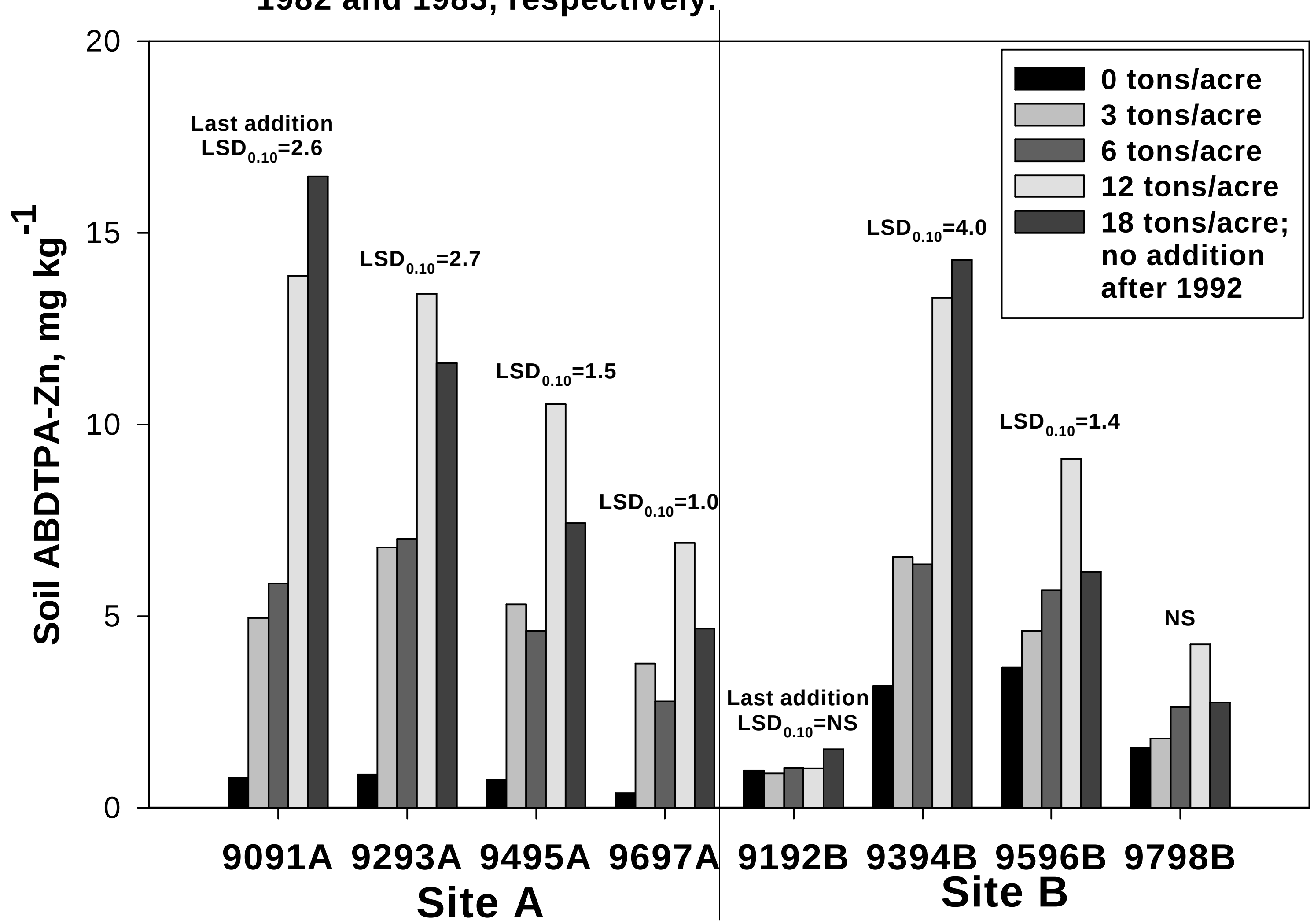


Figure 12: Yearly average soil ABDTPA-Cd concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

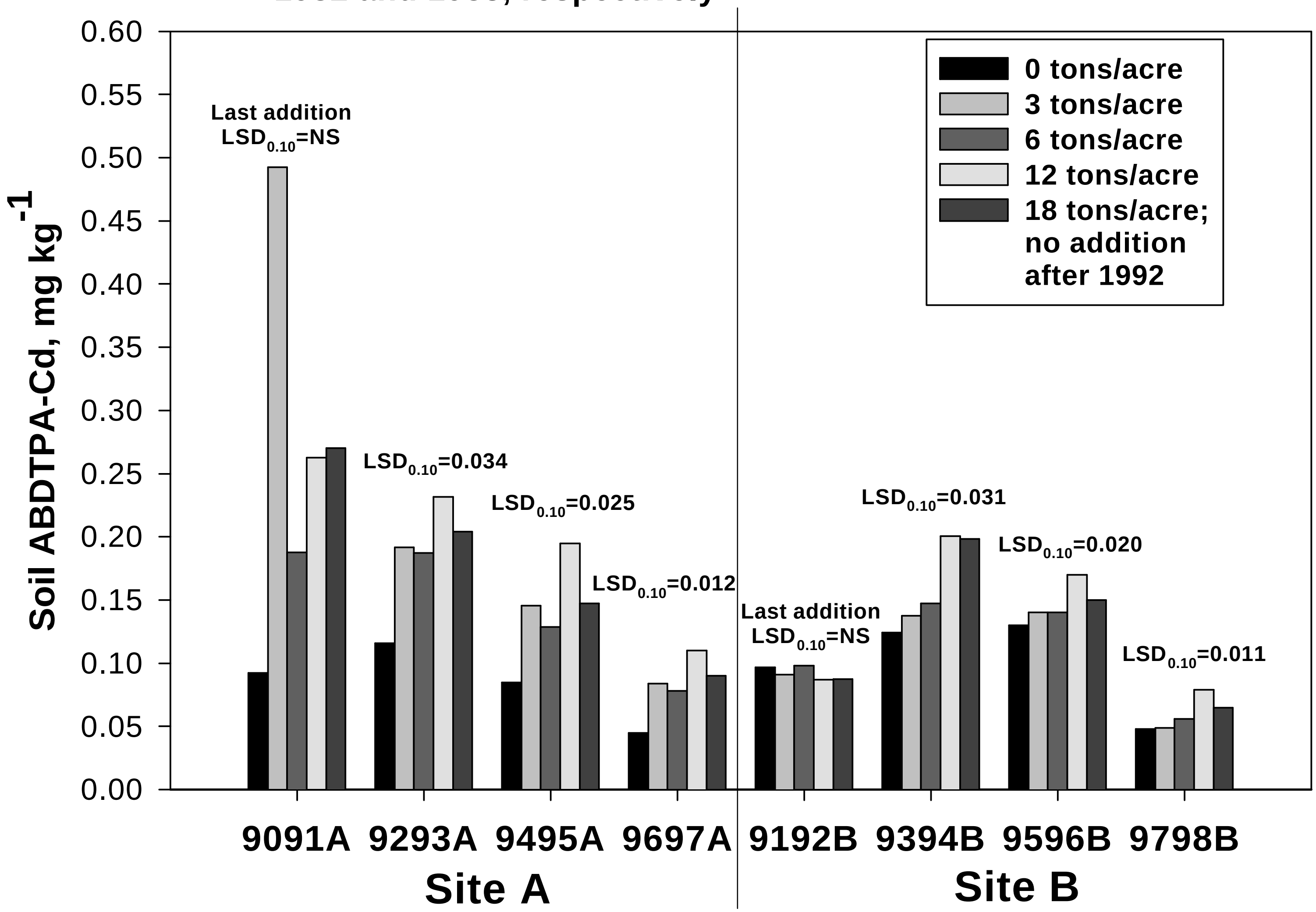


Figure 13: Yearly average soil ABDTPA-Cu concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

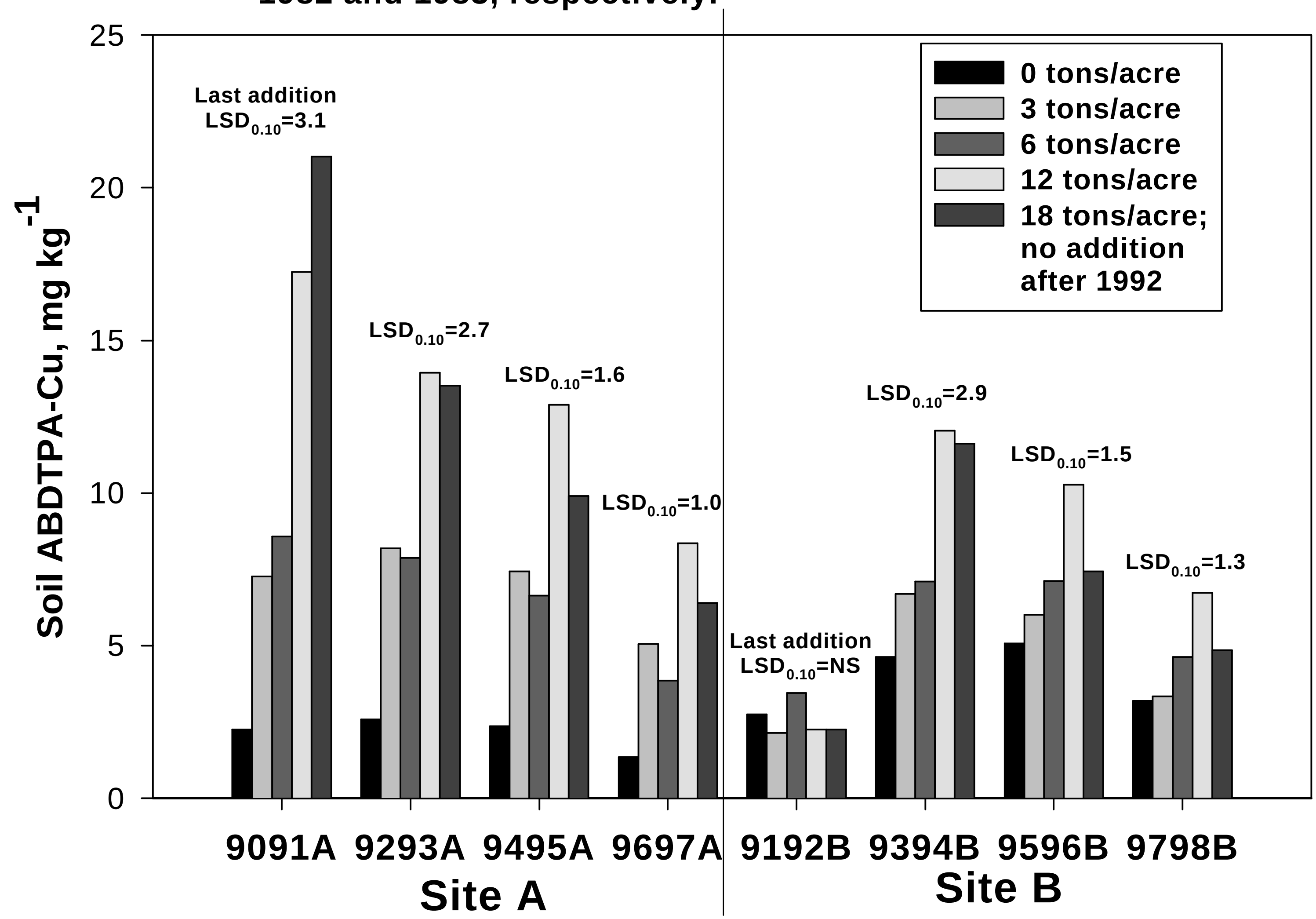


Figure 14: Yearly average soil ABDTPA-Ni concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

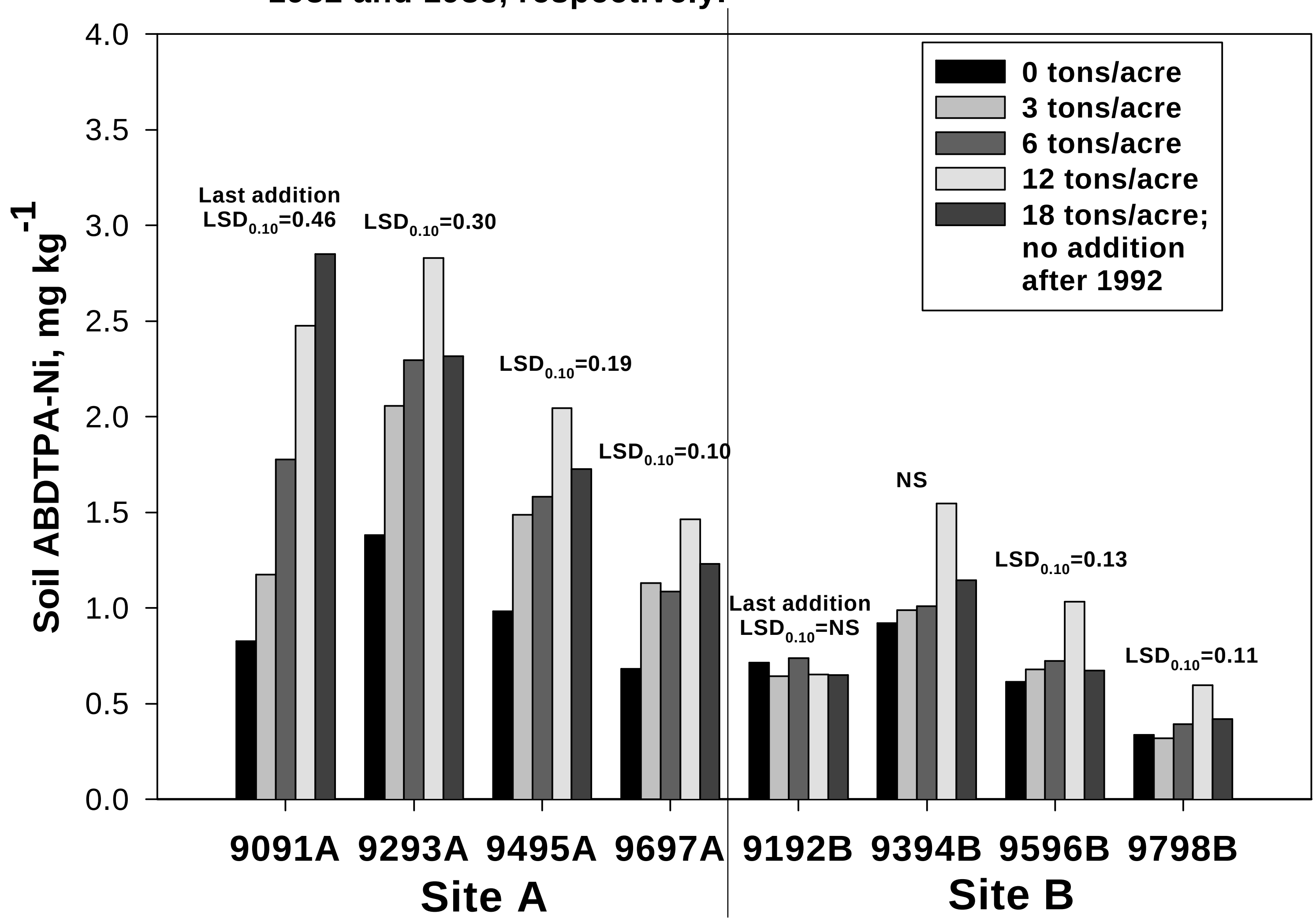


Figure 15: Yearly average soil ABDTPA-Pb concentrations at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

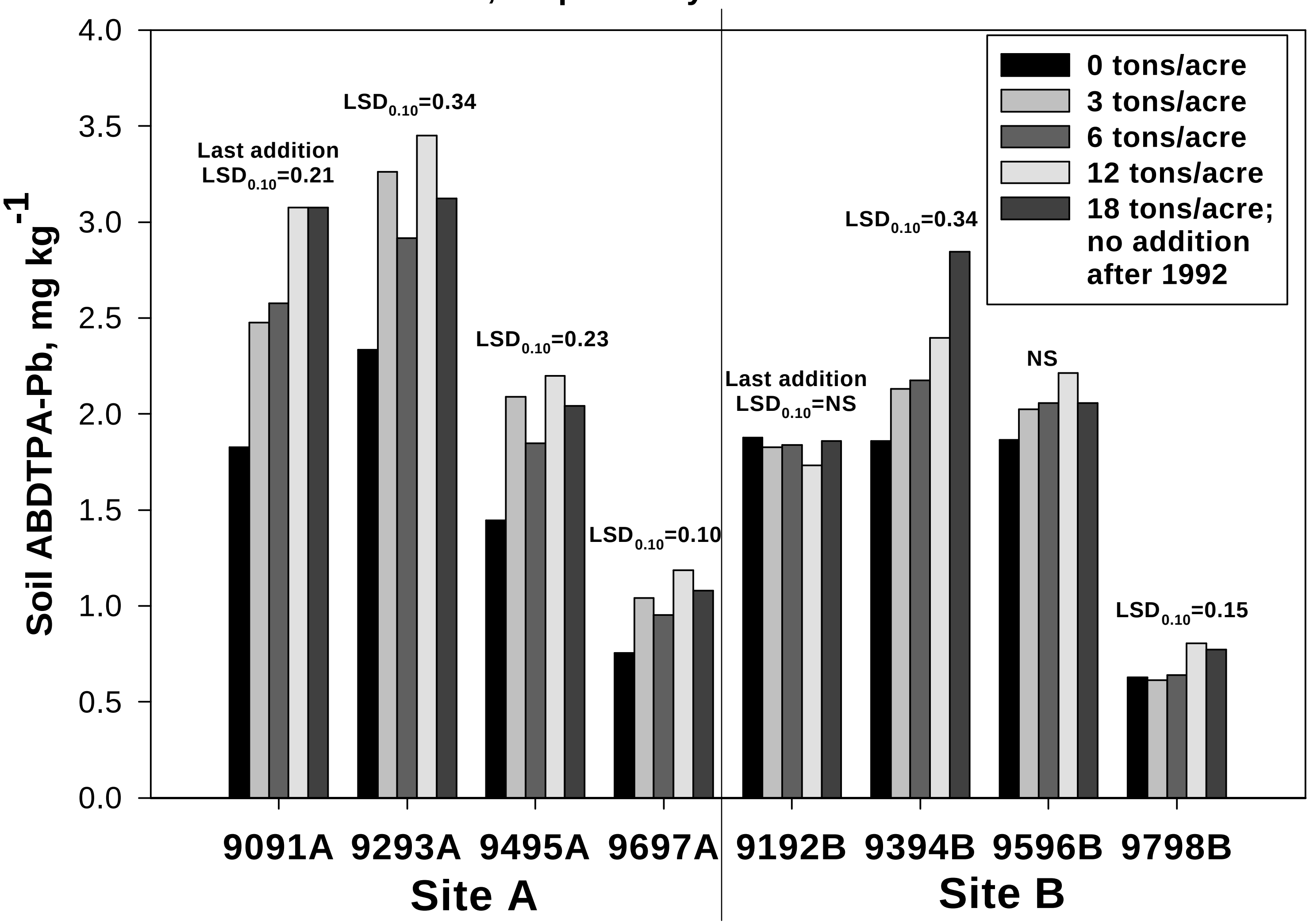


Figure 16: Yearly average soil NO_3-N in 0-8-inch depth at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respecitively.

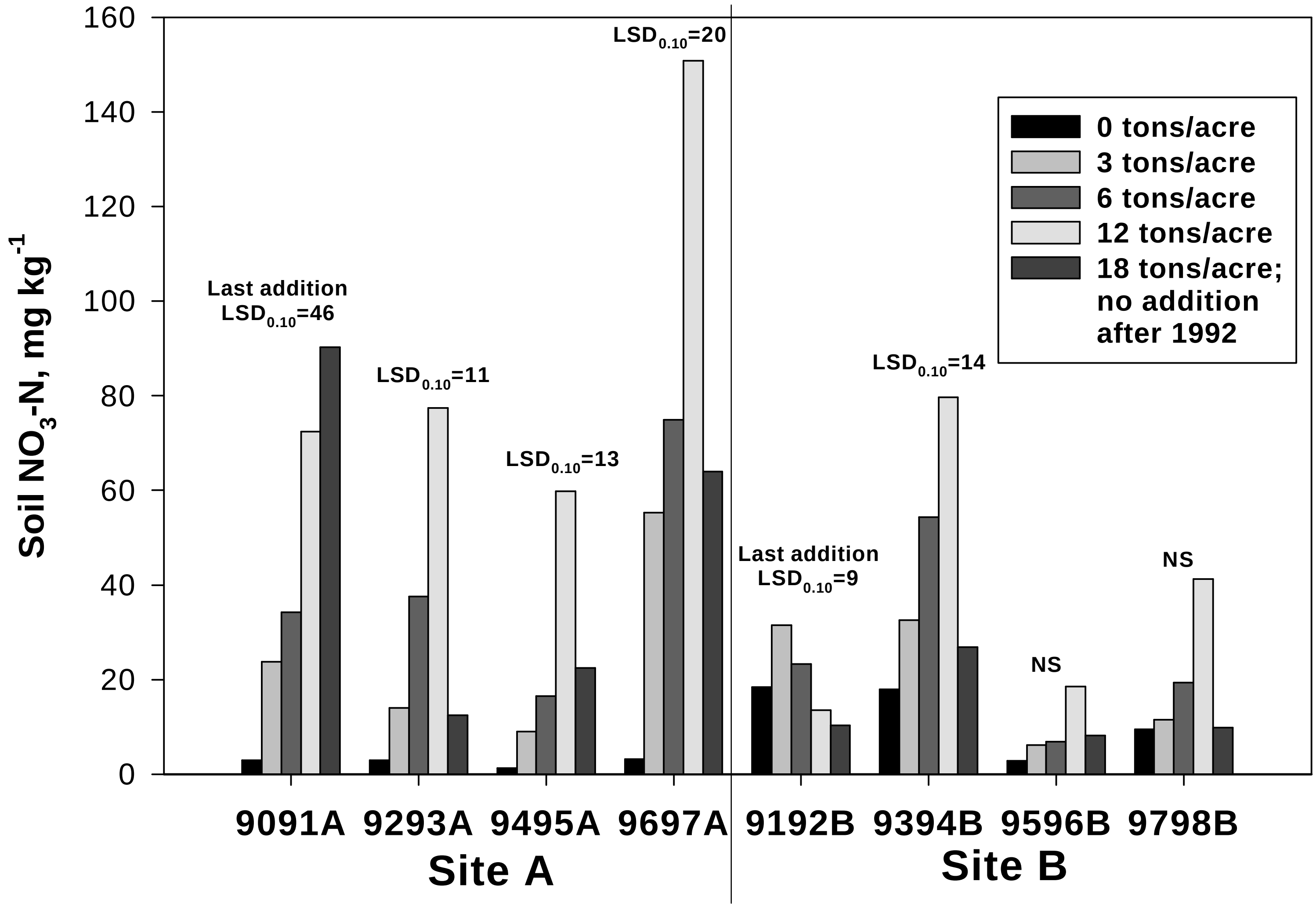


Figure 17: Yearly average soil NH_4-N in 0-8-inch depth at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respectively.

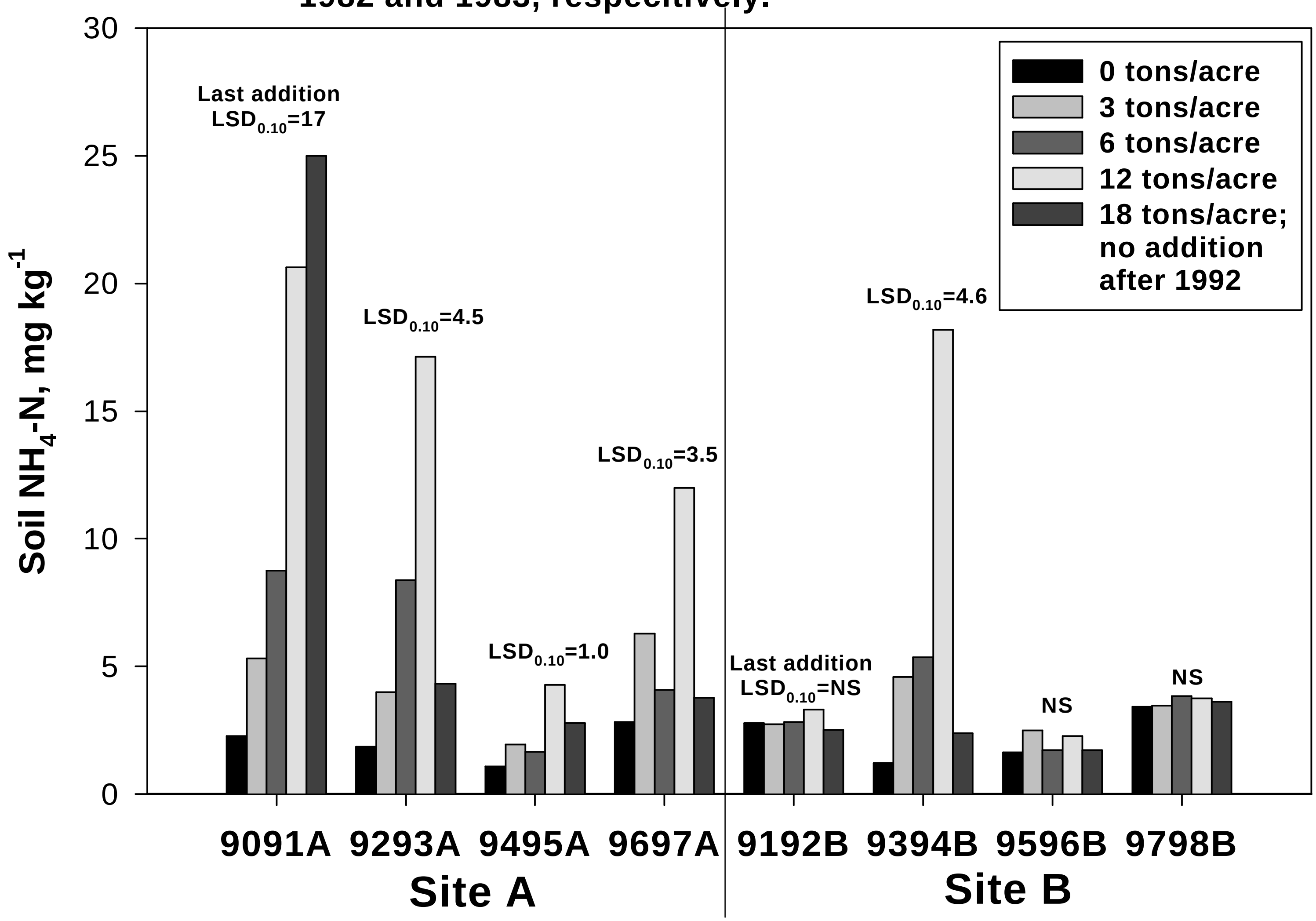


Figure 18: Yearly average soil NO_3-N in 8-24-inch depth at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respecitively.

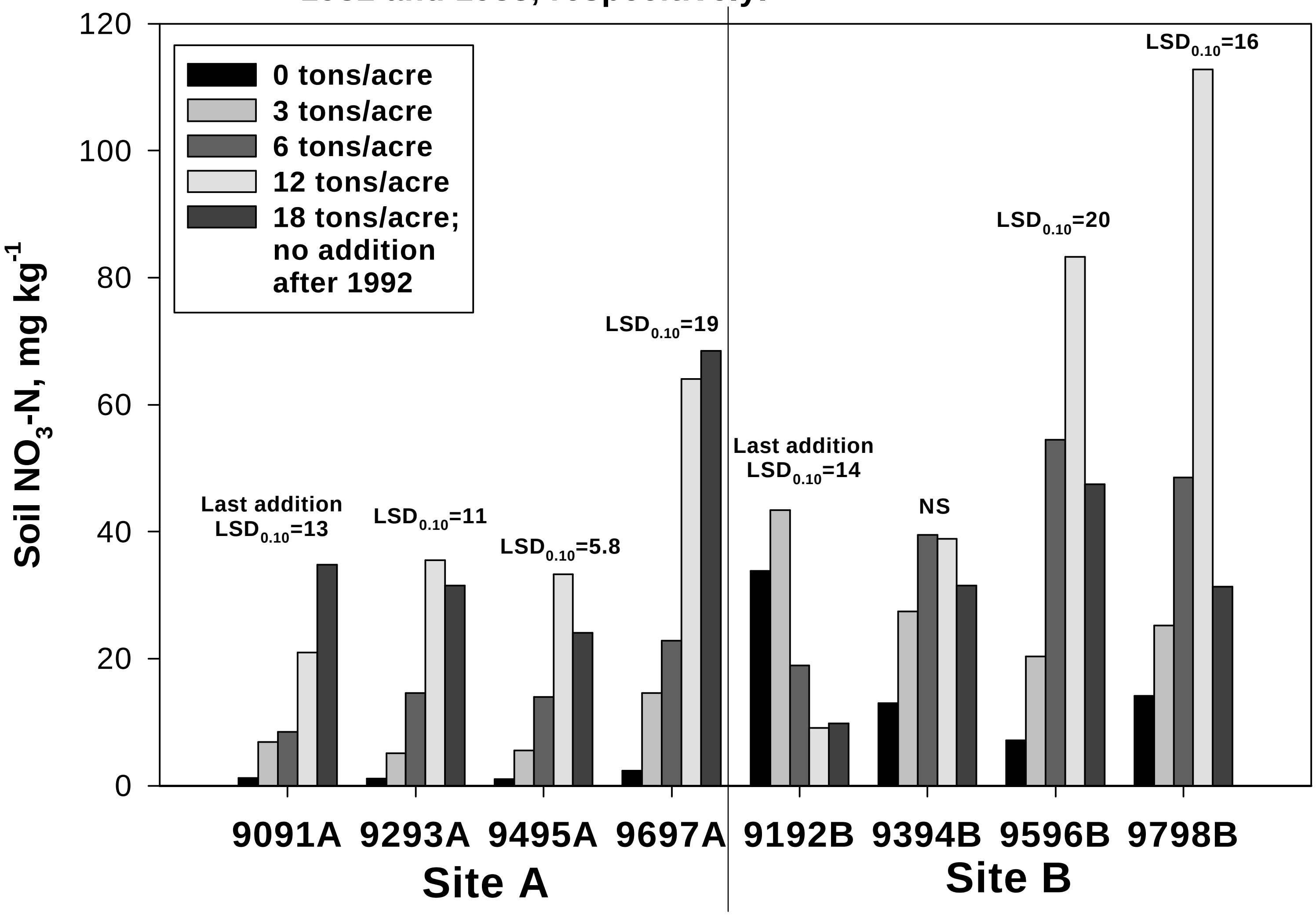


Figure 19: Yearly average soil NH_4-N in 0-8-inch depth at West Bennett, 1990 through 1998. Sites A and B first received biosolids in 1982 and 1983, respecitively.