THESIS

CHANGES IN GOLF COURSE FAIRWAY SOILS UNDER EFFLUENT WATER IRRIGATION

Submitted by

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ABSTRACT

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As the use of effluent irrigation increases, salinity and sodicity issues associated with its use continue to be of great concern to the golf course industry. The purpose of our research was to (i) observe salinity accumulation patterns on 4 fairways of two effluent water irrigated golf courses using 2 different types of sensors and to (ii) determine long-term changes in soil chemistry in soils under effluent water irrigation on golf course fairways.

Temporal and spatial accumulation patterns were measured using a network of in-situ soil sensors located at two depths 15 and 30 cm for 5TE sensors and 8 and 19cm for Turf Guard sensors (TG2). Sensors measured electrical conductivity (EC), volumetric soil water content (SWC), and soil temperature data were collected continuously during the 2008 and 2009 growing seasons. Correlation was observed between 5TE sensor-measured soil salinity vs. saturated paste extracted soil salinity ($r = 0.77$). A significant exponential relationship was observed between TG2 sensor-measured soil salinity vs. saturated paste extracted soil salinity ($R^2 = 0.97$). In-ground measurements indicated that salinity can vary widely across a seemingly homogenous golf course fairway in a manner

reflective of the underlying soil physical characteristics. Plots exhibiting low and high salinities presented opposite seasonal trends at Heritage Golf Course. Strong correlation was observed between average soil salinity and mean soil water content (r =0.76), soil salinity and the percentage of sand in the soil texture composition (r = -0.63) for Heritage fairway 1. High salinity was found on fairway 19 at Common Ground Golf Course. However, the salinity level as high as 10.6 dS/m is not a result of water reuse, but a historical geological contribution. Drainage appears to be vital in maintaining low soil salinity levels under effluent irrigation in clay soils. Slow to infiltrate, percolate and difficult to leach; predominately clay soils irrigated with effluent water can accumulate soil salinity over time. Our data suggested that a robust drainage network in predominantly clay soils irrigated with effluent could better manage salinity accumulation associated with poor drainage.

To determine long-term changes in soil chemistry in soils under effluent water irrigation on golf course fairways, soil testing data was provided by the superintendent for the years of 1999, 2000, 2002, 2003, and 2009 for Heritage Golf Course in Westminster, Colorado. Soil samples were tested by Brookside Laboratories, Inc, New Knoxville, OH. Parameters of each soil sample tested included pH, extractable salt content (calcium, magnesium, potassium, sodium, iron, manganese, copper, zinc, phosphorus , and boron), base saturation percent of calcium, magnesium, potassium and sodium, soil organic matter (SOM), and cation exchange capacity (CEC). Regression analysis was used to evaluate the changes in individual soil parameters over time after the use of effluent water for irrigation. Soil pH, CEC, extractable aluminum, copper, manganese and iron along with both base saturation percentages and exchangeable percentages of calcium and magnesium did not change over time. The strongest indications of change are seen for extractable boron (R^2 = 0.56), Bray II extracted phosphate (R^2 = 0.56), and sodium base saturation percentage (R^2 = 0.44). The regression analysis indicated that B, P, and sodium increased linearly during the 8 year's irrigation with effluent water. Further studies are needed to determine if these parameters would continue to increase or would stabilize. Continued accumulation of sodium could eventually result in loss of soil structure.

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CHAPTER 1

SPATIAL AND TEMPORAL SALINITY ACCUMULATION PATTERNS ON GOLF COURSE FAIRWAY SOILS UNDER EFFLUENT IRRIGATION

Abstract

As the use of effluent irrigation increases, salinity and sodicity issues associated with its use continue to be of great concern to the golf course industry. The purpose of our research was to observe salinity accumulation patterns on 4 fairways of two effluent water irrigated golf courses using 2 different types of sensors. The Heritage (39º 53' 59.34" N 105º 07' 00.04") and Common Ground (39º 42' 53.88" N 104º 52' 09.11") golf courses are in the area of Denver, Colorado. Temporal and spatial accumulation patterns were measured using a network of in-situ soil sensors located at two depths [15 and 30 cm for 5TE sensor and 8 and 19cm for Turf Guard sensor (TG2). Sensors measured electrical conductivity (EC), soil water content (SWC), and soil temperature. Data were collected continuously during the 2008 and 2009 growing seasons. Correlation was observed between 5TE sensor-measured soil salinity vs. saturated paste extracted soil salinity (r = 0.77). A significant exponential relationship was observed between TG2 sensor-measured soil salinity vs. saturated paste extracted soil salinity (R^2 = 0.97).

In-ground measurements indicated that salinity can vary widely across a seemingly homogenous golf course fairway in a manner reflective of the underlying soil physical characteristics. Plots exhibiting low and high salinities presented opposite seasonal

trends at Heritage Golf Course. Strong correlation was observed between average soil salinity and mean soil water content (r =.76), soil salinity and the percentage of sand in the soil texture composition (r = - .63) for Heritage fairway 1. High salinity was found on fairway 19 at Common Ground Golf Course. However, the salinity level as high as 10.6 dS/m is not a result of water reuse, but a historical geological contribution. Drainage appears to be vital in maintaining low soil salinity levels under effluent irrigation in clay soils. Slow to infiltrate, percolate and difficult to leach; predominately clay soils irrigated with effluent water can accumulate soil salinity over time. Our data suggested that a robust drainage network in predominantly clay soils irrigated with effluent could better manage salinity accumulation associated with poor drainage.

INTRODUCTION

Global demand for water increases proportional to population growth and global precipitation pattern changes. Water demand is greatest in arid regions where high quality water is typically allocated for drinking water purposes (Devitt et al., 2004). The use of water for irrigation of landscapes and turfgrass is often viewed as a low priority use for high quality fresh water resources (Marcum, 2006).

Traditional usage of poor quality water for irrigation has left large areas of land unproductive for plant growth (Marcum, 2006; Ghassemi et al., 1995; Pessarakli and Szabolics, 1999). Facing the water demands of present day in the arid and semi-arid regions, high quality water is limited, and sometimes restricted for landscape irrigation (Devitt et al., 2004).

To maintain high quality turf in arid regions where annual precipitation is a limiting factor, irrigation is required (Carrow, 2006). In these geographic regions, conventional irrigation consumes surface and ground water resources, and has a negative impact on the availability, accessibility and reliability of water resources (Pereira et al., 2002).

Saline water resources include poor quality groundwater aquifers, municipal effluent and agricultural drainage (Miyamoto and Chacon, 2006).The use of non-potable water has been mandated in arid areas for turfgrass irrigation (Marcum, 2006 and Lockett et al., 2008).

Effluent is the product of modern wastewater treatment systems. Some of the main constituents include: salts of different types, nutrient elements, and organic compounds (Toze, 2006). The benefits associated with effluent water include its nutrient content and availability, water conservation and reclamation, and nutrient recycle

(King et al., 2000). The contribution of effluent water irrigation to water conservation varies by location. Water reuse satisfied 25% of the water demand in Israel, for example, where 66% of total treated sewage is reused (Lazarova and Asano, 2004). Water reuse is expected to reach 10% to 13% of water demand in Australia and California (Lazarova and Asano, 2004). In the Denver area, effluent water irrigation can free up enough fresh water to supply 40000 to 50000 households. Effluent water contains a range of micro-elements at levels sufficient to satisfy the need of most turfgrasses for these substances. It may also contain enough macro-nutrients, nitrogen (N), phosphorus (P), and potassium (K) to figure significantly in a fertilization program. The economic value of these nutrients can be substantial. Water reuse for irrigation in urban landscapes is a powerful means of water conservation, water reclamation, and nutrient recycling. Due to the dense plant canopy and active root systems, turfgrass landscapes are increasingly viewed as environmentally desirable disposal sites for wastewater. In fact, dense, well-managed turfgrass areas are among the best bio-filtration systems available for removal of excess nutrients and further reclamation of treated wastewater.

Effluent water contains high levels of soluble salts that are undesirable as irrigation water (U.S.G.A., 1994). Effluent water has relatively high sodium concentrations relative to calcium and magnesium (Qian and Mecham, 2005).

Turfgrass systems can be successfully irrigated with effluent water (Thomas et al., 2006) although there are some limiting effects. Effluent water composition is dependent on source and prior uses (Asano, 1987). An approximate inorganic salt load of 300 ppm may result from each single cycle of residential water use (Bishop, 1990). The potential for long-term changes to soil chemistry is attributable to increased salt and other specific element contents of effluent water (Asano, 1987).

Golf course managers are often concerned about salinity and sodicity issues associated with effluent water irrigation. Eighty percent of golf course managers have little or no experience managing golf courses under effluent irrigation (Devitt et al., 2004). A concern is how to maintain soil health, turf quality and water quality. Long-term and continued use of effluent water may lead to increased soil sodicity, and the eventual reduction of soil infiltration, permeability, and aeration in clayey soils that exacerbate salinity problems (Qian and Mecham, 2005).

Sometimes, changes in soil chemistry can be accompanied by changes in the physical properties of soil with effluent irrigation. Coppola et al., 2004 evaluated the hydrological response of soils under effluent irrigation. Distinct changes were observed; surface soil bulk densities increased and hydraulic conductivity decreased. The observed changes in soil hydraulic conductivity under effluent irrigation could lessen the ability of a soil to be effectively leached for excess salts. Effective leaching of soil salts achieves a reduction of soil salinity specifically in a root zone (Carrow et al., 2000).

Changes in soil chemistry were observed when effluent irrigation was used. Mancino and Pepper, 1992 found that increases in ion load and pH did not harm the functional quality of a sandy loam soil; it remained viable for turf growth. Devitt et al., 2007 and Miyamoto and Chacon, 2006 examined salinity accumulation variability along with spatial and temporal patterns of accumulation in effluent irrigated sites. Spatial variability of salinity accumulation was found to be greatest over Aridisol soil types of various depths, deep sandy soils had minimal salt accumulation (Miyamoto and Chacon, 2006). For a golf course that transitions to effluent irrigation the variation of salinity from year to year can be quantified by an equation accounting for the total number of days under effluent irrigation, irrigation system uniformity and the leaching fraction applied (Devitt et al., 2007). Salinization potential can be approximated using an empirical formula accounting for the salinity of irrigation water and soil texture classification (Miyamoto and Chacon, 2006).

Effluent irrigation along the Front Range of Colorado (Denver metropolitan region) has been studied using conventional methods including soil sampling at various depths followed by lab analysis. Qian and Mecham (2005) found significant differences in SAR, EC, and ESP along with extractable(s) sodium, calcium, phosphorus, boron and magnesium and pH between sites using effluent irrigation and those with surface water for irrigation. Further, it is suggested that persistent management practices (such as calcium additions) may be helpful in mitigating some of the negative impacts associated with effluent irrigation.

Temporal and spatial salinity accumulation patterns have also been examined in other regions of the U.S., using in situ sensors to measure soil salinity of putting greens and fairways. Salinity variation observed across 1600 days was nearly twice as great for the fairways when compared to putting greens (Devitt et al., 2007). Fairway soils are natural, unlike the engineered soil system that comprises a United States Golf Association (U.S.G.A.) sand based putting green. Putting greens were found to have less salt accumulation (Devitt et al., 2007).

A study was conducted on Heritage Golf Course (an established effluent irrigated golf course) and Common Ground Golf Course (a course that has recently transitioned to effluent irrigation) between 2008 and 2009. The objectives of this study were (1) to determine temporal and spatial salinity accumulation patterns in fairway soils irrigated with effluent water and (2) to determine the relationship of soil salinity with multiple variables, including soil texture, soil water content, and compaction for the established effluent irrigated course.

METHODS AND MATERIALS

Heritage Golf Course

Heritage Golf Course was one of 12 courses studied in a previous experiment (Qian and Mecham, 2005). Utilization of an effluent irrigated golf course site included in the previous study offered many advantages, including the availability of numerous historical data.

The Heritage Golf Course in Westminster, Colorado is located north of metro Denver near the foothills (39º 53’ 59.34” N 105º 07’ 00.04”). The principal soil series found from the previous study included Renohill, Ulm and Platner (Qian and Mecham, 2005).

Two Perennial ryegrass fairways were selected, fairway 1 at the start of the front nine and fairway 10 at the beginning of the back nine. Within these two fairways individual sensors were installed along transects of uniform turf quality with little undulation. Individual transects were 27.4 meters in length, with a total of six plots spaced at 4.5 meter intervals apart.

At each plot two 5TE sensors (Figure 1) manufactured by Decagon Devices were installed into an undisturbed soil profile at depths of 15 and 30 cm below the soil surface. The 5TE was the latest in Decagon’s ECH2O®-TE sensor series. The 5TE simultaneously monitors soil water content, soil salinity, and soil temperature. Volumetric soil water content is measured using dielectric permittivity of the media adjacent to the prongs. Bulk soil electrical conductivity was measured by a resistance reading via an alternating current applied to a two probe array. The soil temperature was measured by a thermistor housed in the sensor body. Wire leads from each sensor were contained within subsurface conduit and connected to a data logger (Campbell Scientific CR1000 unit) located at the edge of the fairway. Data logging units ran a program that record soil salinity, soil water content, and soil temperature three times daily (6 am, 2 pm and 10 pm). Data loggers were accompanied by a multiplexing unit (Campbell Scientific AM16/32B) and a 12 volt 7.5 amp hour DC battery that was regularly rotated with a freshly charged unit. Installation of sensors was completed in June of 2008 (Figure1.1). Datalogging equipment was removed from the site just before the most extreme months of winter in an attempt to prolong usable investigation lifetime. Data collection on fairways started in August 2008 and concluded in December 2009.

Measurements of soil compaction and texture were taken from the sensor equipped plots on both fairways. Compaction was measured using a digital penetrometer (Field Scout SC-900) periodically during the 2009 growing season. Compaction readings were recorded from surface depths down to 30 cm for the profiles directly adjacent to the sensor installation points for each plot. Turf quality was visually rated on a 1 to 9 scale, with 1 being dead, 9 being dark green, dense, and actively growing turf, and 6 being acceptable turfgrass quality. Quality was rated 11 times with approximately two weeks between readings from mid June until September. Texture analysis consisted of a rudimentary jar test for quantifiable percent compositions (Sammis, 1996) and field ribbon-feel tests.

An irrigation audit was performed on each fairway's study location in early April 2009. Irrigation distribution uniformity was measured by auditing with 126 cups on 1.5 meter grid with 10 minute run times. Distribution Uniformity (DU) was calculated as:

DU = (average water output of the low quarter / average water output) x 100%.

Laboratory Calibration of 5TE

5TE sensor-measured soil electrical conductivity (EC) was compared to conventional saturated paste extracted soil EC to assess data accuracy. Conventional measurement of soil salinity utilizes the electrical conductivity of an extract from a saturated soil paste made using distilled water (U.S. Salinity Laboratory Staff, 1954). Soils with various salinity levels were used for the test ranging from less than 1 dS/m in conductivity up to soils with as high 20 dS/m of conductivity. Soil samples with known salinities were utilized and blended by hand to create the range of salinity values recorded. The sensor measured salinity was taken by placing sensors into a soil sample of approximately 2464 cm^3 in volume with moisture content within the range of 30-40% by volume and manually compacted to a range of 95-105 psi. A total of 22 sensor readings were then taken by running the CR1000 5TE monitoring program used in the field and the soil directly surrounding the sensors prongs (72cm^3) was then removed for saturated paste extraction. Values that were sensor obtained were linearly regressed against the conventionally measured salinity to assess the accuracy of sensor measurement. Using the linear equation derived from the regression analysis, sensor measured values were then adjusted to reflect salinity levels comparable to conventionally measured salinity (saturated paste extraction).

Statistical Analysis Methodology

Pearson Correlations were performed using SAS version 9.2 statistical software to determine the relationships of electrical conductivity, soil water content, compaction, sand percentage, silt percentage, clay percentage and descriptive statistics. Proc Means procedure of SAS was used to determine descriptive statistics including mean, standard deviation, and coefficient of variation.

Common Ground Golf Course

The Common Ground Golf Course in Aurora, Colorado (39º 42’ 53.88” N 104º 52’ 09.11”) was renovated in 2008. Prior to renovation Common Ground Golf Course was using municipal potable water to irrigate turf. Included in the renovation was a transition to municipal effluent water for irrigation. The course reopened at the start of the 2009 golfing season.

Toro Turf Guard Dual Level (TG2) sensors use principles of soil permittivity and frequency response to measure soil water content and salinity of soils. The theory and principles of using permittivity and frequency response to measure soil salinity have been well researched and proven effective with early work being done in the 1970’s by Rhoades and Ingvalson (1971). TG2 sensors use this established method of measurement to simultaneously measure soil water content and soil salinity. The sensors collect data every five minutes. The resolution of the sensors is within 0.1% for all three readings of temperature, EC (dS/m) and SWC. Using two sets of three prongs (6.4 cm x 0.48 cm) positioned 11 cm apart along a body, the sensor can conduct measurements at 2 depths simultaneously cm). The sensor body contains a battery (3-year expected lifetime), the components to produce and monitor a generated frequency along with communication components for radio frequency data acquisition. Data on soil water content, salinity, and soil temperature is relayed by a radio frequency mesh network. The RF mesh network requires signal repeaters and a base-station with broadband internet connectivity. The number of repeaters required is dependent on terrain or obstacles to signal transmission. The station uploads the data to the Golf Vision Interface.

In July of 2009 a total of six Toro Turf Guard Dual Level (TG2) sensors were installed into two Kentucky bluegrass, Annual bluegrass and Perennial ryegrass fairways at the newly renovated Common Ground Golf Course. Three sensors were placed approximately 31 meters apart along the length of fairway 1. Common Ground fairway 1 is situated within an area not previously used as a playable area. Another three sensors were installed into Common Ground fairway 19 within the short course. These sensors were positioned 3 meters apart. Fairway 19 is located in a corner of the property known to be salt prone prior to renovation. All installed sensors monitor soil EC, soil water content and soil temperature at 8 and 19 cm below the soil surface. Soil texture was analyzed by a rudimentary jar test for quantifiable percent compositions (Sammis, 1996).

Laboratory Calibration of TG2

Toro Turf Guard (TG2) sensor-measured soil electrical conductivity (EC) was compared to conventional saturated paste extracted soil EC to assess sensor data accuracy. Conventional measurement of soil salinity utilizes the electrical conductivity of an extract from a saturated soil paste made using distilled water (U.S. Salinity Laboratory Staff, 1954). Soils with various salinity levels were used for the test ranging from less than 1 dS/m in conductivity up to soils with salinity levels as high 20 dS/m in conductivity. A total of 13 soil samples with known salinities were utilized and blended by hand to create the range of salinity values. TG2 sensors were placed into samples of soil with moisture content around 30-40% by volume and manually compacted to a range of 95-105 psi. Sensor readings were then taken using a single base station with no repeaters. After the sensor measurement was taken, the portion of soil immediately surrounding the prongs (82 cm^3) was prepared into a saturated paste and put under a vacuum to collect an extract sample. Non-linear regression analysis was conducted to determine the relationship between sensor measured salinity and the conventional saturated paste extract salinity.

RESULTS AND DISCUSSION

Heritage Golf Course

Laboratory Calibration 5TE

Strong linear correlation was observed between 5TE sensor-measured soil salinity versus saturated paste extracted soil salinity (Figure 1.3, r = 0.77), suggesting these sensors are accurate in monitoring the real-time soil salinity. Using the linear equation derived from regression, sensor measurements were adjusted to salinity values that would be expected from a conventional saturated paste extract (U.S. Salinity Laboratory Staff, 1954). 5TE sensors performed comparably to a similar independent study using stationary soil salinity sensors (Devitt et al., 2007).

Spatial and Temporal Salinity Patterns on Fairways

Spatial and seasonal changes of fairway soil salinity are presented in Figures 1.4A-F and 1.5A-F along with descriptive statistics in Tables 1.1 A-D. Elevated salinity was not found for most plots. Plots 3, 4, 5, and 6 for fairway 1 and plots 2, 3, 4 and 5 for fairway 10 had salinity levels less than 3.

However, soil salinity varied from plot to plot on each fairway. When daily salinity data was averaged over the season for individual sensors, higher salinity levels are present at the cart path side of fairways edges, i.e., plot 2 for Fairway 1 (Figures 1.4B) and plots 1 and 6 for Fairway 10 (Figures1.4A and F). The salinity levels of these plots often exceed 3-4 dS/m, with plot 2 on Fairway 1 reaching 5 dS/m. The salinity threshold of Perennial ryegrass was found to be 5.6 dS/m, with a 50% yield reduction observed at 12dS/m (Kotuby et al., 2000; Brown and Berstein, 1953). Previously, Qian et al. (2001) reported that the salinity levels of 3.2 dS m^{-1} caused 25% shoot growth reduction for a salt-sensitive Kentucky bluegrass cultivar and 4.7 dS m^{-1} for a salt-tolerant Kentucky bluegrass cultivar. Turfgrass grown on fairways was perennial ryegrass (*Lolium perenne* L.). Perennial ryegrass can tolerate soil salinity better than Kentucky bluegrass. It is interesting that plots exhibiting low and high salinities presented opposite seasonal trends, especially from the summer 2008 into the spring of 2009. In early August to September when the weather was relatively dry and routine irrigation was practiced, the low-salt plots had averaged soil salinity less than 2 dS/m whereas the high salt plots had average soil salinity of about 4 dS/m (Figures 1.4A-F and 1.5A-F). As the golf course gradually reduced water input from September to November, high salinity plots increased soil salinity further and low salinity plots showed reduced salinity to below 1.5 dS/m. These patterns continued into the spring of 2009. After reinstallation of the datalogger in March, low-salt plots had average soil salinity less than 1.5 dS/m and the re-start of routine irrigation in late March increased salinity of about 0.5 units in these plots. In contrast, the restart of routine irrigation in March reduced soil salinity about 1 unit to around 4 dS/m on Fairway 1 and 3-4 dS/m on Fairway 10 for the high salt plots (Figures 1.4A-F and 1.5A-F). In April and October of 2009 Colorado experienced higher than average precipitation (Figure 1.2). Soil salinity of the high salinity plots was gradually reduced with each significant rainfall event.

A majority (67 %) of Heritage plots had higher average soil salinity at the 15cm depth than salinities at the 30cm depth. Beneath uniform turf surfaces several different behaviors of soil salinity accumulation may be present. These behaviors include salinity increases over time, salinity fluctuation, salinity reduction, along with similar salinities between depths and salinity differences between depths. Clay soils are slow to drain, causing soil salinity to increase under effluent irrigation. During and after heavy precipitation events, salinity was reduced due to dilution effect. Supplemental drainage via drainage tiles within fairways is often located approximately center of the fairway. It is interesting that plots with higher salinities were positioned further away from centralized drainage. Plots with less salinity were within closer proximity to the drain tile at the center of the fairway.

Soil Water Content

Spatial and seasonal changes of soil water content (SWC) are presented in Figures 1.6A-F and 1.7A-F along with some descriptive statistics in Tables 1.2 A-D. Although the irrigation distribution uniformity ranged from 90 to 92%, there were differences in SWC between plots. Plots 1 and 2 on fairway 1 had SWC mainly within the 40-50 % range which was significantly higher than SWC of other plots (mainly within a 25-35 % range). SWC patterns of The Heritage Golf Course fairway 1's individual plots show that the majority of plots have greater SWC at the shallower depths (Figures 1.6A-F). This result was likely because fairway 1was located on a slope. Water runoff during precipitation and irrigation might have occurred, which would have reduced the amount of water penetrating deeper. Although seasonal variations existed, the general rank of soil water content among plots persisted throughout the season. Plot 1 for both fairways exhibited the greatest SWC levels. Fairway 1 SWC levels appear to decrease with each consecutive plot position further away in proximity from the cart path; plot 5 and 6 had the lowest SWC with little seasonal fluctuation. These plot positions were not within close proximity to centralized drainage tile, yet behaved similar to plots near drainage because of subterranean sand layers. Overall, fairway 10 had greater SWC when compared with fairway 1. SWC levels showed generalized reductions as plot positions became further away from cart path side of fairway as was seen in fairway 1. The high SWC could be a reflection of poor drainage. In April and October of 2009 the study site experienced higher than average precipitation (Figure 1.2).

Soil Compaction

Average compaction values appear to be the greater at 30 cm depth than 15 cm below soil surface for both fairways (Figures 1.8A and 1.8B). Plots at the far edge of fairway 1 show the greatest compaction at the 30 cm depth. On fairway 10 significant differences in soil compaction were not seen among plots. The relationship between compaction and salinity accumulation was not significant in this study. However, other researchers have found upward movement of water increases as surface layer bulk densities became greater (Affleck, 1980). Miyamoto and Chacon (2006) found that compacted soil was more prone to salinity accumulation due to reduced leaching effectiveness.

Turf Quality

The average turf quality rating over time indicated that plots with high SWC had higher turf quality than plots with low SWC for fairway 1 (Figure1.9A). The lower turf quality rating within plots with lower SWC may indicate that turf quality is negatively impacted by limited SWC.

Those plots with lower average quality within fairway 10(Figure 1.9B) did not have significantly lower SWC in comparison to those with higher quality (plots 1-3 and 6). Soil moisture data from fairway 10 indicates that SWC across all plots rarely dropped to 20-25 % with only pre and post season SWC approaching levels as low as 20-

25 %. Poor drainage and lower hydraulic conductivity is most likely the cause of limited SWC fluctuation, which might have limited gas exchange in the root zone.

Soil Texture

On fairway 1, plots 1 and 2 had clay content at 86% in the root zone that we sampled, which is slightly higher than the clay content of other plots, ranging from 78 to 82% (Figure 1.10A). On fairway 10, plots 1 and 2 had highest clay content (83-85%), followed by plots 4, 5, and 6 (77-79%), and plot 3 had the lowest clay content of 65% (Figure 1.10B). Fairway 1 plots with greater salinity also had greater fractions of clay in their texture composition when compared to lower salinity plots that had slightly smaller fractions of clay and larger fractions of sand making up their texture composition (Figure1.4A). However, this relationship was not found within fairway 10.

Pearson Correlation

Strong correlation was found between soil salinity and soil water content (SWC) for both fairways (Tables 1.3A and 1.3B), i.e. plots with higher salinity also exhibited higher SWC. Soil with higher clay content would result in greater soil water retention, exhibiting higher soil water content. Yet this relationship was only observed for fairway 1. The fact that the degree of difference in soil texture is much smaller than the degree of difference in soil water content in Fairway 10 (Figures 1.5A-F and 1.6A-F) suggests that other factors (poor drainage) may have also contributed to the high soil water content. Additional investigation into the porosity of clay soils could further strengthen the findings of this study. Based on these data, it is suggested that poorly drained sites are less effectively leached, maintain higher soil water content, and are prone to long-term soil salinity build up. During periods of elevated atmospheric evaporative demand soil salinity at surface depths could increase. Poor hydraulic conductivity maintains higher soil moisture longer by limiting drainage, along with diluting salinity when considerable precipitation events disperse salinity in soil solution.

Continued operation of these soil sensor systems will provide additional data for further analysis. A better understanding may help us to define the best management practices. Salinity can vary widely across a seemingly homogenous golf course fairway in a manner reflective of the underlying soil physical characteristics. Our data indicated that the level of soil salinity appears to be related to soil texture and soil water content (drainage effectiveness).

Common Ground Golf Course

Laboratory Calibration of TG2

Laboratory testing indicated that Turf Guard sensors-measured soil salinity showed very strong exponential relationship to a conventional saturated paste extracted EC measurement (Figure 1.11, R^2 =0.97).

Toro Turf Guard sensors at the Common Ground Golf Course have been collecting data since their installation in July of 2009. By using the exponential equation derived from regression, sensor measured salinity were converted to conventional measured EC using saturated paste extract (U.S. Salinity Laboratory Staff, 1954).

Technical difficulties with 2 units resulted in a total of four sensors that offered continuous data.

Spatial and Temporal Salinity Patterns on Fairways

Soil salinity at 8 cm depth ranged from 2 to 6 dS/m for Fairway 1 and from 4.5 to 10.6 dS/m for Fairway 19 (Figures 1.23A-B). Fairway 1 exhibited change of soil salinity in responding to irrigation events at both depths. Greater salinity was observed at shallow depths (8 cm) than at deeper depths (19 cm) for Fairway 1. The reason that we observed higher soil salinities at Common Ground when compared to Heritage is because the sensors were installed at shallower soil depths (8 and 19 cm vs. 15 and 30 cm). Surface soil layers are dynamic, transient and complex in nature especially with regards to salinity (Devitt et al., 2007). The same can be said for the level of salinity variation observed thus far for this investigation.

High salinity was found on Fairway 19. Fairway 19 (the short course) is located at a corner of the property, in an area known to be salt prone prior to renovation. Rudimentary soil texture analysis (Jar-test) showed that Fairway 19 has high clay contents (Figures 1.14 B). Common Ground Golf Course was just transitioned to using recycled wastewater in 2009. Therefore it is clear that the salinity levels as high as 10.6 dS/m is not the result of water reuse alone, but has a historical/land-use component. Depression areas and areas lacking natural subsurface drainage to the underground water are more prone to salinity degradation.

Salinity accumulation patterns from the transitional course reflect changes in response to irrigation application events. The majority (83 %) of Common Ground plots had greater soil salinity at the 8 cm depth versus salinities at the 19cm depth. Additional variables need to be quantified in order to compare behaviors between the established effluent course results and those of the transitional effluent course.

Field mapping of soil moisture, salinity, compaction and turfgrass quality has been explored in an attempt to quantify and inventory the variability of field conditions (Carrow et al., 2009). The mapping efforts were aimed to identify management zones within a single golf course that would warrant variable precision management strategies, specifically precision salinity and irrigation management. The Center for Advanced Turf Technology of Toro has developed precision tools and technologies to better manage substantial variations in salinity. Salinity of fairway soils is of particular importance with regards to effluent irrigated golf courses because salinity levels can become elevated enough during peak summer months (Carrow et al., 2009). Salinity accumulation patterns from both the established effluent irrigated course and the newly effluent irrigated course have similarities. Salinity trends from both sites show an ebb and flow type of pattern over time as effluent irrigation is applied in staggered applications. The dynamic nature of these salinity accumulations under effluent irrigation complicates the management strategy for maintaining turf health. Clay soil's resistance to effective leaching is partially attributed to poor drainage characteristics.

Soil Water Content

Soil water content (SWC) data from Fairway 1 indicated that SWC at 8 cm fluctuates in response to staggered irrigation applications (Figure 1.13A). Soil water content at the 20cm depth showed a seasonal reduction. However, we do not know the cause of the dramatic SWC reduction measured by TG sensor #1 on fairway 1 at the beginning of August (Figure 1.13B). An irrigation head malfunction could have resulted in the drop in SWC due to turfgrass evapotranspiration. The SWC of Fairway 19 had less fluctuation between the sensors until around September-October when reduced irrigation inputs significantly reduced soil water content (Figures 1.13C-D). Fairway 19's soil moisture data lack of fluctuation may indicate significant differences of the hydrological characteristics between fairways 1 and 19. The fluctuation of the SWC helps in the gas exchange process of the soil – with the addition of fresh oxygen (O_2) and the expulsion of carbon dioxide (CO_2) produced by the plant roots and microbes.

Soil Texture

Small differences in texture composition can be seen between fairway 1 and 19 (Figures 1.14A-B). Fairway 19 had 3% higher clay content than fairway 1 which may be the result of erosion depositions and long-term weathering. Black layer and areas of anaerobic aroma were noted during the installation of TG2 sensors into Common Ground fairway 19.

Conclusions

Salinity accumulations within a single fairway are highly variable and fluctuate seasonally. The variations observed were partially attributed to soil texture, soil water content, and drainage effectiveness. The relationship between soil salinity and compaction were not significant. The greatest soil salinities for the transitional course were observed within fairway 19, which also had a higher SWC. There is a significant relationship between SWC and soil salinity under effluent irrigation, i.e. higher SWC throughout the season are associated with greater average soil salinity.

Drainage appears to be vital in maintaining low soil salinity levels under effluent irrigation in clay soils. Slow to infiltrate, percolate and difficult to leach; predominantly clay soils irrigated with effluent water can accumulate soil salinity over time. Proper planning, adaptations and cultural practices can help to mitigate some of the negative issues associated with effluent water irrigation. Drainage could be aided by the installation of multiple drain tiles at both the edges and center of fairways. Our data suggested that a robust drainage network in predominantly clay soils irrigated with effluent could better manage salinity accumulation. The salinity variations on golf courses may be managed by modern precision technology (Carrow et al., 2009).

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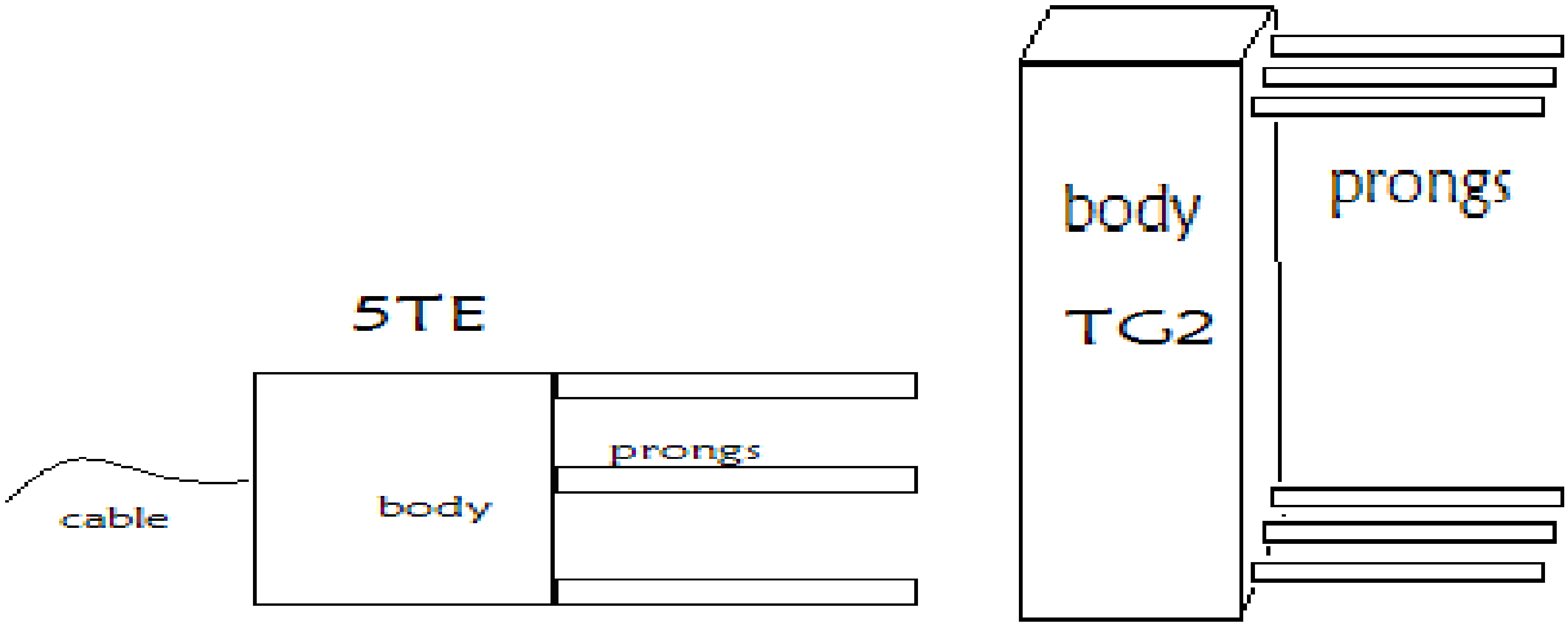

Figure 1 Simple diagrams of the 5TE sensor(s) used at the Heritage Golf Course in Westminster, Colorado and of the TG2 sensor(s) used at the Common Ground Golf Course in Aurora, Colorado.

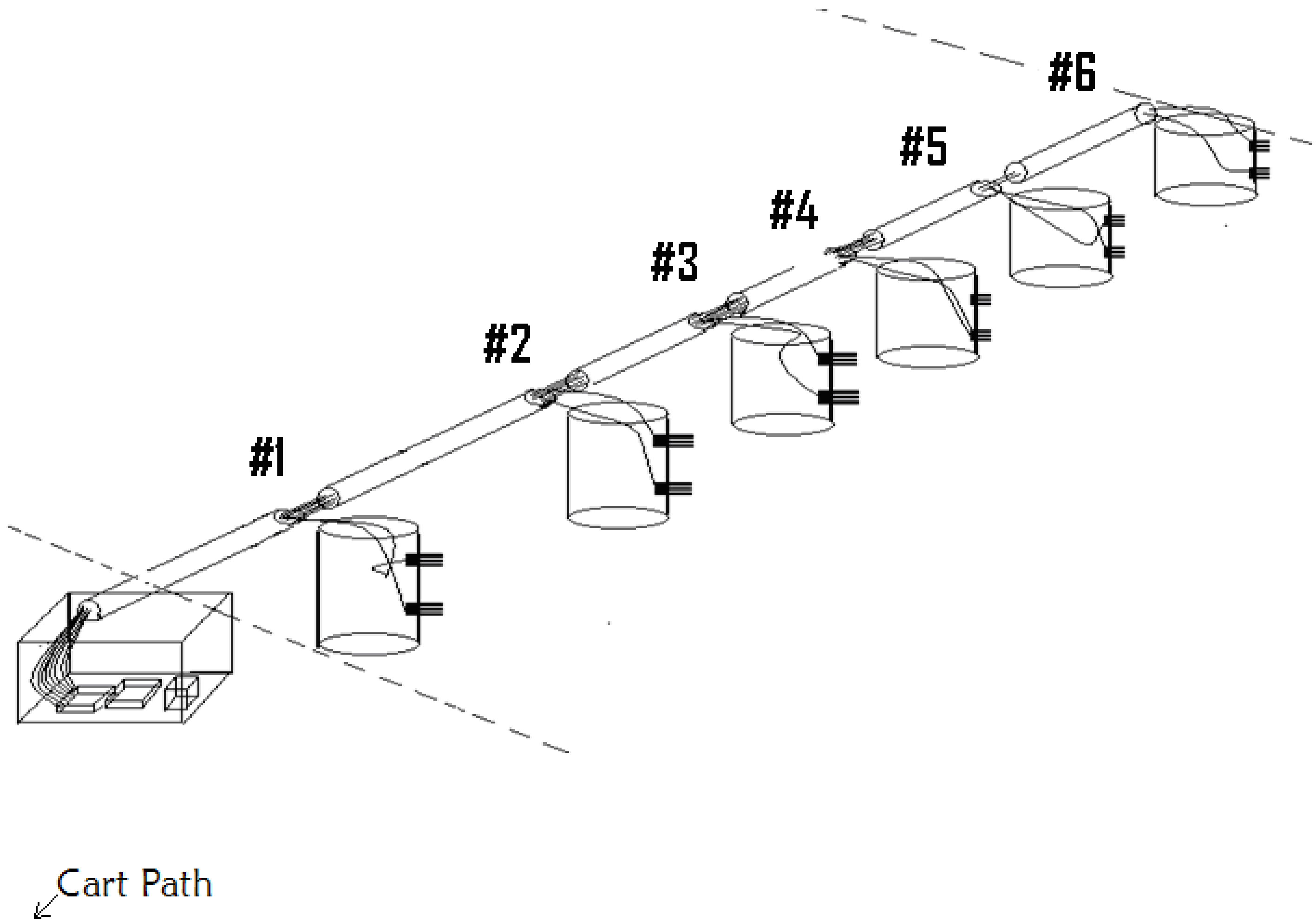

Figure 1.1 5TE system design at the Heritage Golf Course in Westminster, Colorado.

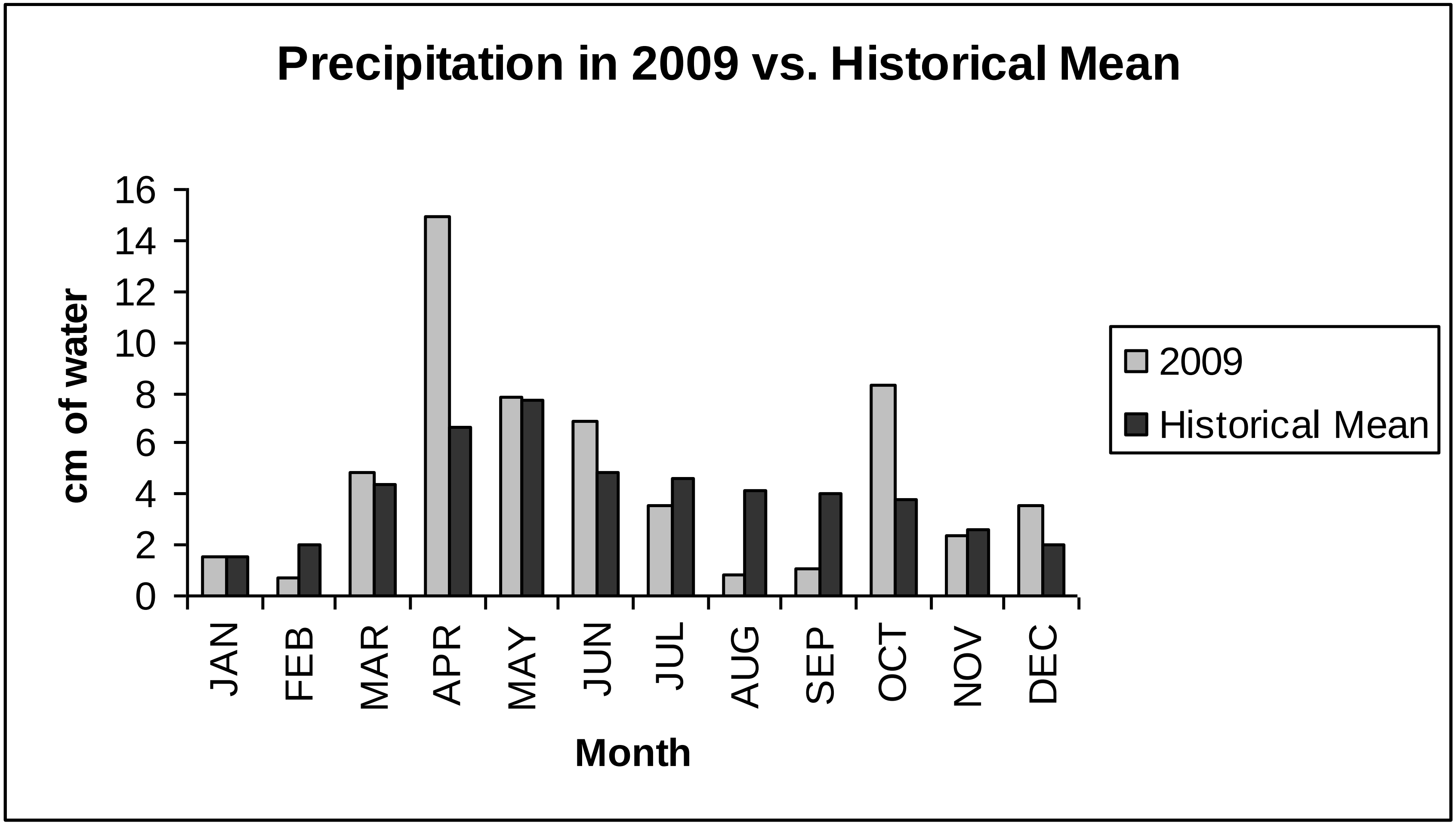

Figure 1.2 Monthly 2009 precipitation amounts versus historical monthly mean precipitations. Data compiled from National Oceanic & Atmospheric Administration Lab (NOAA) in Boulder Colorado. Historical Mean for years 1893-2008.

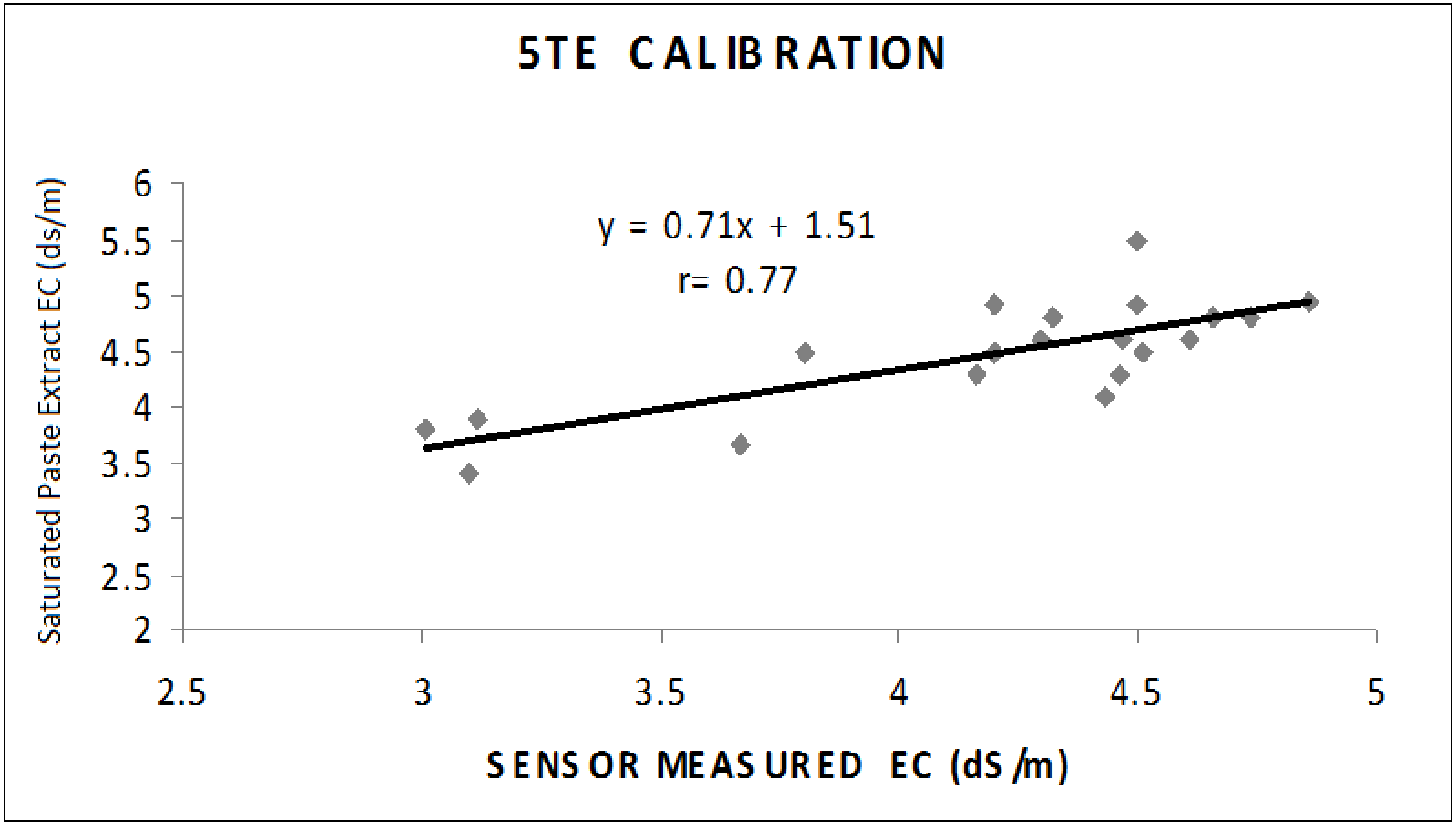

Figure 1.3 Sensor measured electrical conductivity (EC) was linearly regressed against conventional saturated paste extract electrical conductivity (EC).

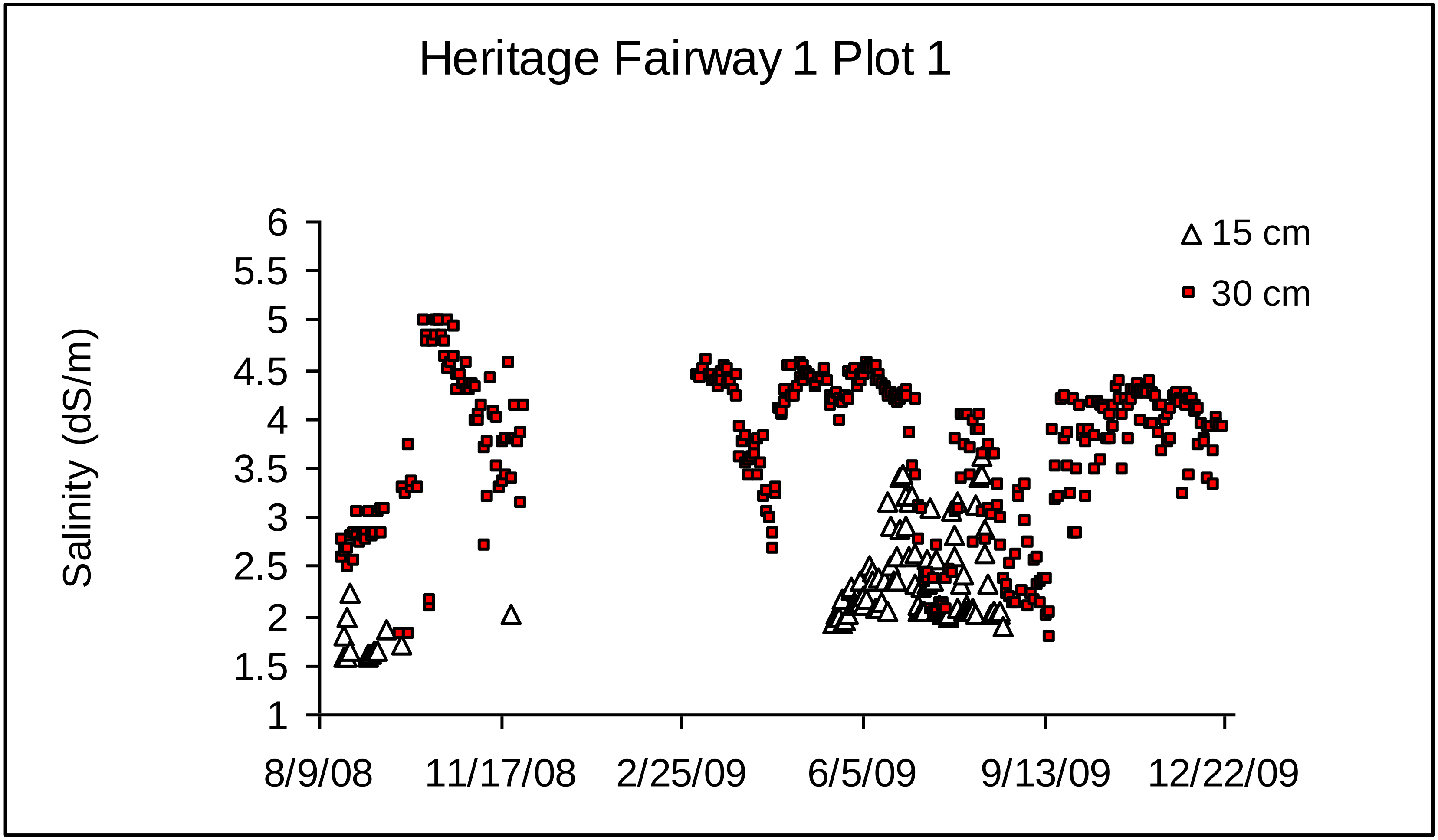

Figure 1.4A Salinity accumulation patterns of Heritage fairway 1 plot 1. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

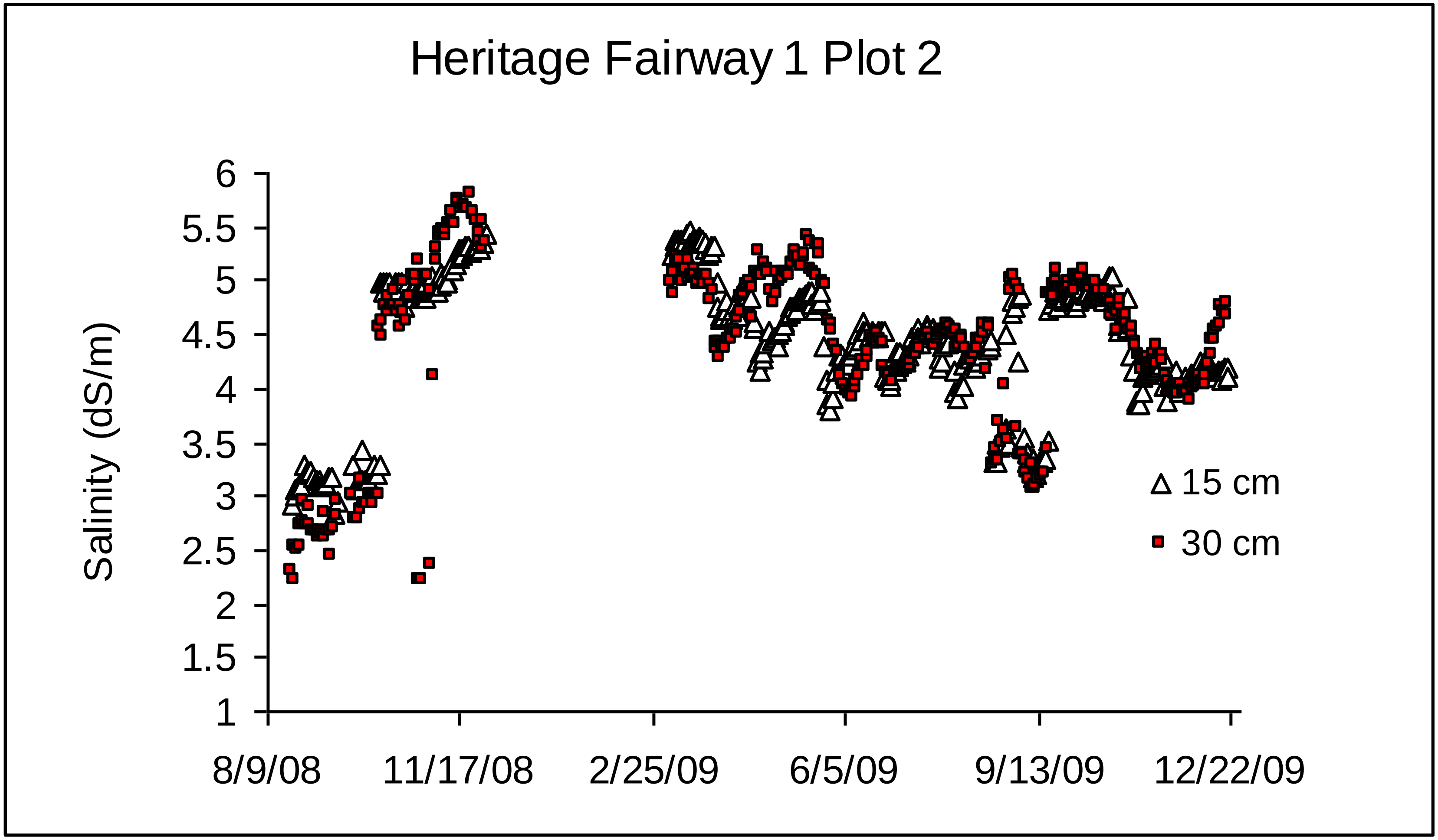

Figure 1.4B Salinity accumulation patterns of Heritage fairway 1 plot 2. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

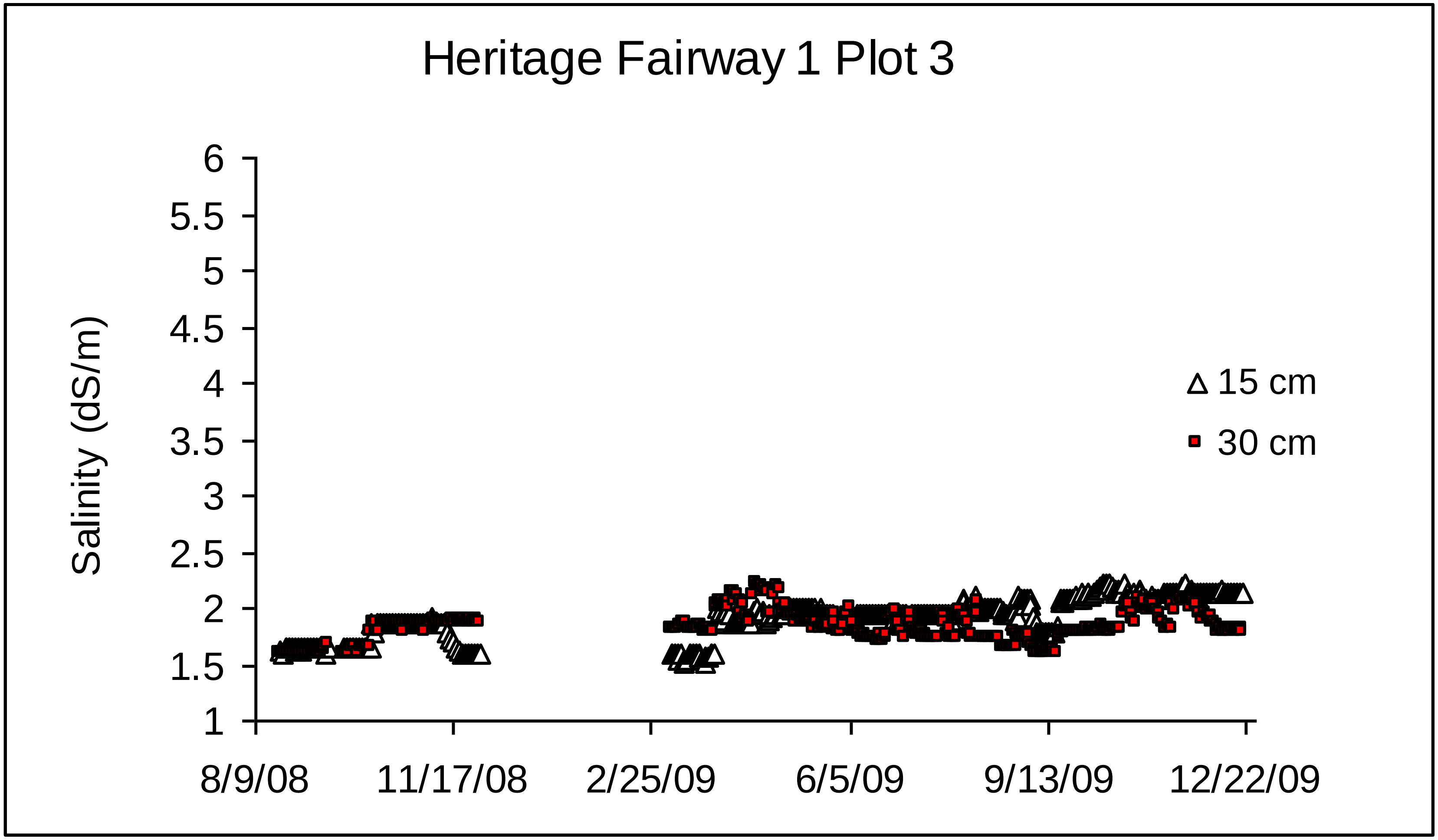

Figure 1.4C Salinity accumulation patterns of Heritage fairway 1 plot 3. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

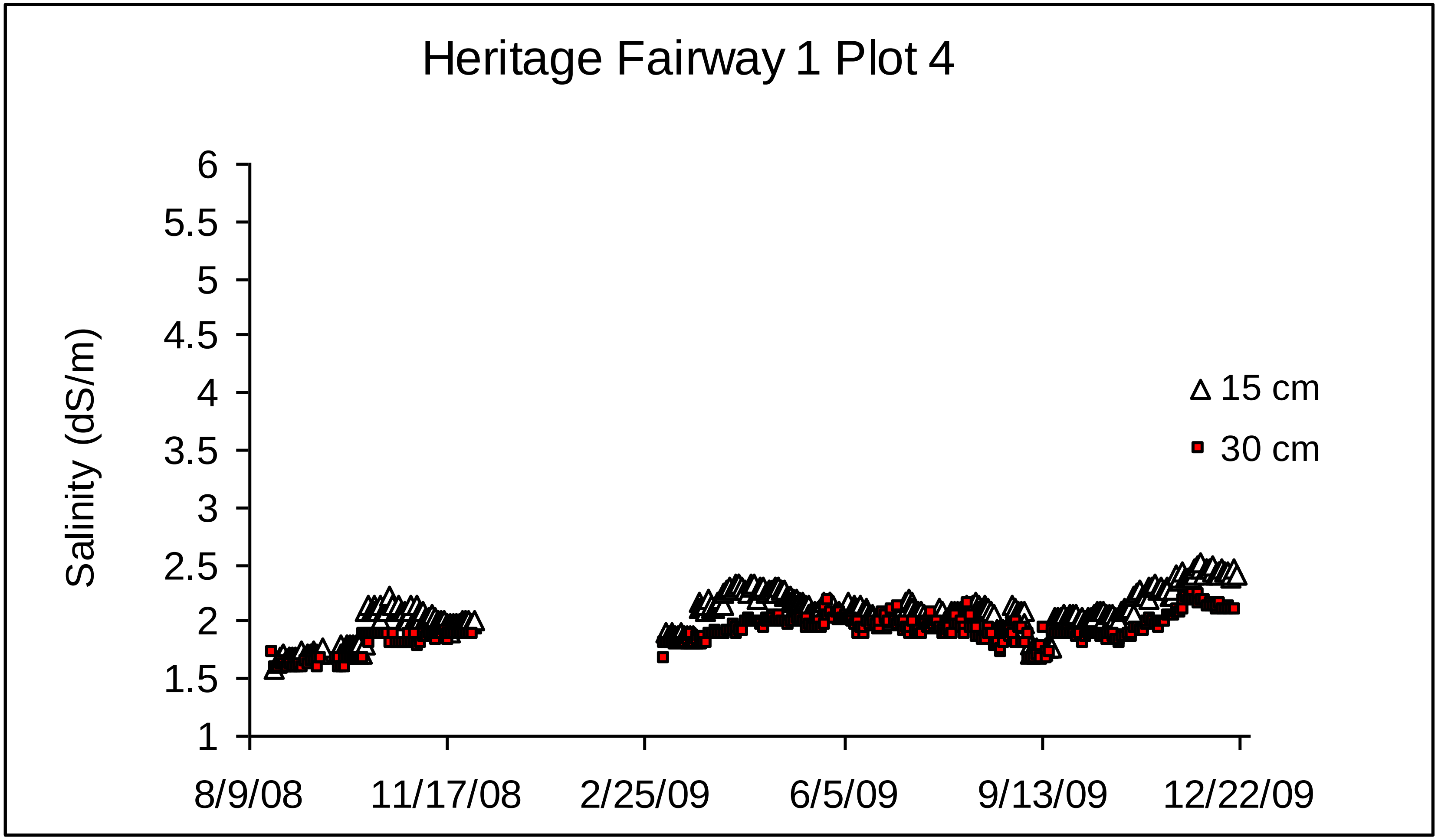

Figure 1.4D Salinity accumulation patterns of Heritage fairway 1 plot 4. 5TE sensors were installed at depths of 15cm and 30cmbelow the soil surface. No data was recorded from November 31 2008 through to March 2009.

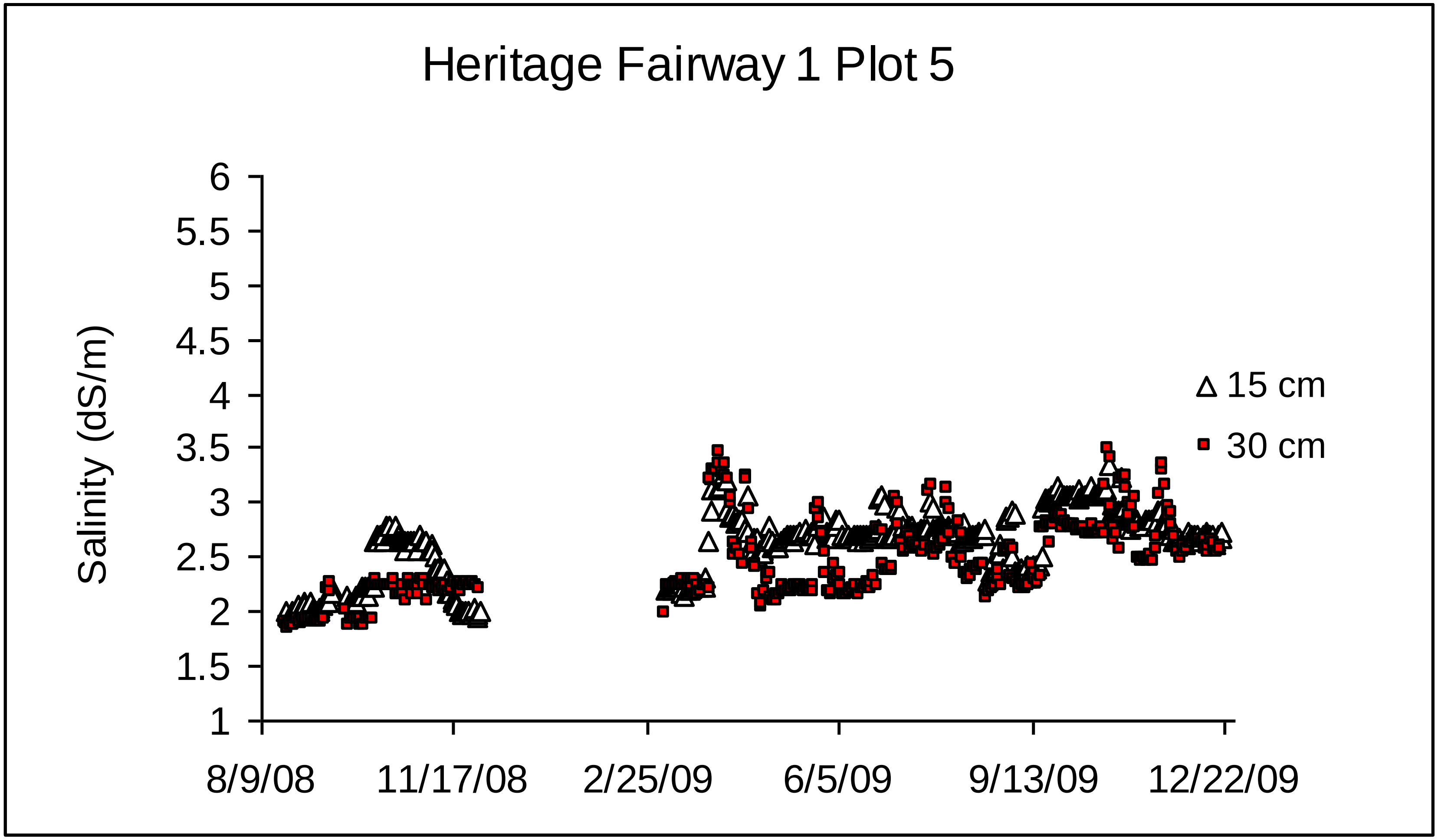

Figure 1.4E Salinity accumulation patterns of Heritage fairway 1 plot 5. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

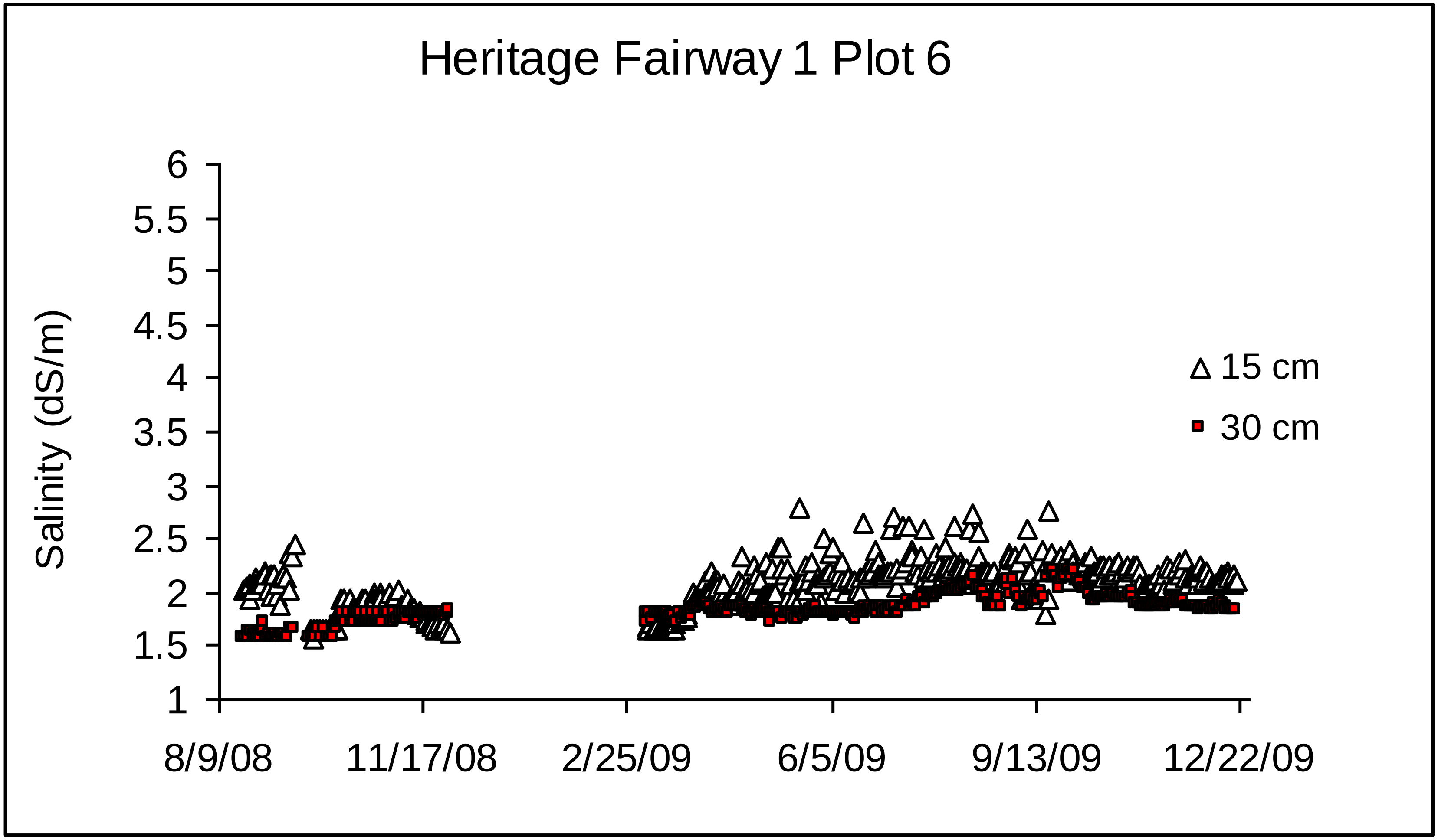

Figure 1.4F Salinity accumulation patterns of Heritage fairway 1 plot 6. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

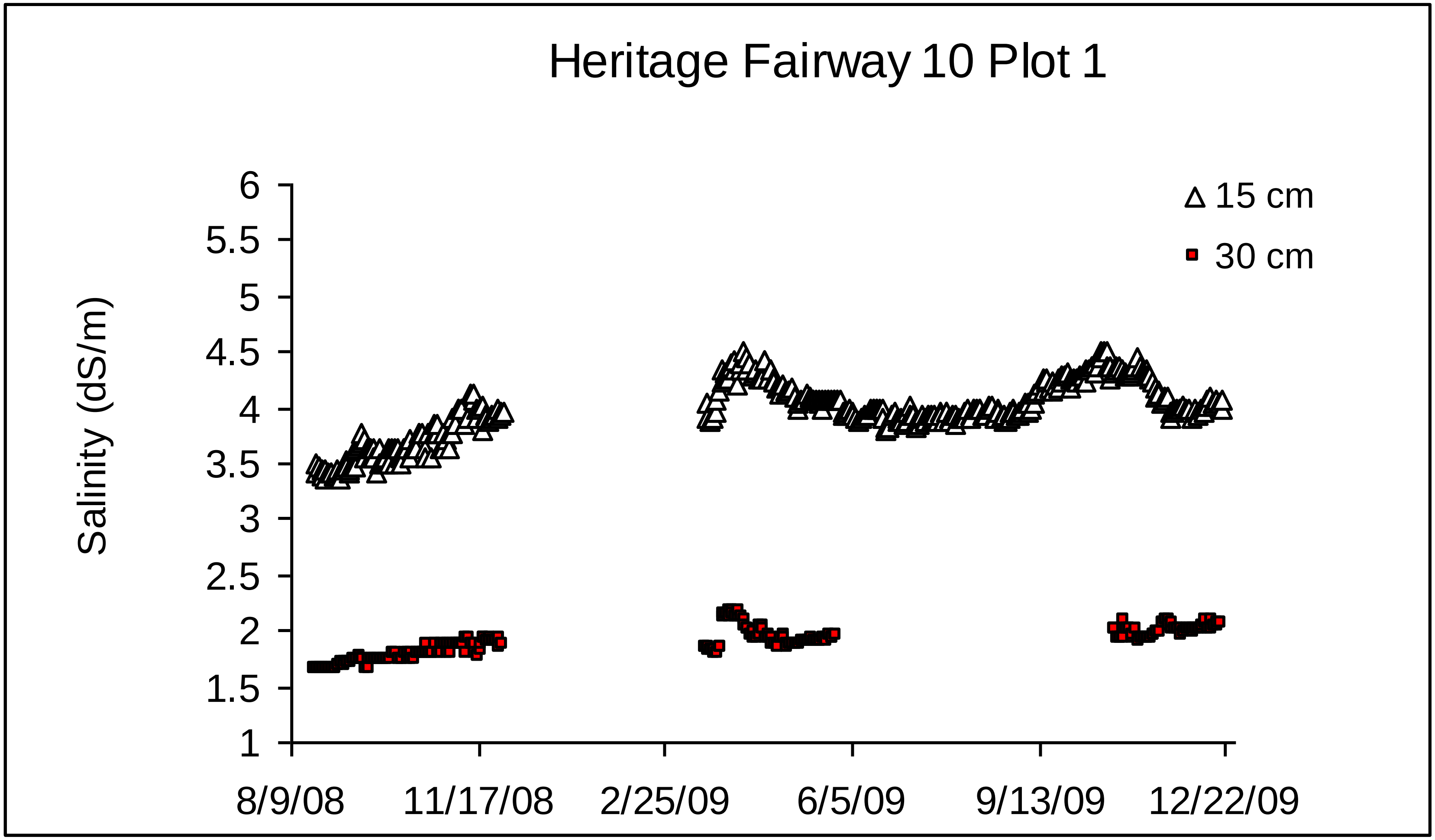

Figure 1.5A Salinity accumulation pattern of Heritage fairway 10 plot 1. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

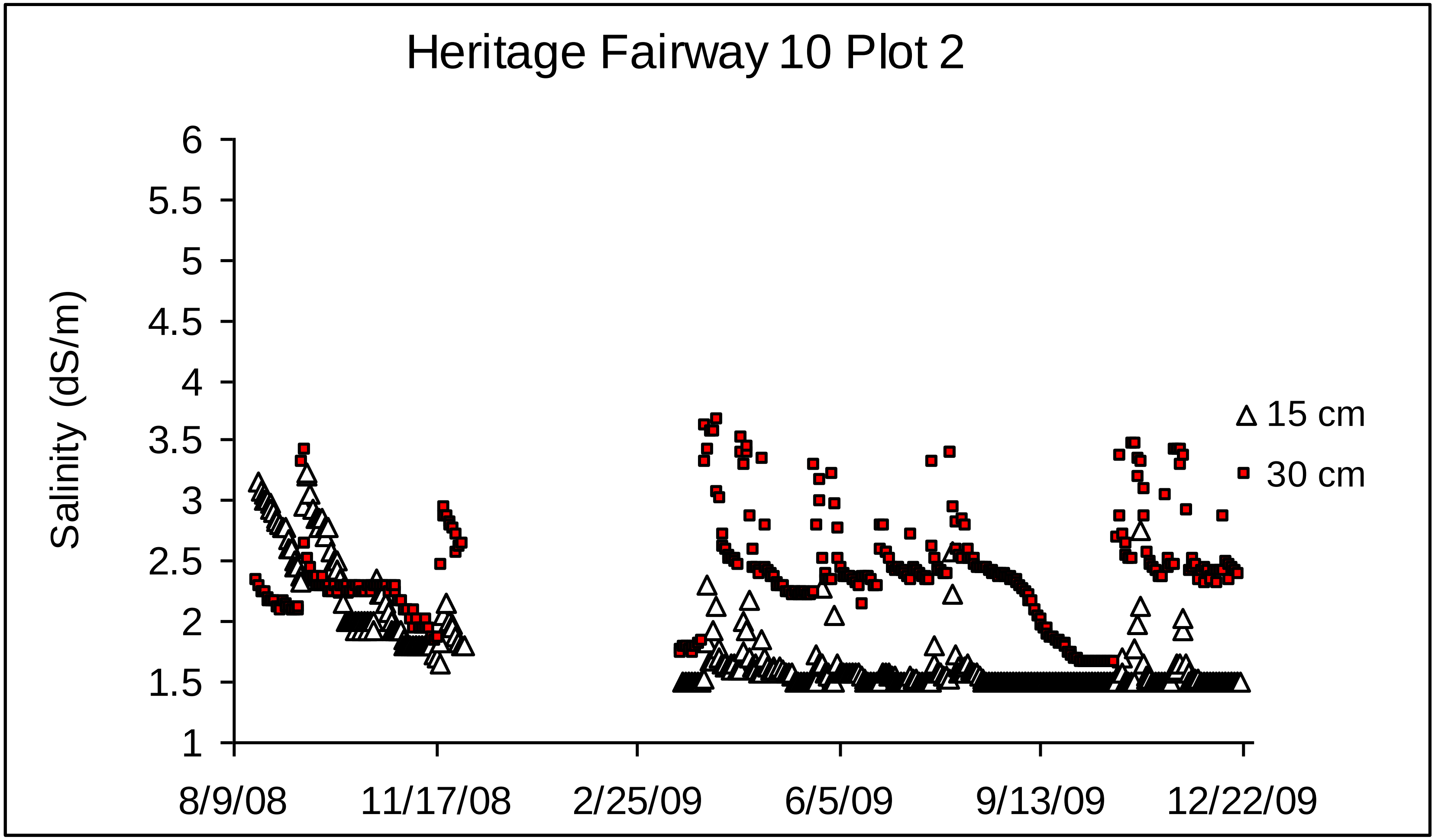

Figure 1.5B Salinity accumulation pattern of Heritage fairway 10 plot 2. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

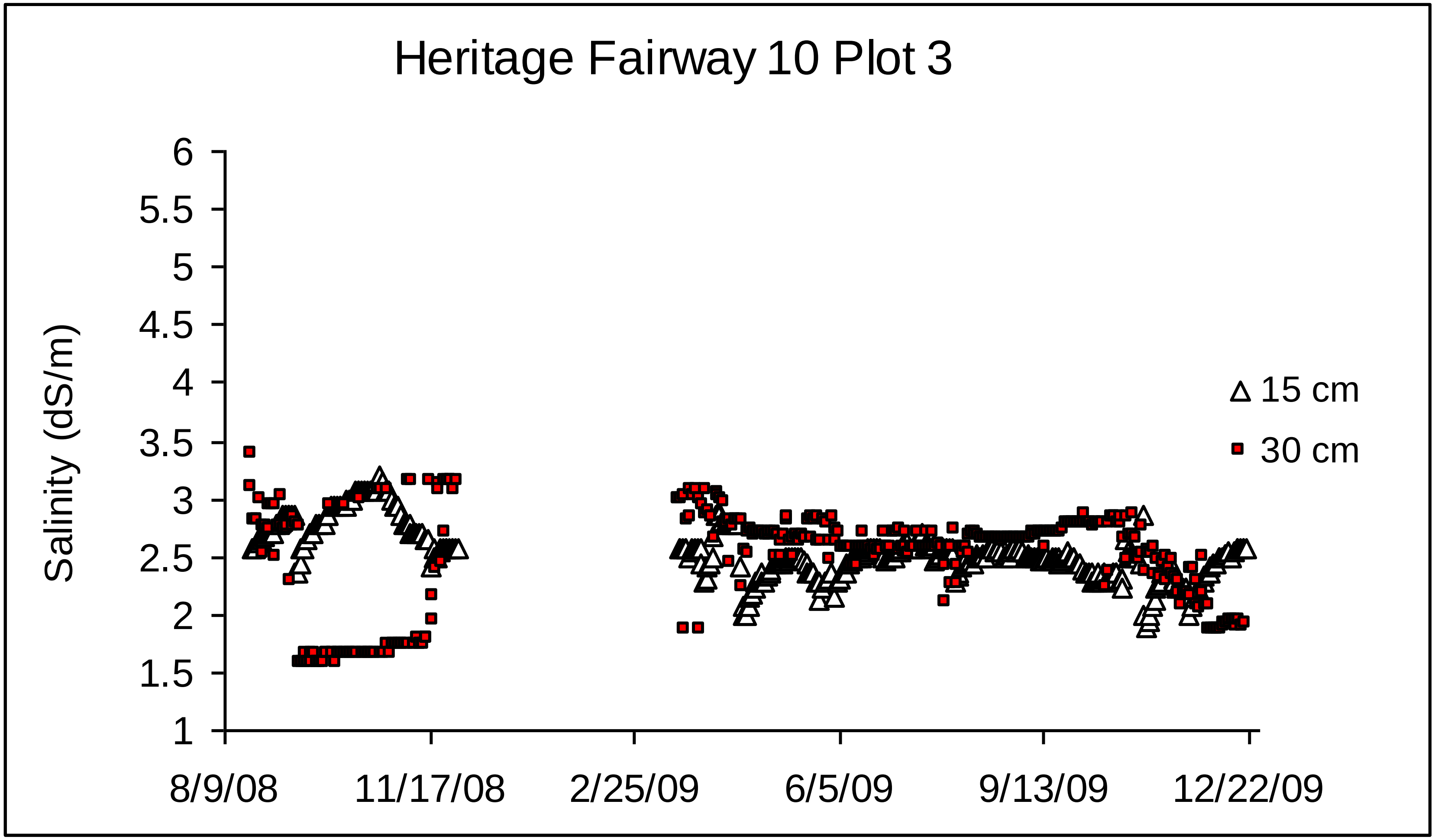

Figure 1.5C Salinity accumulation pattern of Heritage fairway 10 plot 3. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

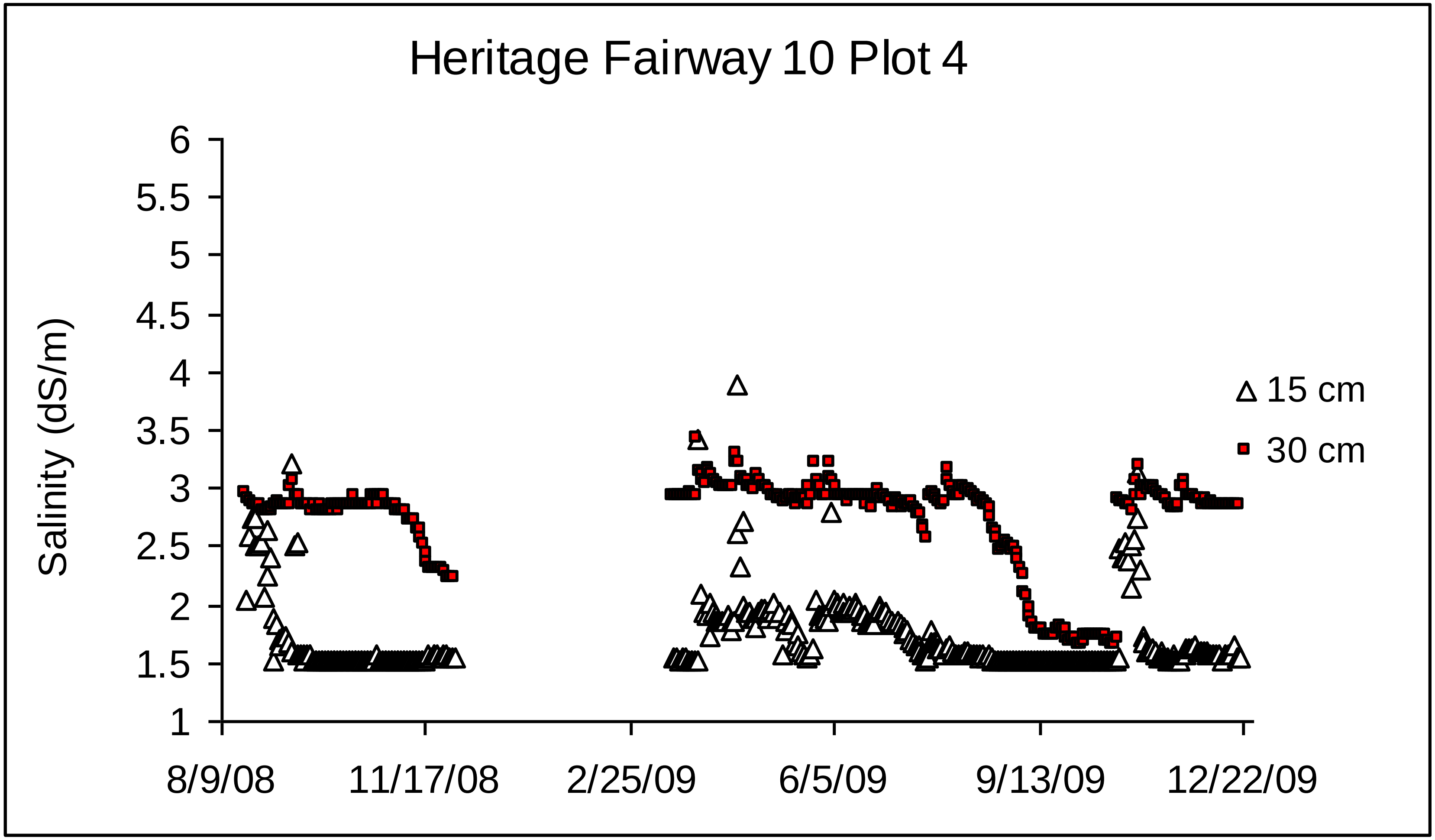

Figure 1.5D Salinity accumulation pattern of Heritage fairway 10 plot 4. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

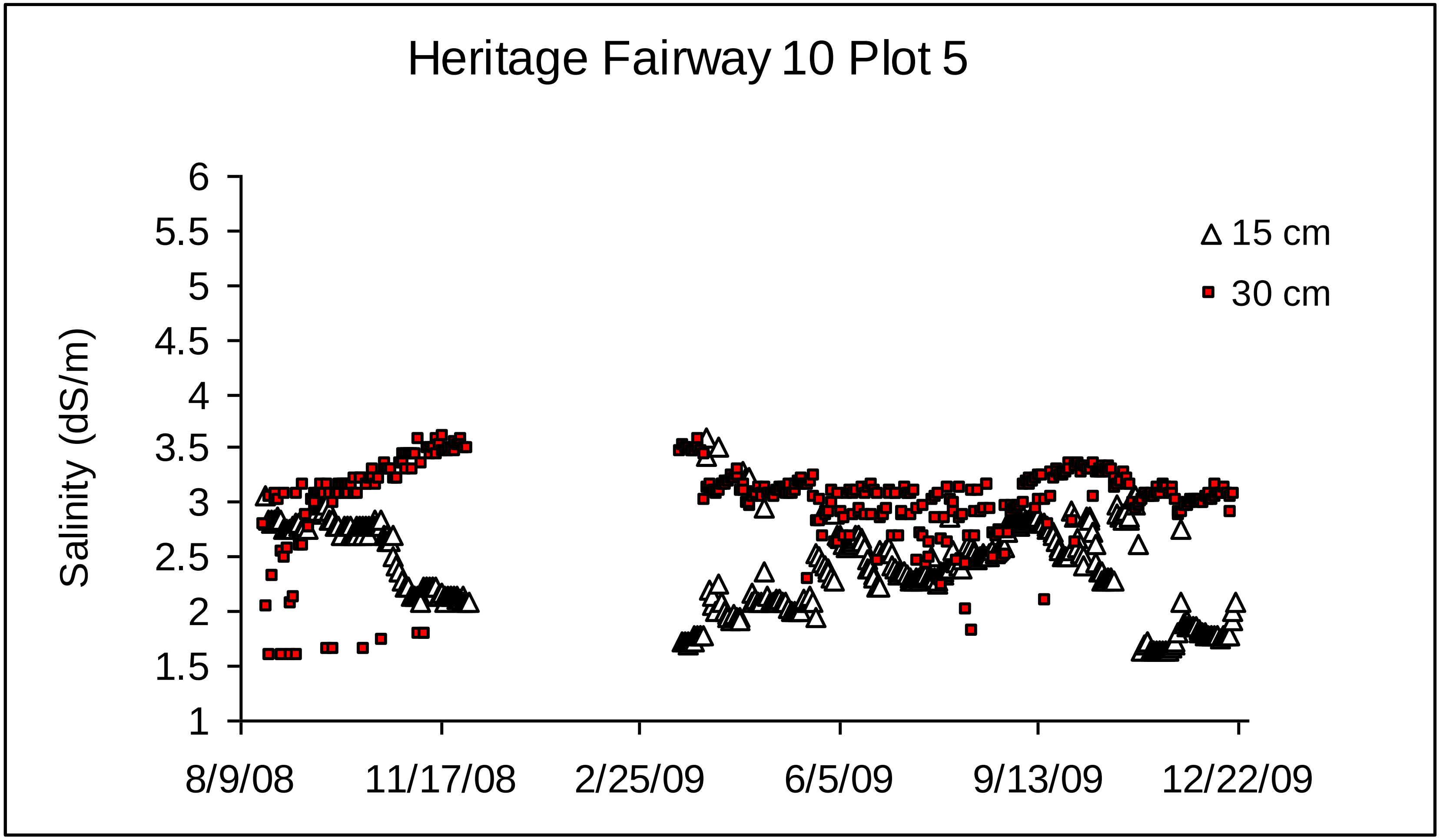

Figure 1.5E Salinity accumulation pattern Heritage fairway 10 plot 5. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

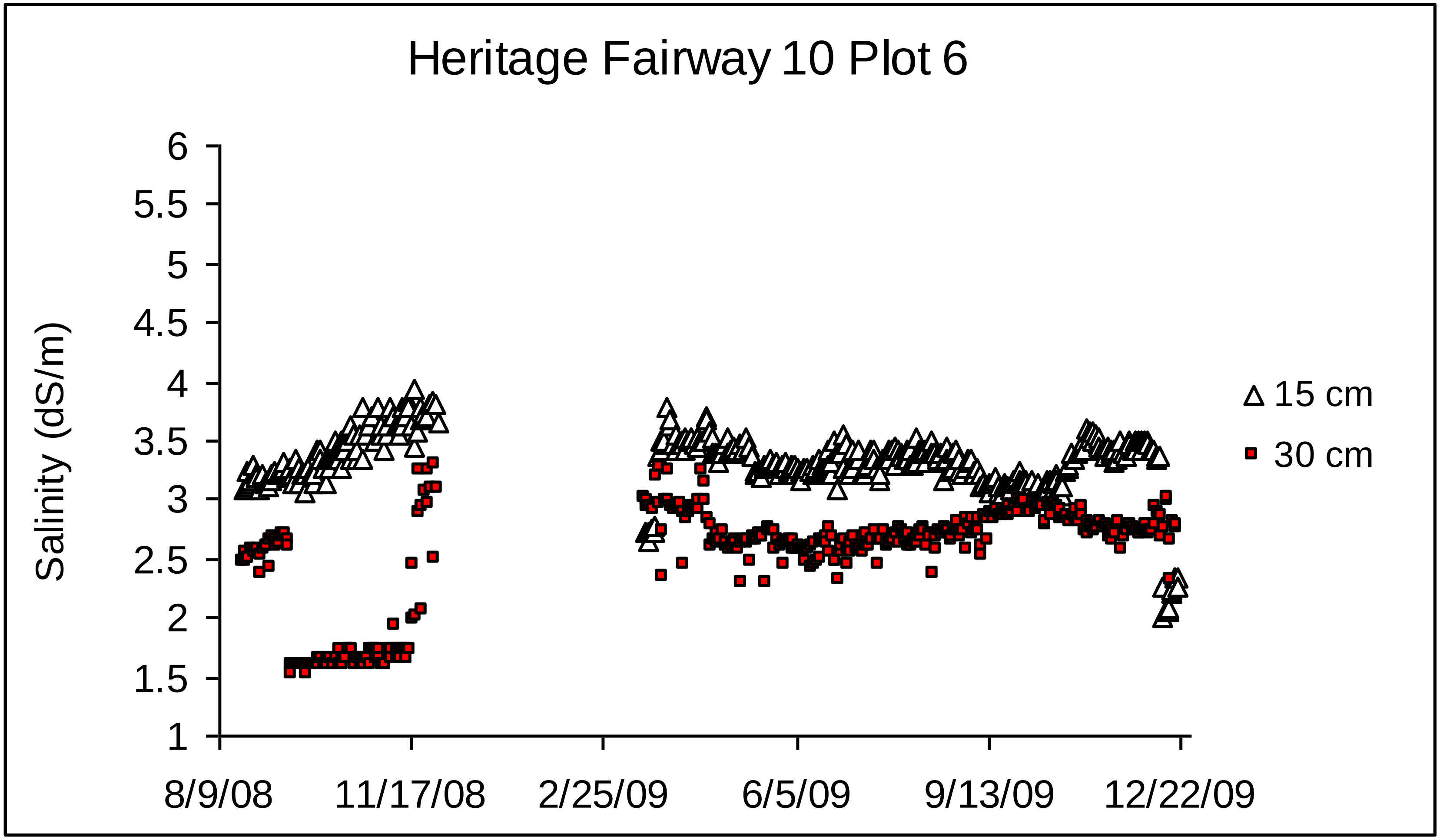

Figure 1.5F Salinity accumulation pattern of Heritage fairway 10 plot 6. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

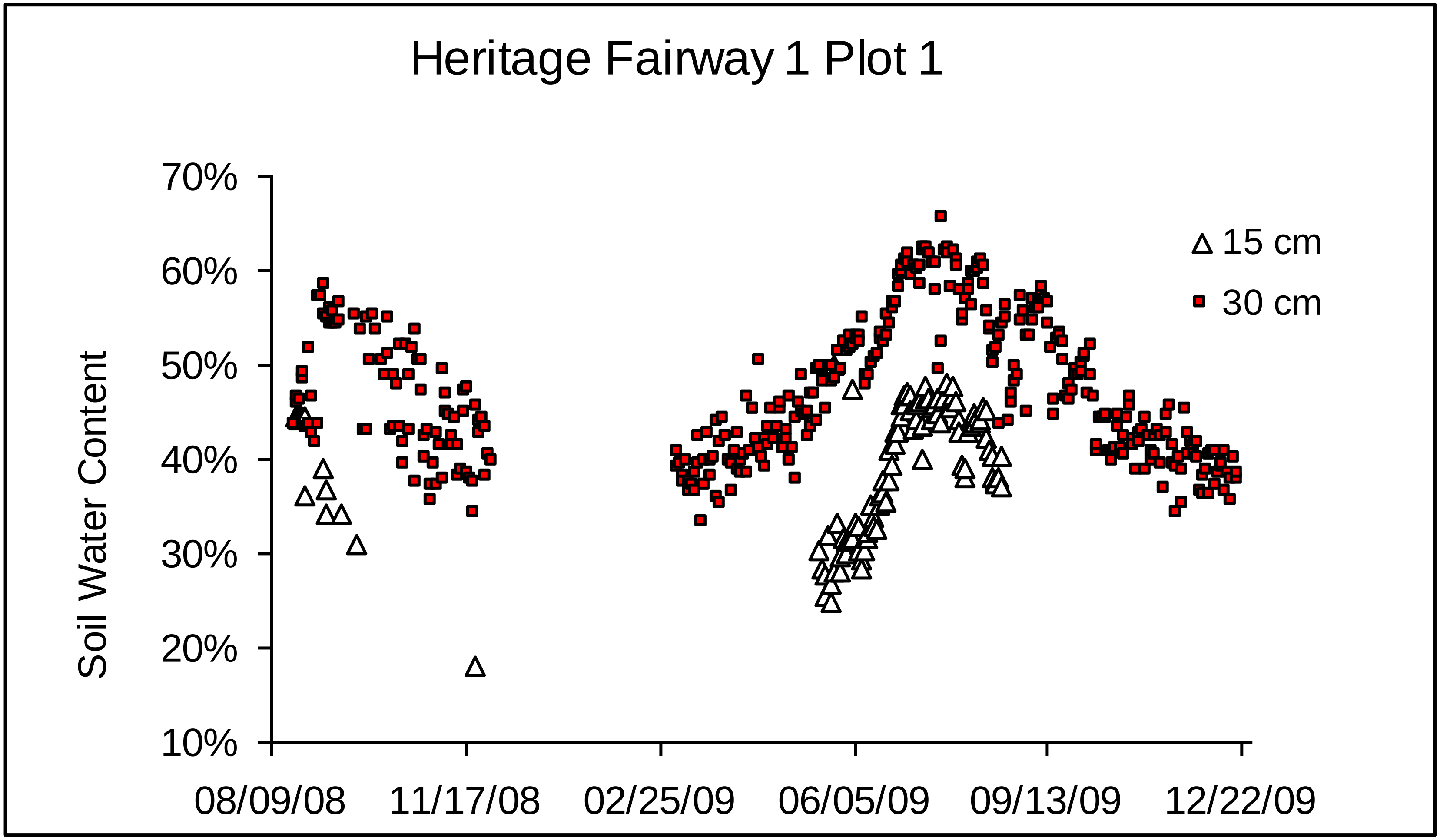

Figure 1.6A Soil water content patterns of The Heritage fairway 1 plot 1. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

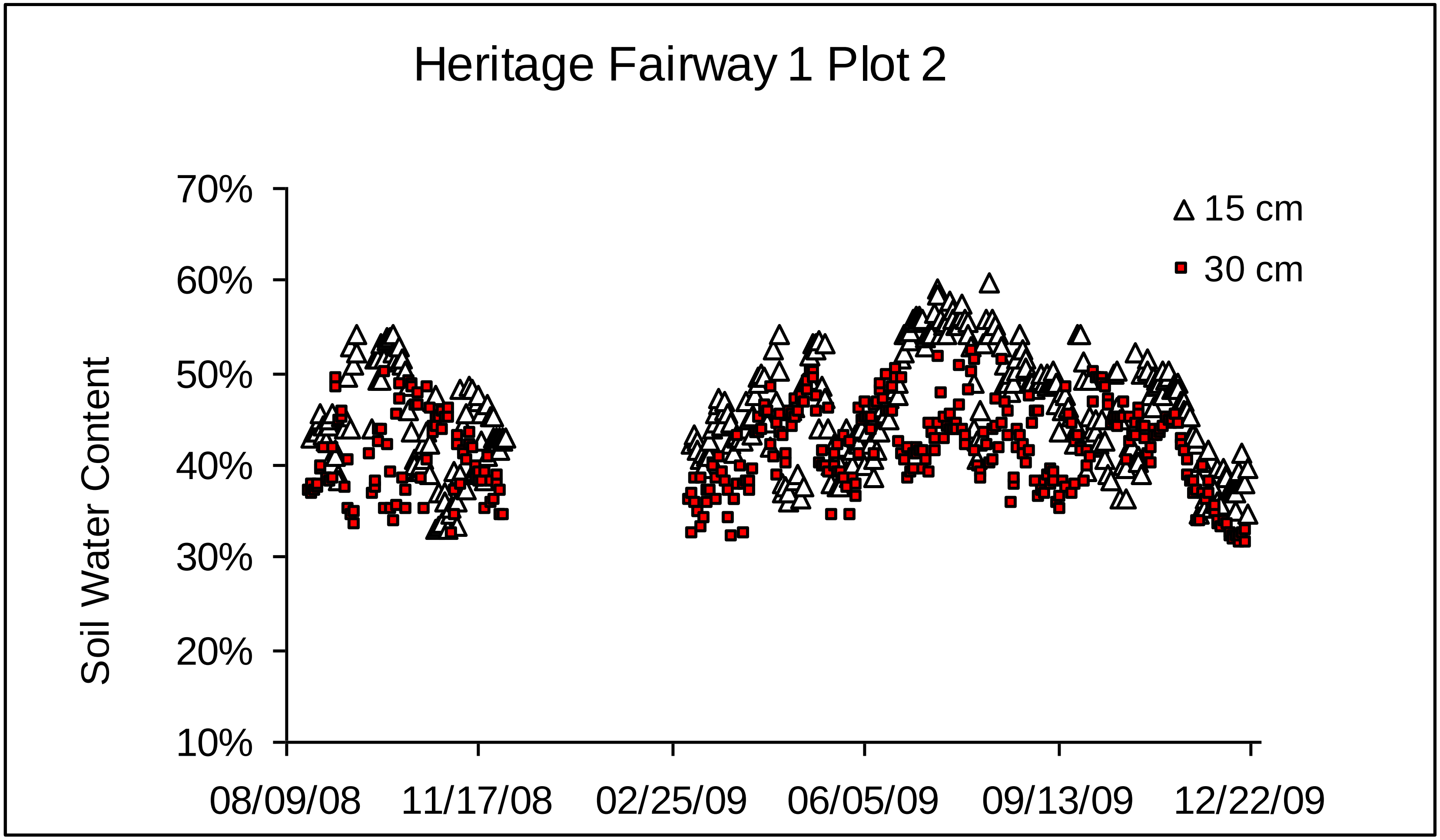

Figure 1.6B Soil water content patterns of The Heritage fairway 1 plot 2. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

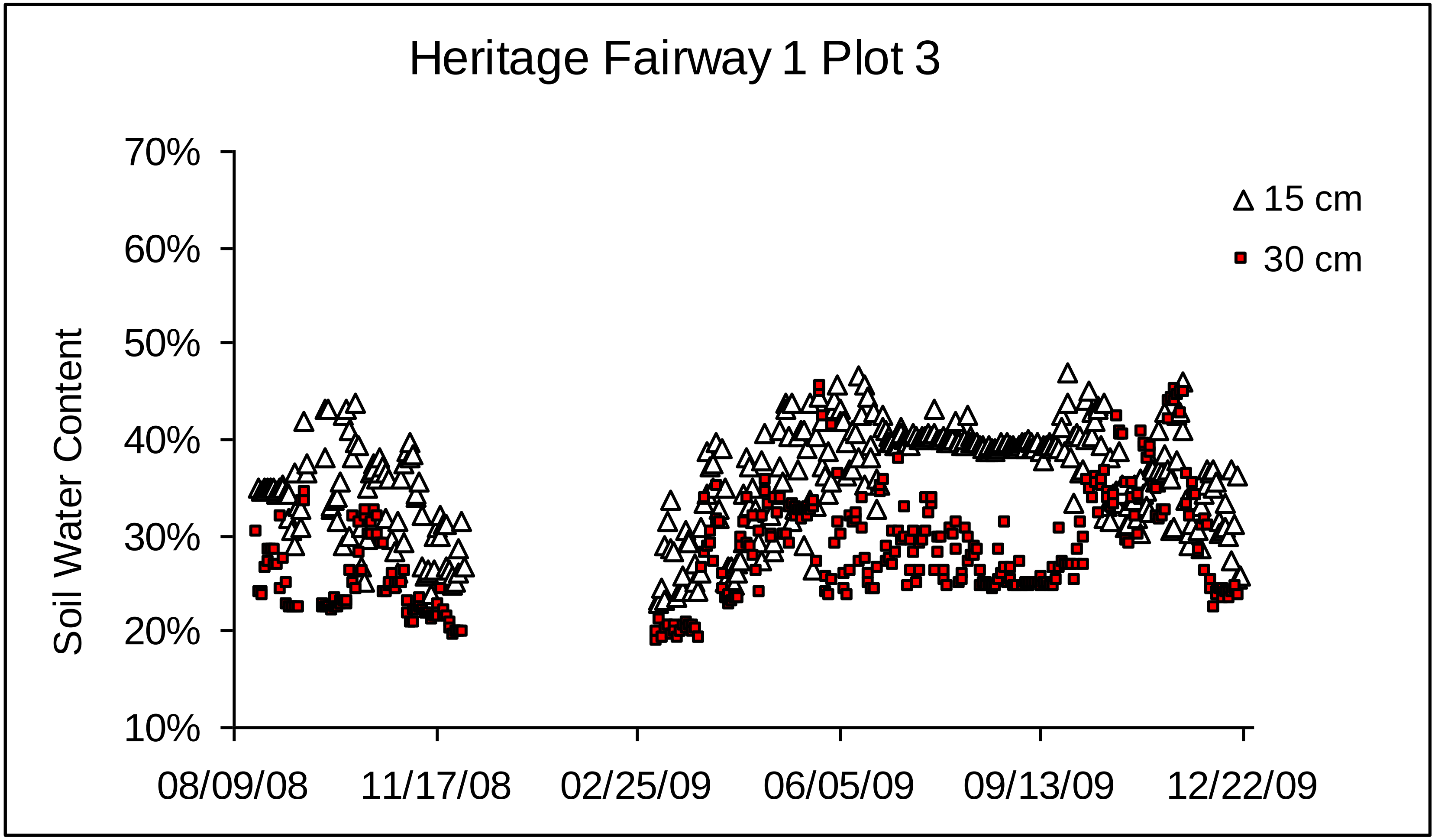

Figure 1.6C Soil water content patterns of The Heritage fairway 1 plot 3. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

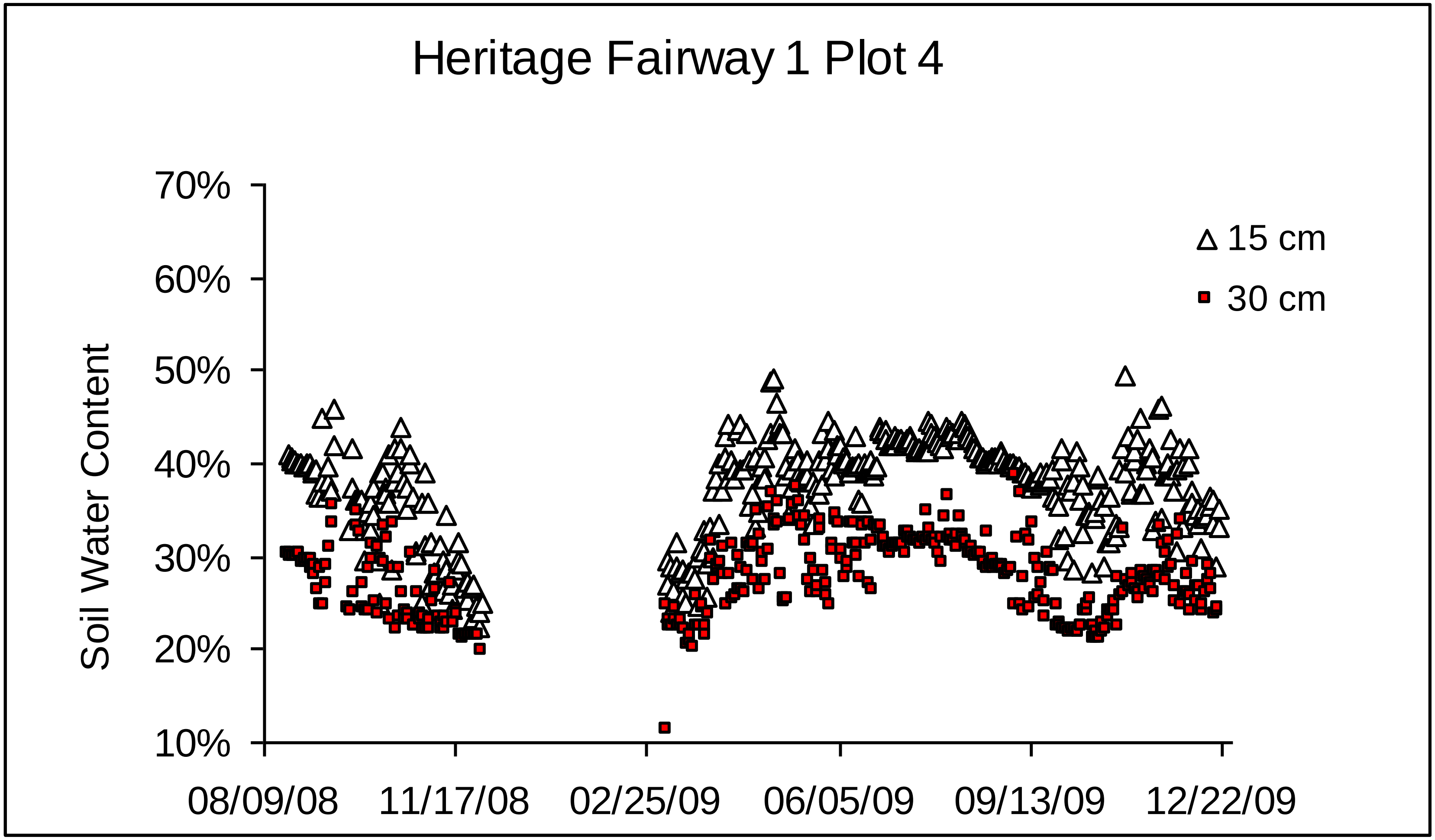

Figure 1.6D Soil water content patterns of The Heritage fairway 1 plot 4. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

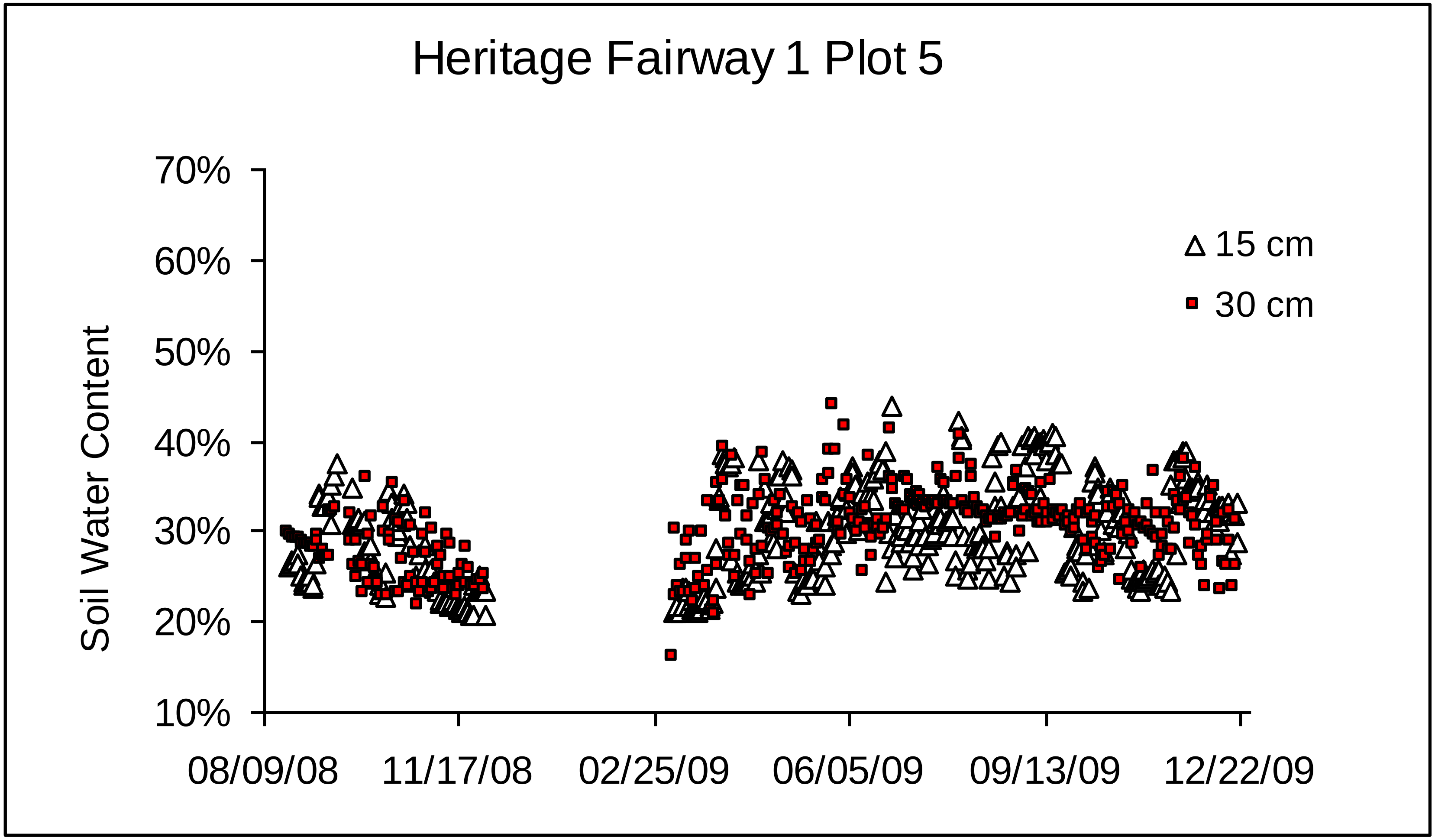

Figure 1.6E Soil water content patterns of The Heritage fairway 1 plot 5. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

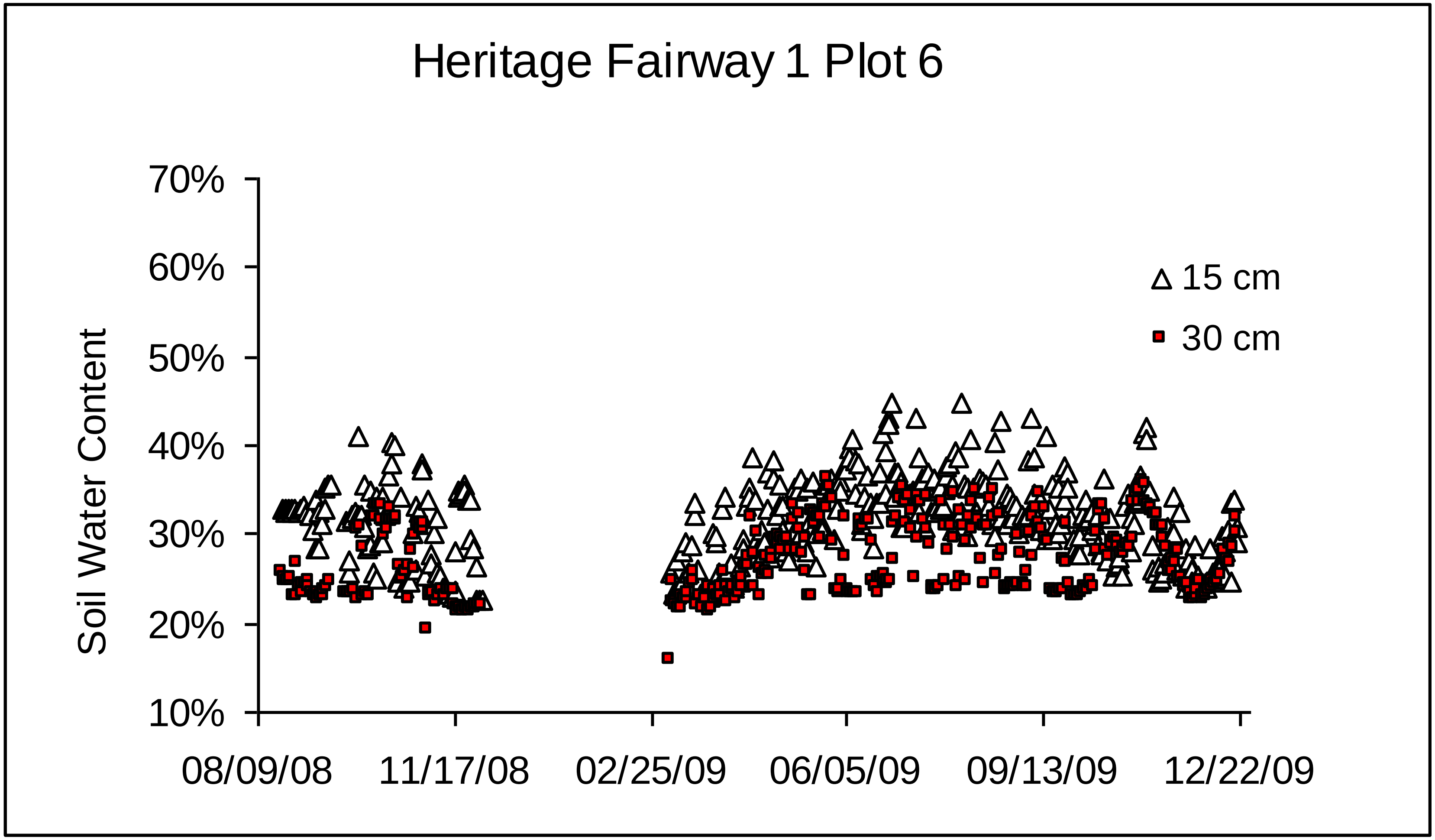

Figure 1.6F Soil water content patterns of The Heritage fairway 1 plot 6. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

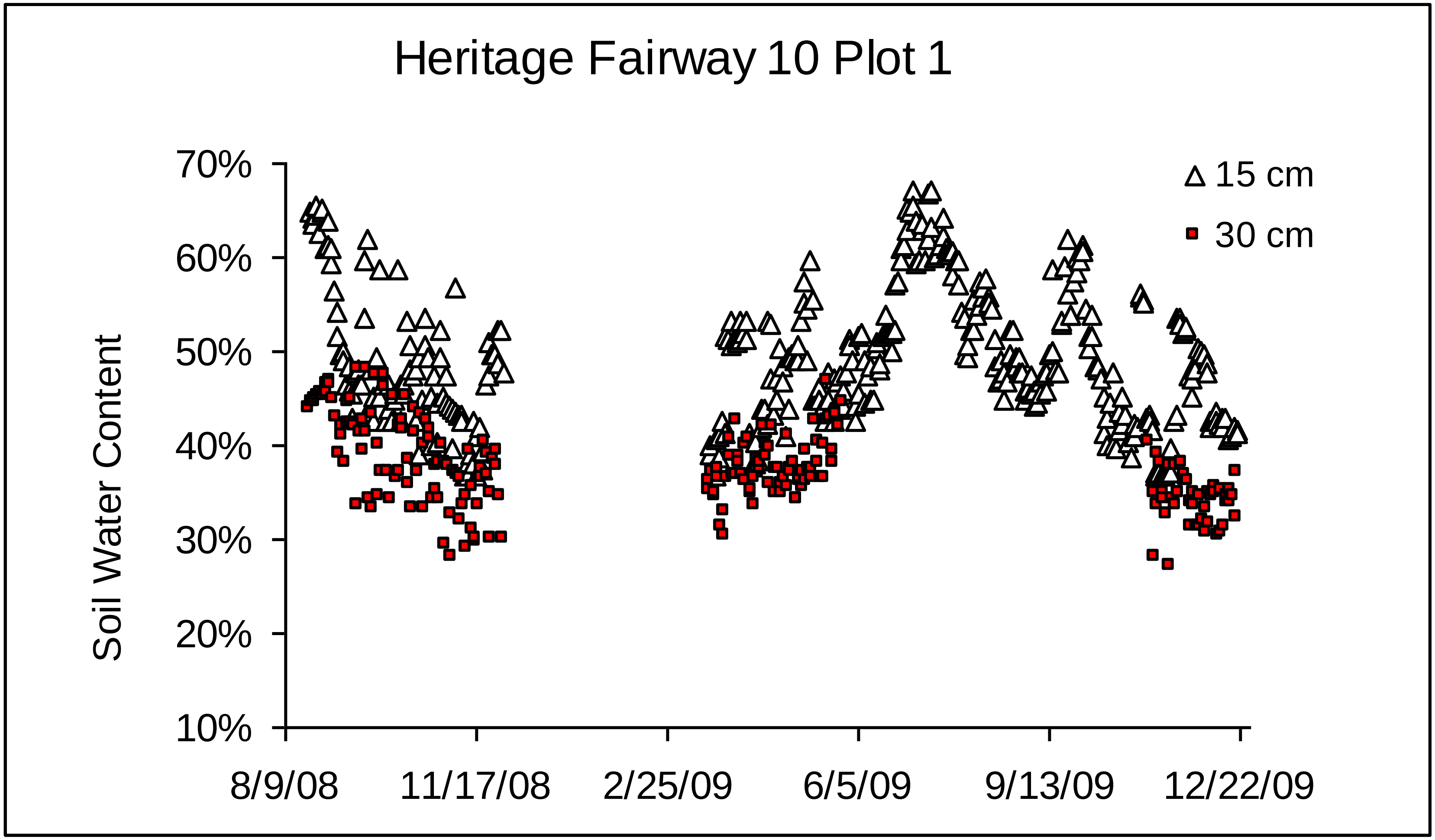

Figure 1.7A Soil water content pattern of The Heritage Golf Course fairway 10 plot 1. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

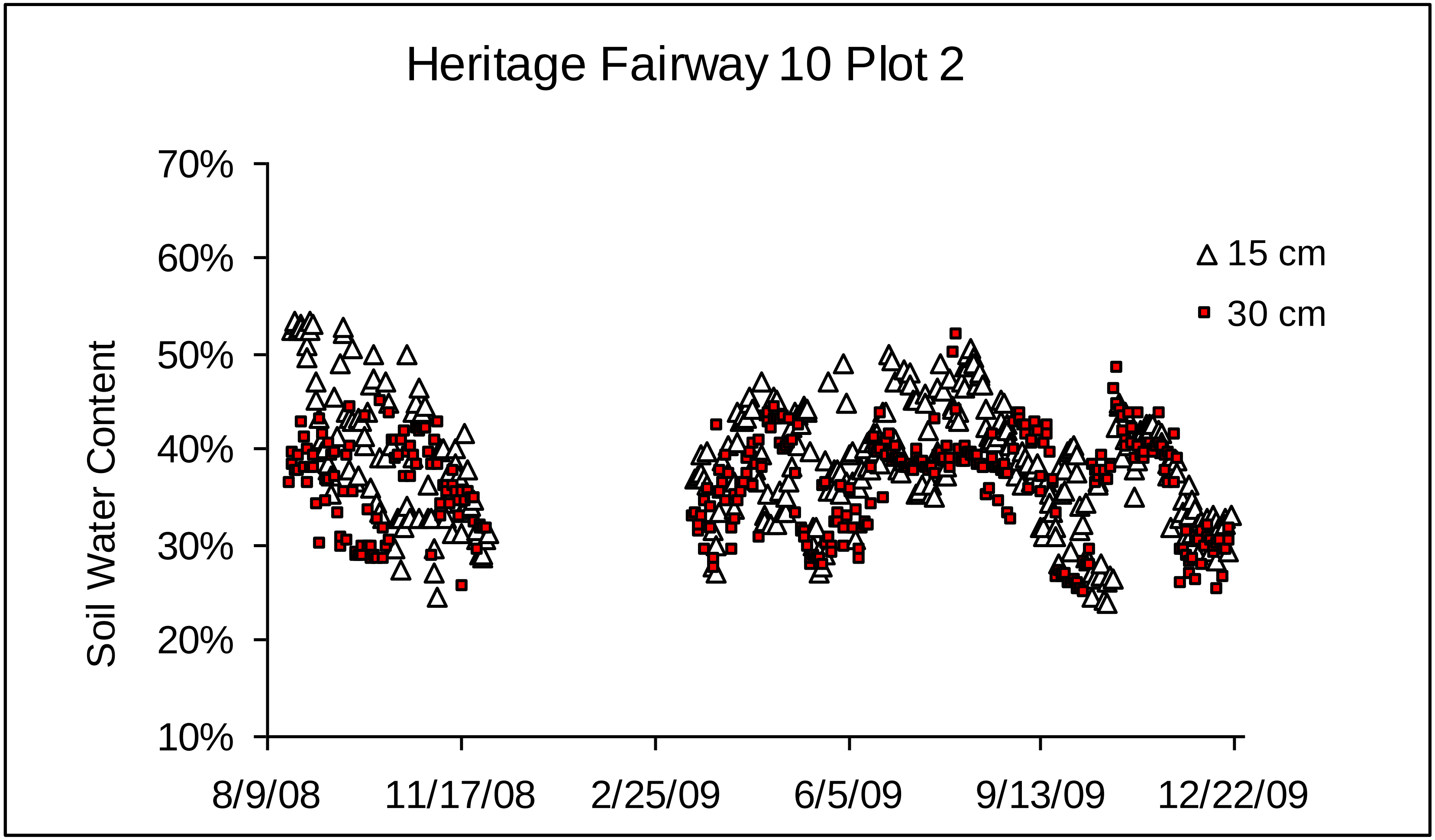

Figure 1.7B Soil water content pattern of The Heritage Golf Course fairway 10 plot 2. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

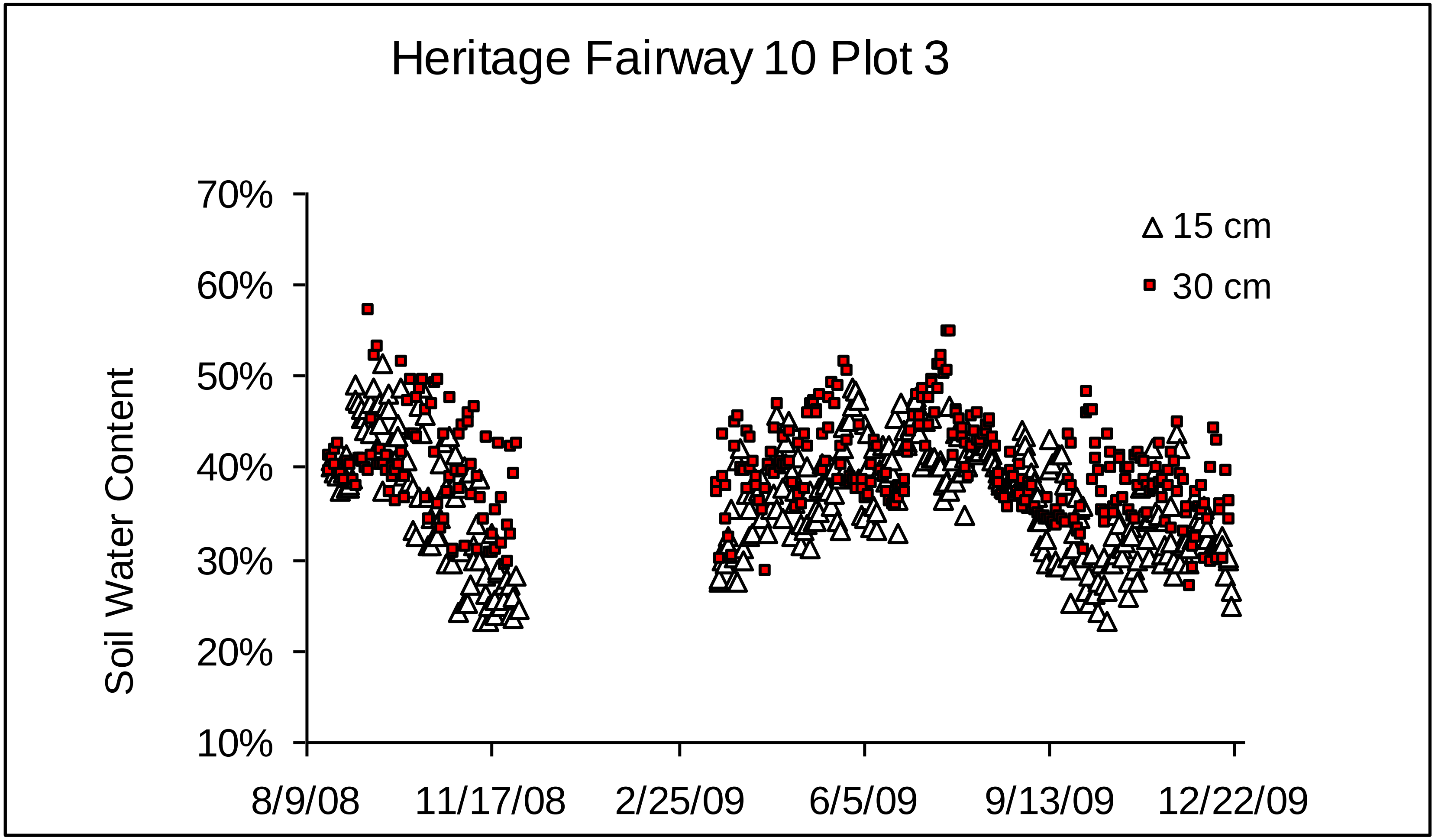

Figure 1.7C Soil water content pattern of The Heritage Golf Course fairway 10 plot 3. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

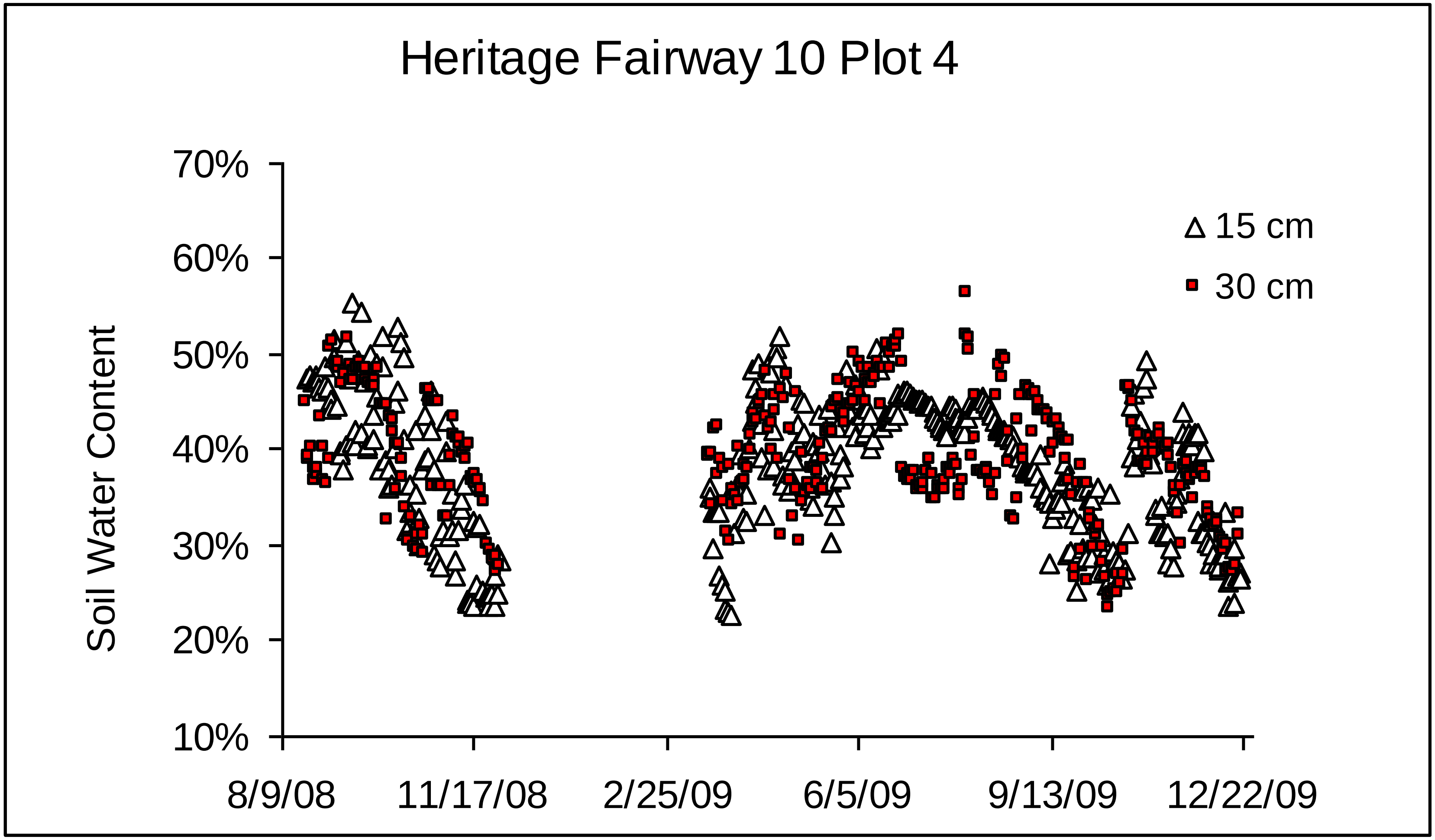

Figure 1.7D Soil water content pattern of The Heritage Golf Course fairway 10 plot 4. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

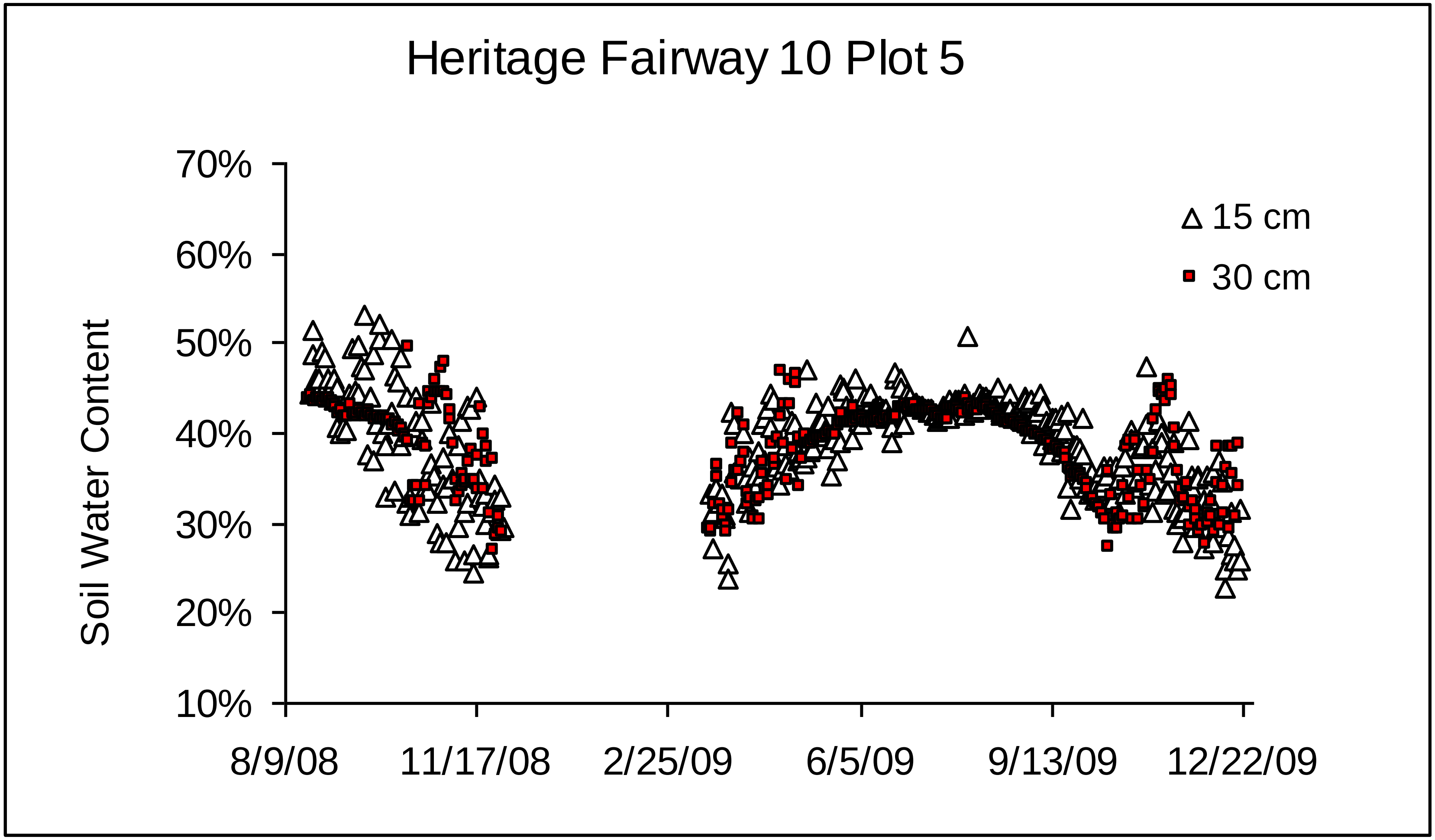

Figure 1.7F Soil water content pattern of The Heritage Golf Course fairway 10 plot 5. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

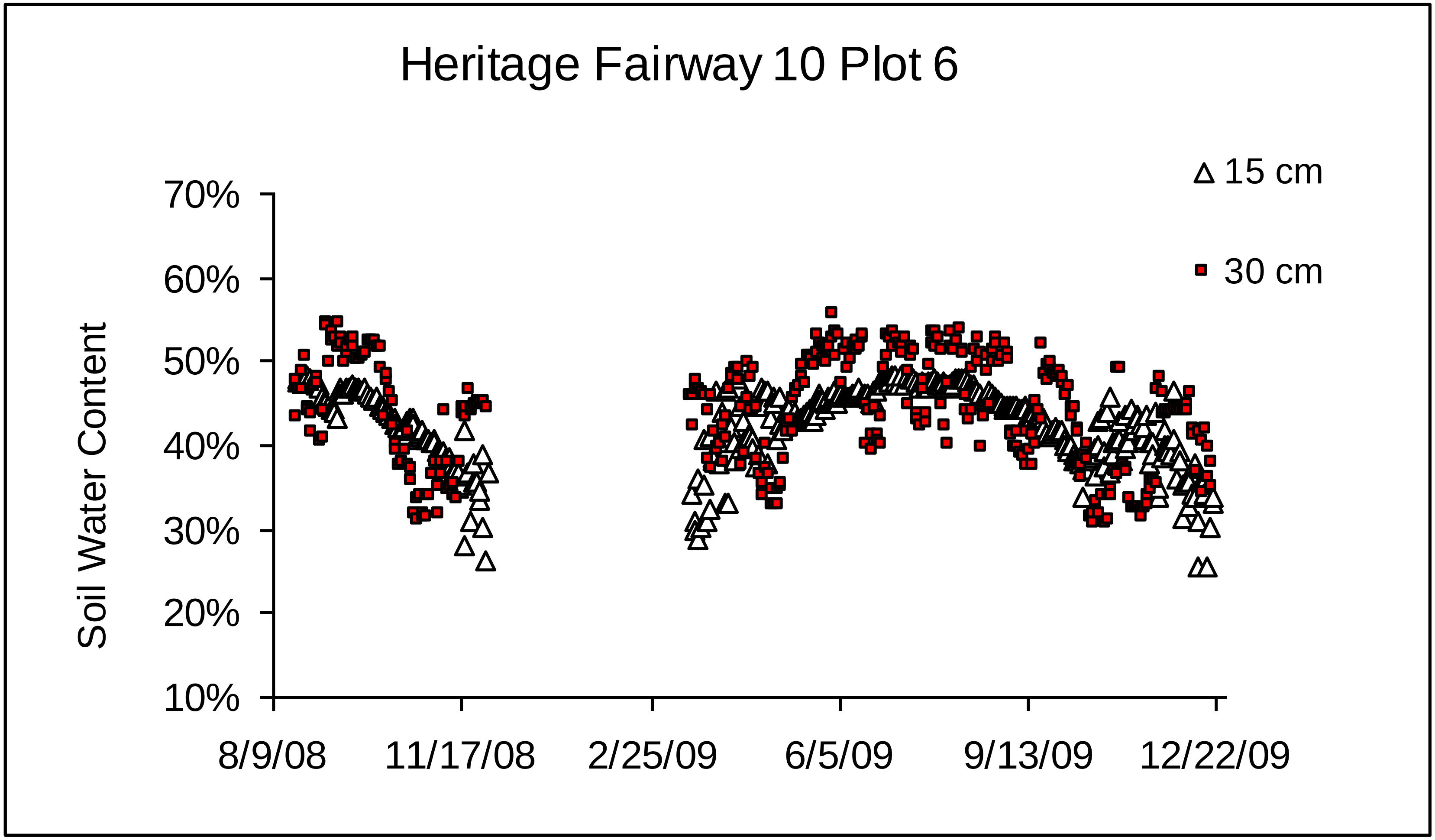

Figure 1.7F Soil water content pattern of The Heritage Golf Course fairway 10 plot 6. 5TE sensors were installed at depths of 15cm and 30cm below the soil surface. No data was recorded from November 31 2008 through to March 2009.

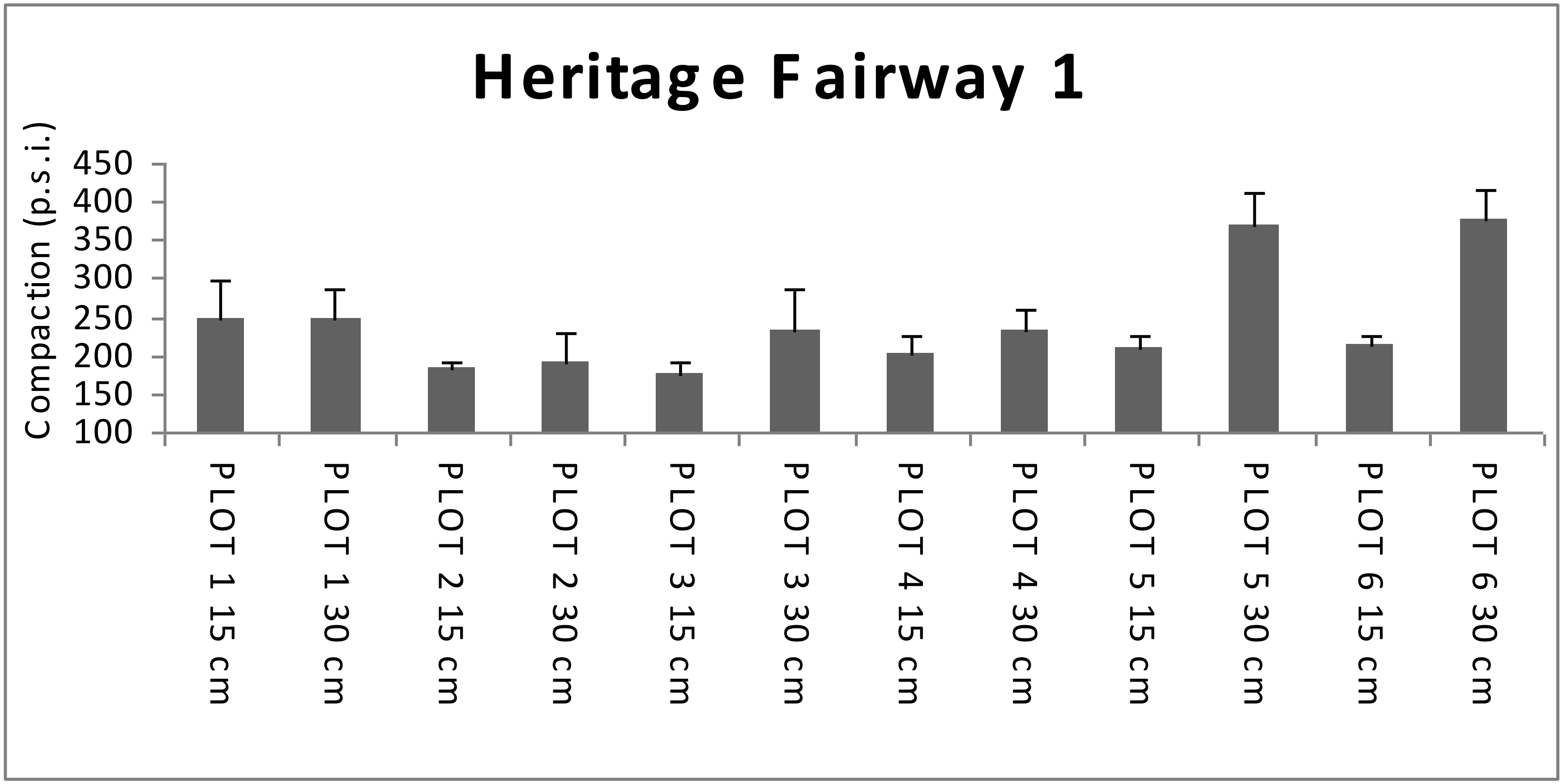

Figure1.8A Average soil compaction (ASC) data for sensor equipped plots at Heritage. Bars indicate standard error for each plot position over two depths.

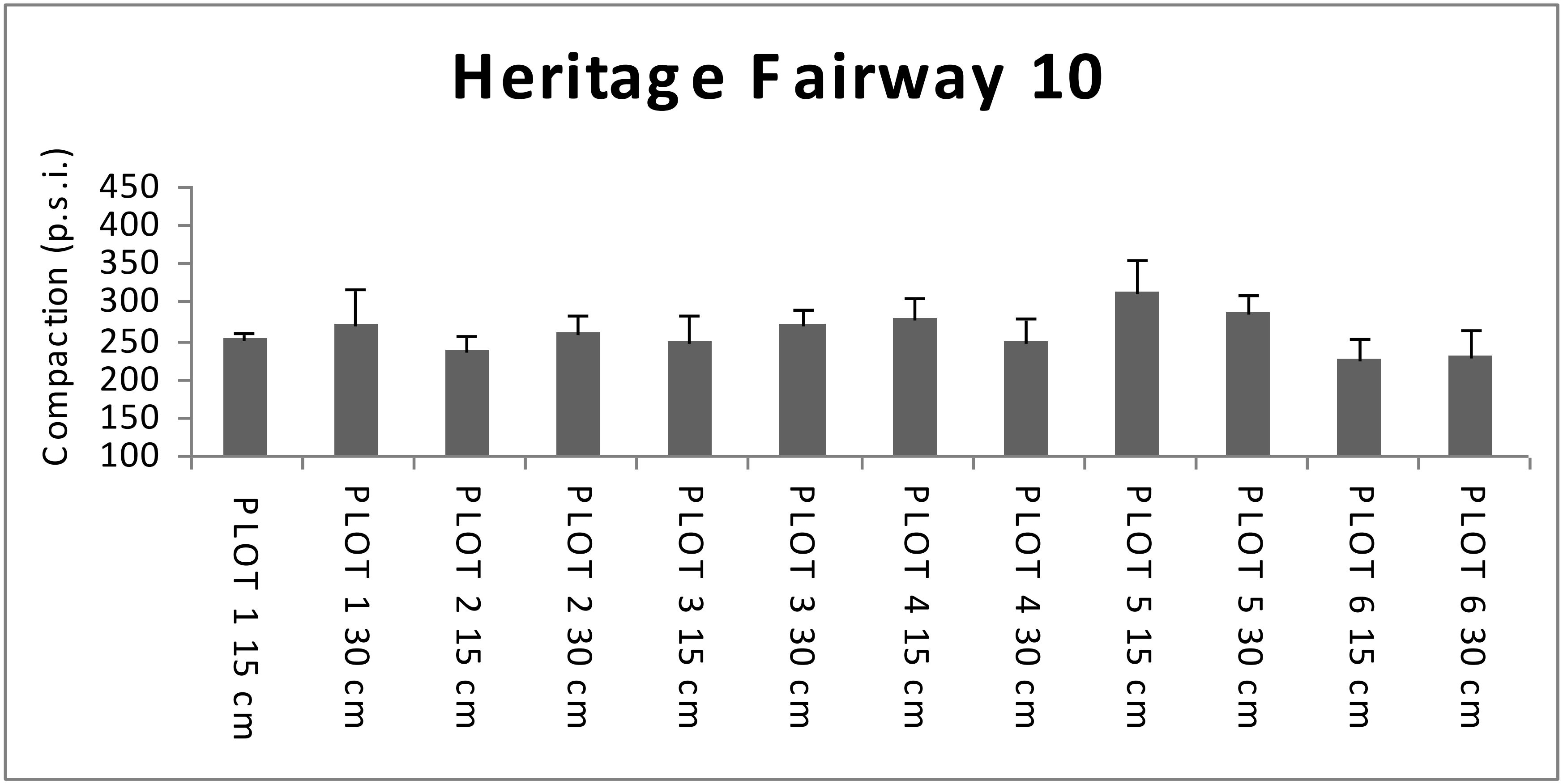

Figure1.8B Average soil compaction (ASC) data for sensor equipped plots at Heritage. Bars indicate standard error for each plot position over two depths.

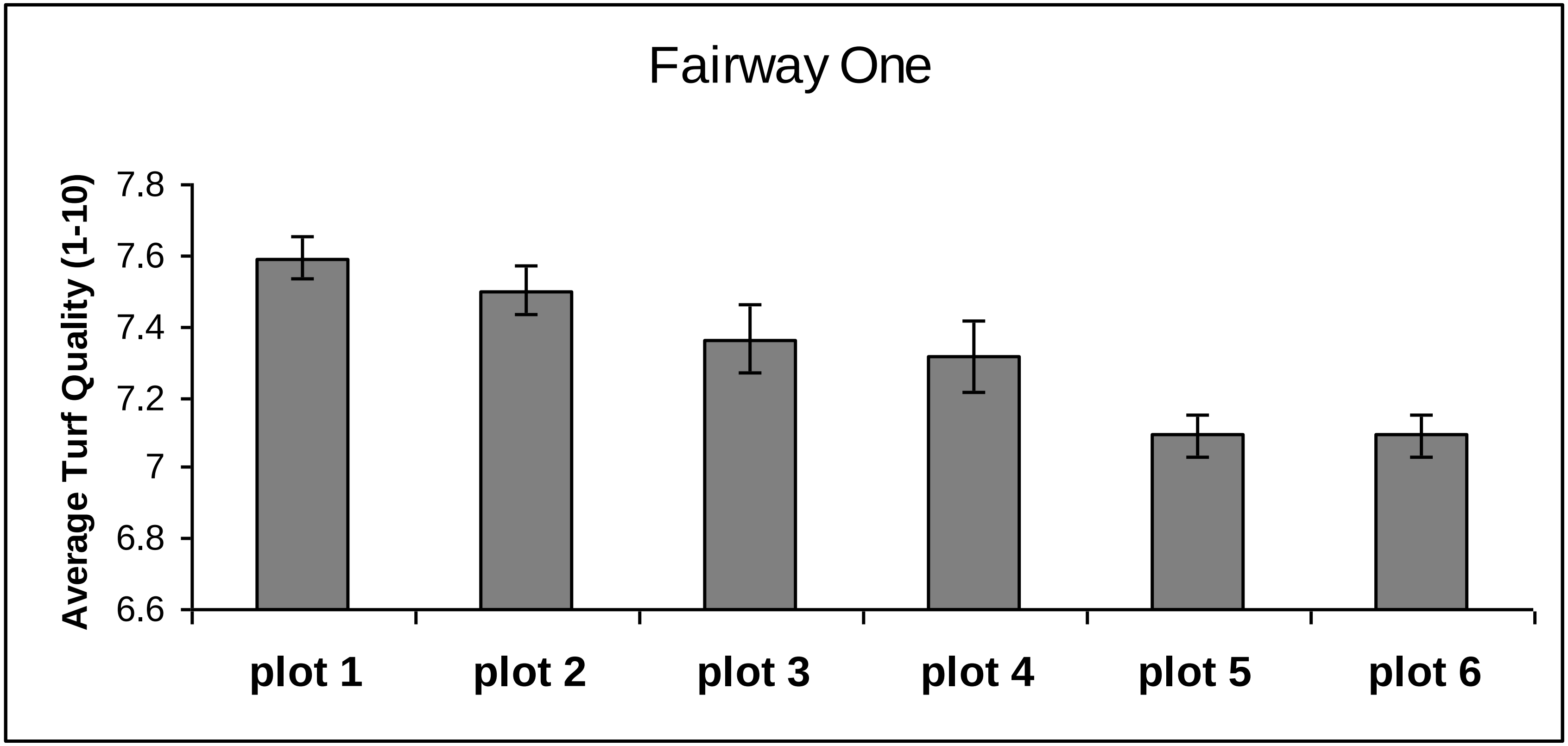

Figure1.9A Turf quality data for The Heritage Golf Course sensor equipped plots. Turf quality was measured visually on a scale of 1-10 accounting for color, density and uniformity. Readings were recorded every two weeks from June through September 2009. Bars indicate standard error for each plot position.

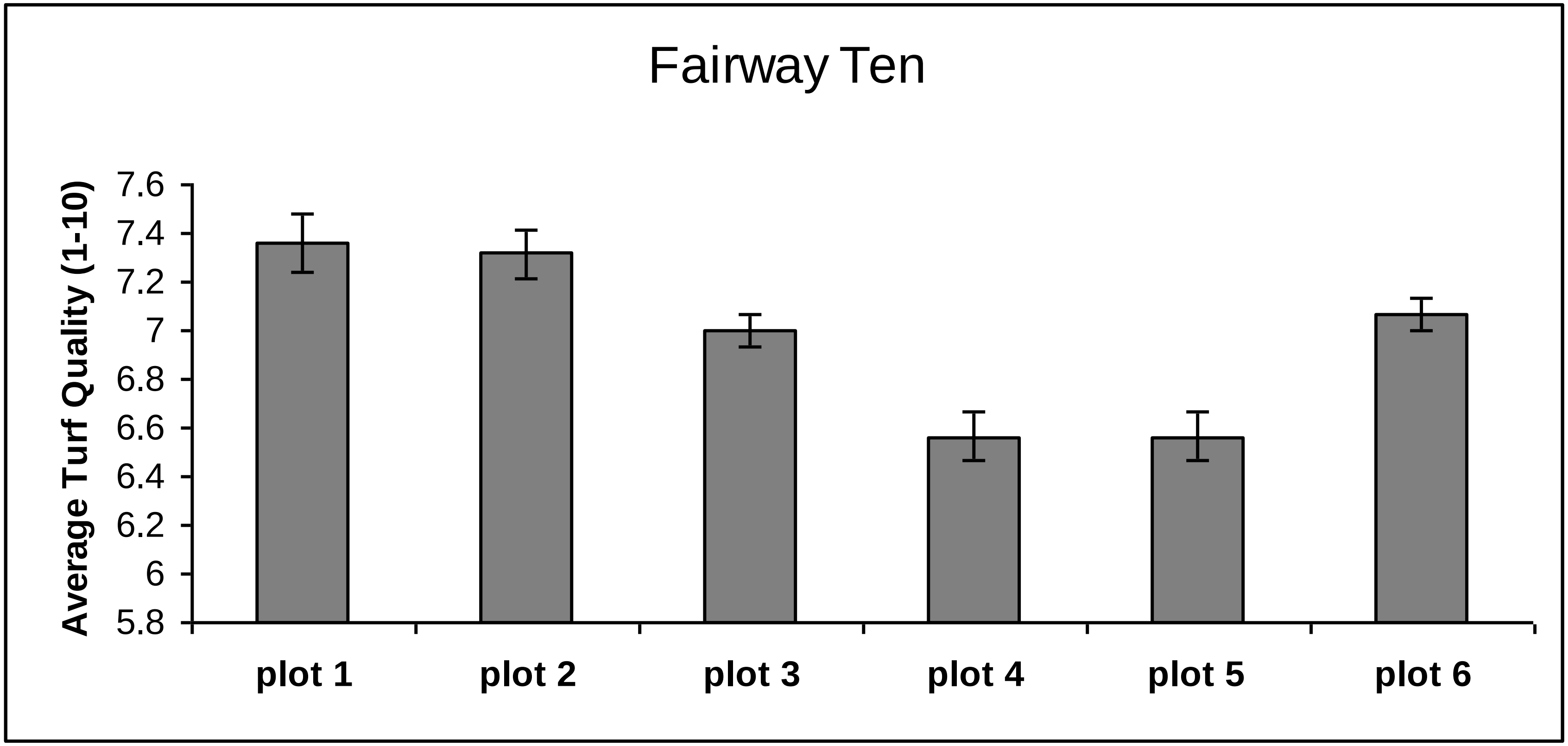

Figure1.9B Turf quality data for The Heritage Golf Course sensor equipped plots. Turf quality was measured visually on a scale of 1-10 accounting for color, density and uniformity. Readings were recorded every two weeks from June through September 2009. Bars indicate standard error for each plot position.

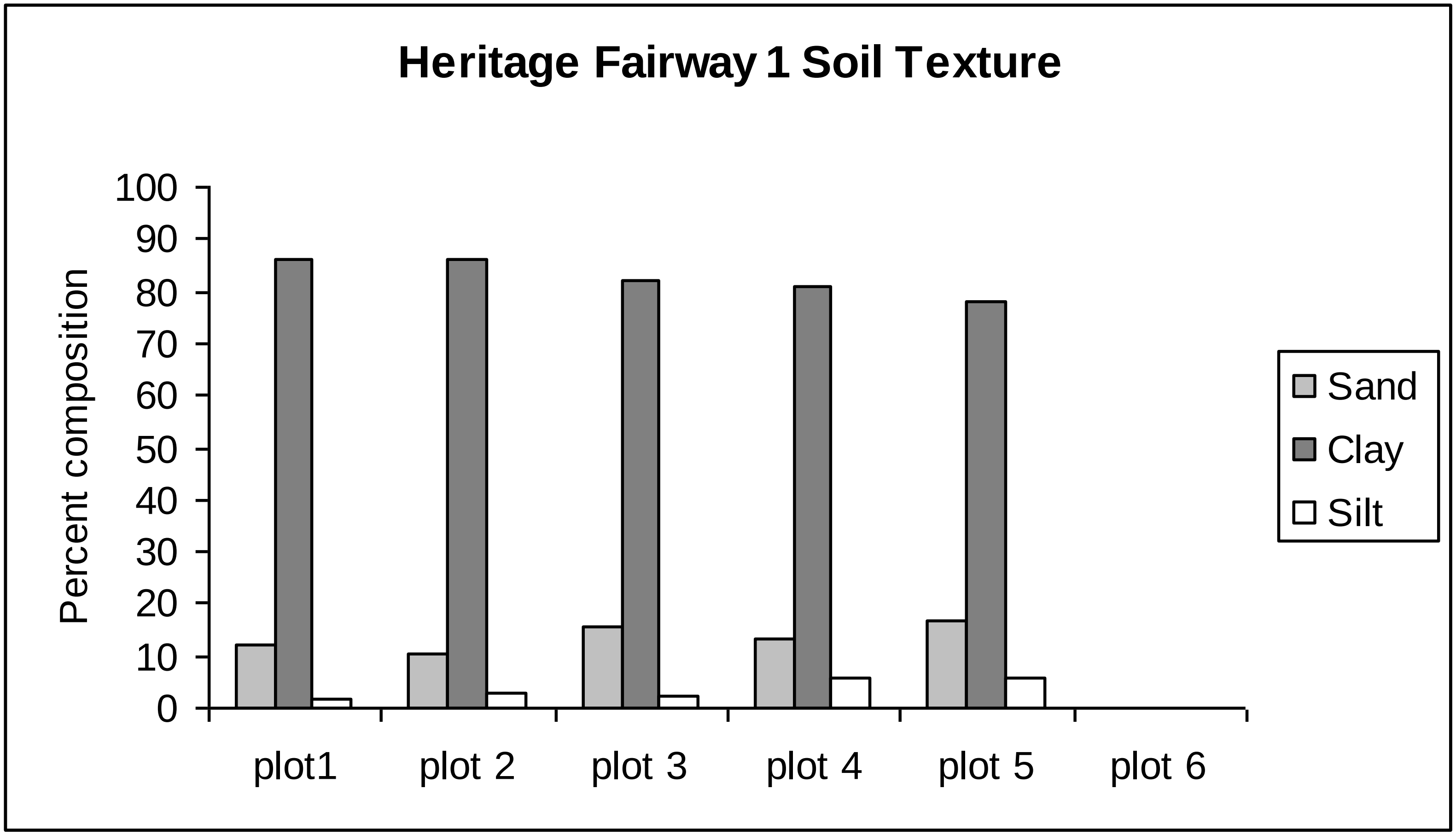

Figure 1.10A The Heritage fairway 1 soil texture data. Texture analysis by rudimentary jar tests (Sammis, 1996).

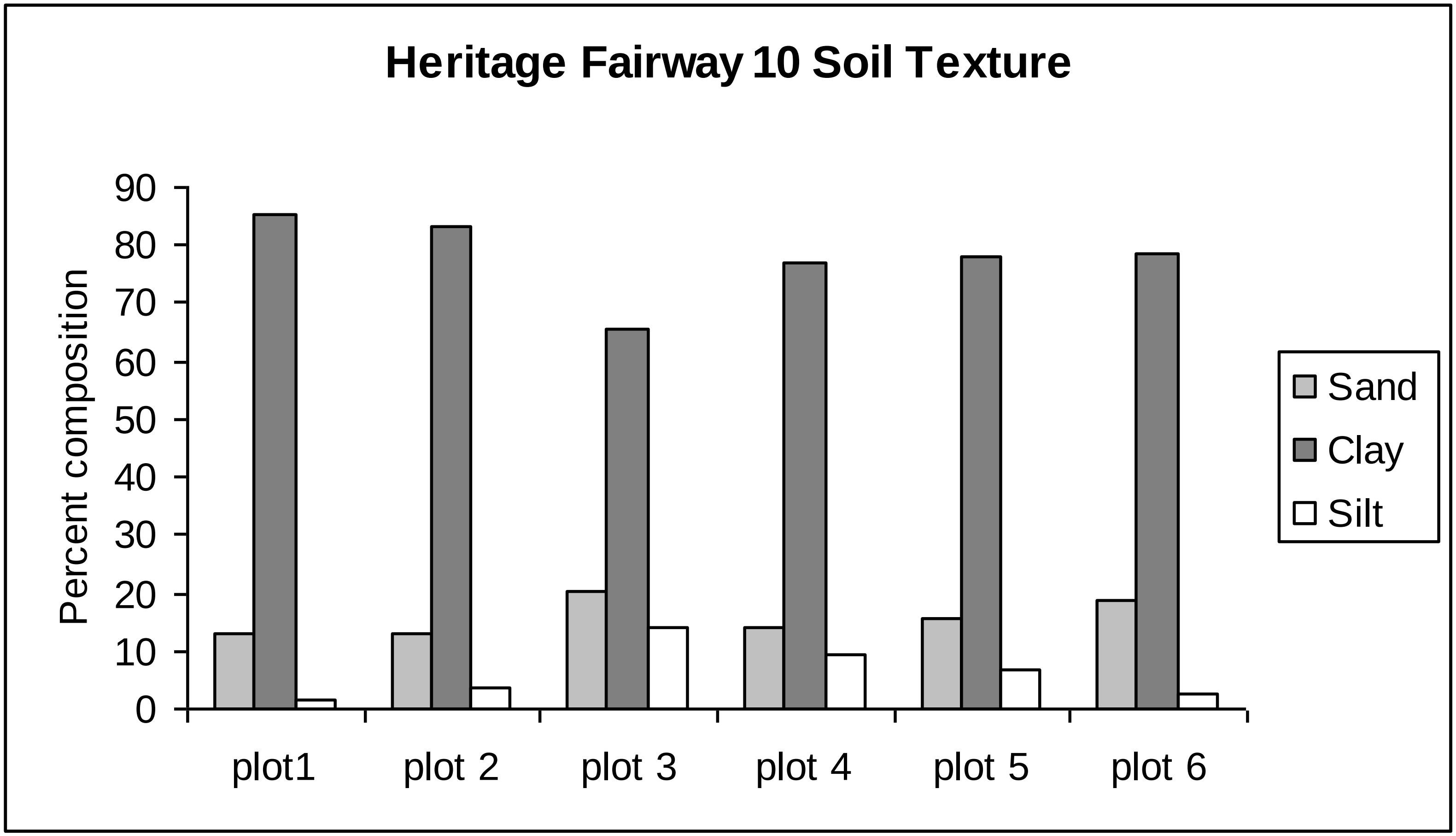

Figure 1.10B The Heritage fairway 10 soil texture data. Texture analysis by rudimentary jar tests (Sammis, 1996).

Table 1.1A Basic descriptive statistics of salinity at the 15cm depth Heritage fairway 1.

Plot	1	2	3	4	5	6
Mean (dS m^{-1})	2.30	4.40	1.91	2.08	2.63	2.08
Standard Deviation	0.46	0.64	0.18	0.19	0.32	0.22
Coefficient of Variation	0.20	0.14	0.10	0.09	0.12	0.11

Table 1.1B Basic descriptive statistics of salinity at the 30cm depth Heritage fairway 1.

Plot	1	2	3	4	5	6
Mean (dS m^{-1})	3.70	0.76	1.83	1.89	2.43	1.8408
Standard Deviation	0.76	0.79	0.14	0.14	0.35	0.1291
Coefficient of Variation	0.76	1.04	0.08	0.07	0.14	0.07

Table 1.1C Basic descriptive statistics of salinity at the 15cm depth Heritage fairway 10.

Plot	1	2	3	4	5	6
Mean (dS m^{-1})	3.98	1.77	2.54	1.72	2.40	3.32
Standard Deviation	0.26	0.41	0.23	0.33	0.40	0.27
Coefficient of Variation	0.06	0.23	0.09	0.19	0.17	0.08

Table 1.1D Basic descriptive statistics of salinity at the 30cm depth Heritage fairway 10.

Plot	1	2	3	4	5	6
Mean (dS m^{-1})	1.88	2.38	2.48	2.73	3.02	2.55
Standard Deviation	0.13	0.43	0.43	0.40	0.36	0.44
Coefficient of Variation	0.07	0.18	0.17	0.15	0.12	0.18

Table 1.2A Basic descriptive statistics of SWC at the 15cm depth Heritage fairway 1 (Percentage expressed in decimal format).

Plot	1	2	3	4	5	6
Mean	0.07	0.46	0.36	0.37	0.29	0.31
Standard Deviation	0.20	0.06	0.05	0.05	0.05	0.05
Coefficient of Variation	2.85	0.13	0.15	0.14	0.18	0.15

Table 1.2B Basic descriptive statistics of SWC at the 30cm depth Heritage fairway 1 (Percentage expressed in decimal format).

Plot	1	2	3	4	5	6
Mean	0.46	0.41	0.28	0.28	0.30	0.27
Standard Deviation	0.10	0.05	0.06	0.04	0.04	0.04
Coefficient of Variation	0.21	0.11	0.20	0.15	0.13	0.15

Table 1.2C Basic descriptive statistics of SWC at the 15cm depth Heritage fairway 10 (Percentage expressed in decimal format).

Plot	1	2	3	4	5	6
Mean	0.49	0.39	0.37	0.38	0.39	0.43
Standard Deviation	0.07	0.06	0.06	0.07	0.06	0.05
Coefficient of Variation	0.15	0.17	0.17	0.19	0.15	0.11

Table 1.2D Basic descriptive statistics of SWC at the 30cm depth Heritage fairway 10 (Percentage expressed in decimal format).

Plot	1	2	3	4	5	6
Mean	0.20	0.36	0.40	0.39	0.38	0.44
Standard Deviation	0.21	0.05	0.05	0.06	0.05	0.07
Coefficient of Variation	1.08	0.14	0.13	0.16	0.12	0.15

Table 1.3A SAS Pearson Correlation of measured variables for Heritage fairway 1. Correlation variables examined were electrical conductivity, soil water content, compaction, percentage of sand, percentage of silt and percentage of clay.

Heritage Fairway 1 Pearson Correlations

	Salinity (EC)	SWC	Comp.	% Sand	% Silt	% Clay
Salinity (EC)		0.76**	-0.35	-.63*	-0.18	0.57
SWC			-0.32	-.76**	-0.51	0.82**
Comp.				0.38	0.31	-0.40
% Sand					0.32	-0.85**
% Silt						-0.76**

* And ** Significance level at <0.05 and 0.01, respectively.

Table1.3B SAS Pearson Correlation results of measured variables for Heritage fairway 10. Correlation variables examined were electrical conductivity, soil water content, compaction, percentage of sand, percentage of silt and percentage of clay.

Heritage Fairway 10 Pearson Correlations

	Salinity (EC)	SWC	Comp.	% Sand	% Silt	% Clay
Salinity (EC)		0.73**	-0.25	0.02	-0.32	0.22
SWC			-0.38	0.05	-0.41	0.27
Comp.				-0.22	0.25	-0.05
% Sand					0.51	-0.78**
% Silt						-0.94***

*, ** And *** Significance level at <0.05, 0.01 and 0.001, respectively.

.

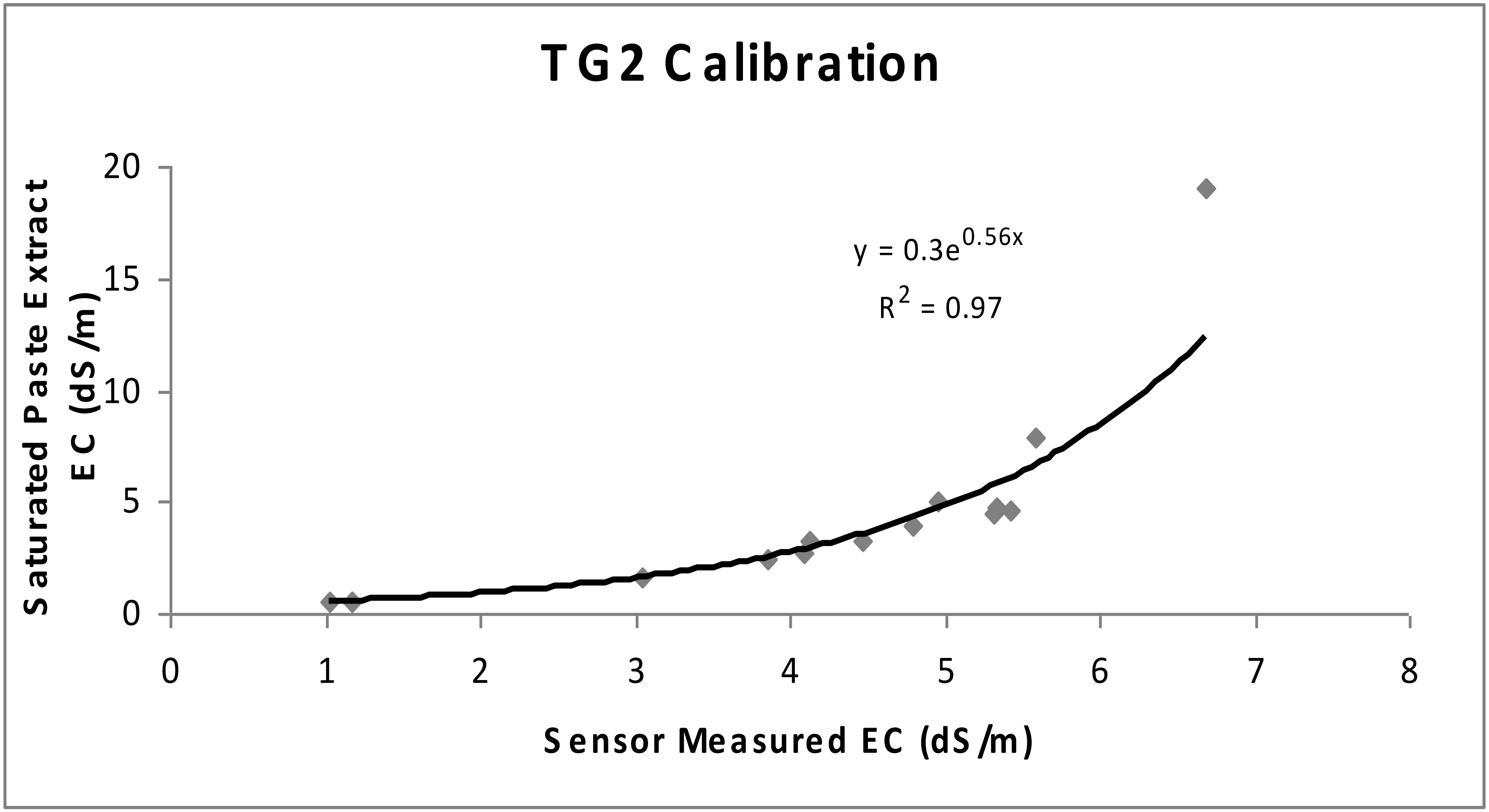

Figure 1.11 Non-linear regression of sensor measured electrical conductivity (EC) and conventional saturated paste extract electrical conductivity (EC).

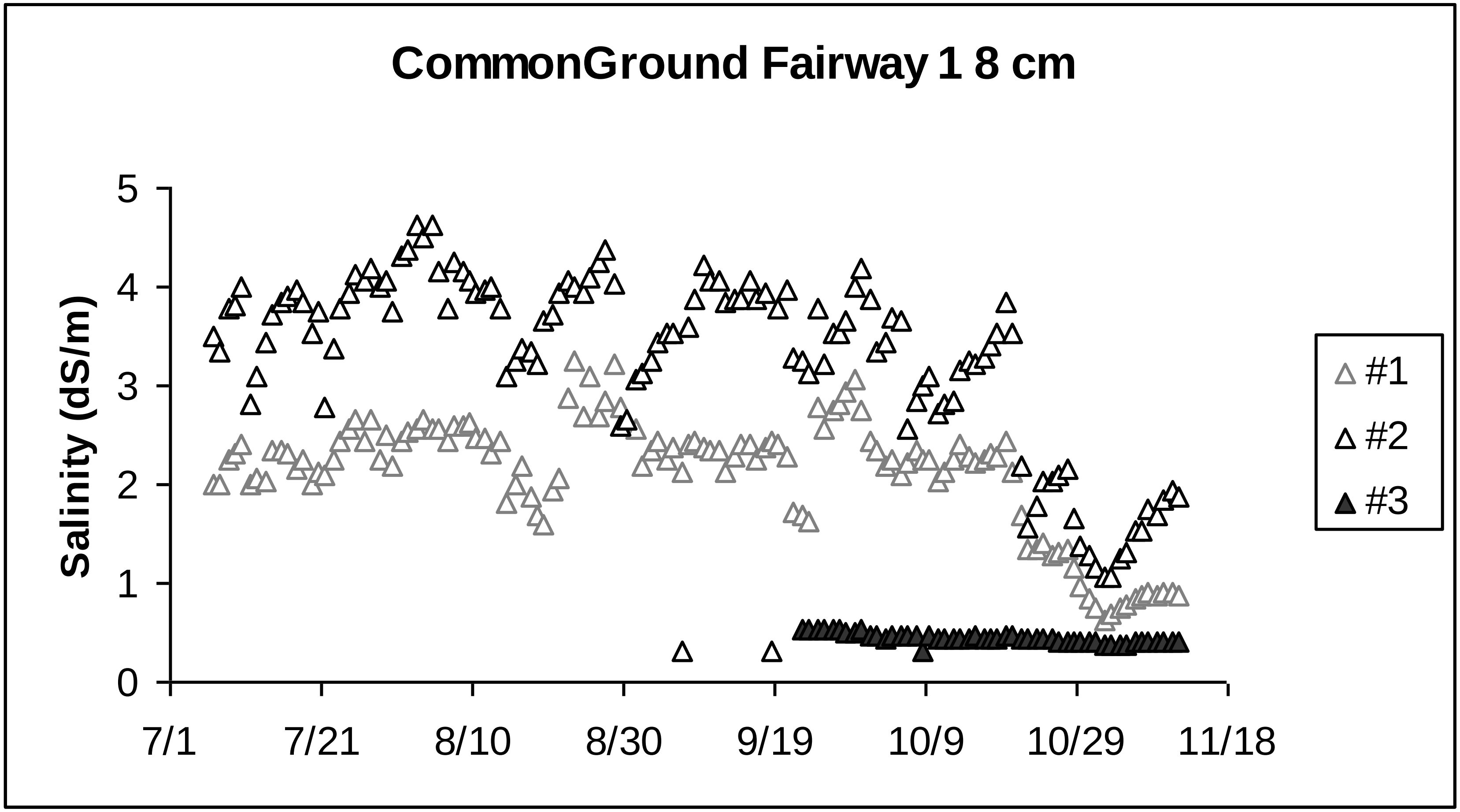

Figure 1.13A Salinity accumulation patterns of individual sensors from Common Ground fairway 1. TG2 sensor 3experienced some error

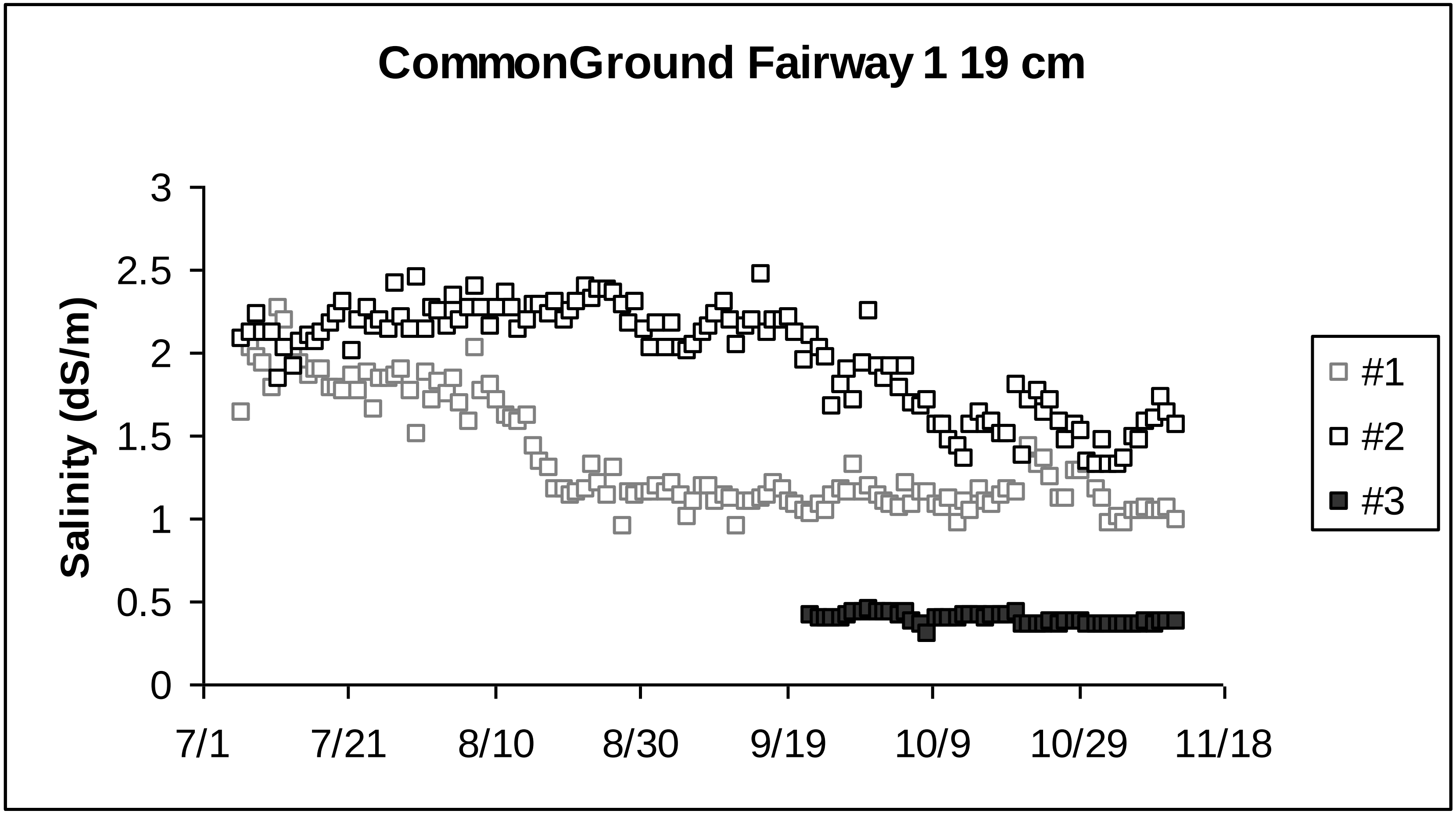

Figure 1.13 B Salinity accumulation patterns of individual sensors from Common Ground fairway 1.TG2 sensor 3 experienced some error.

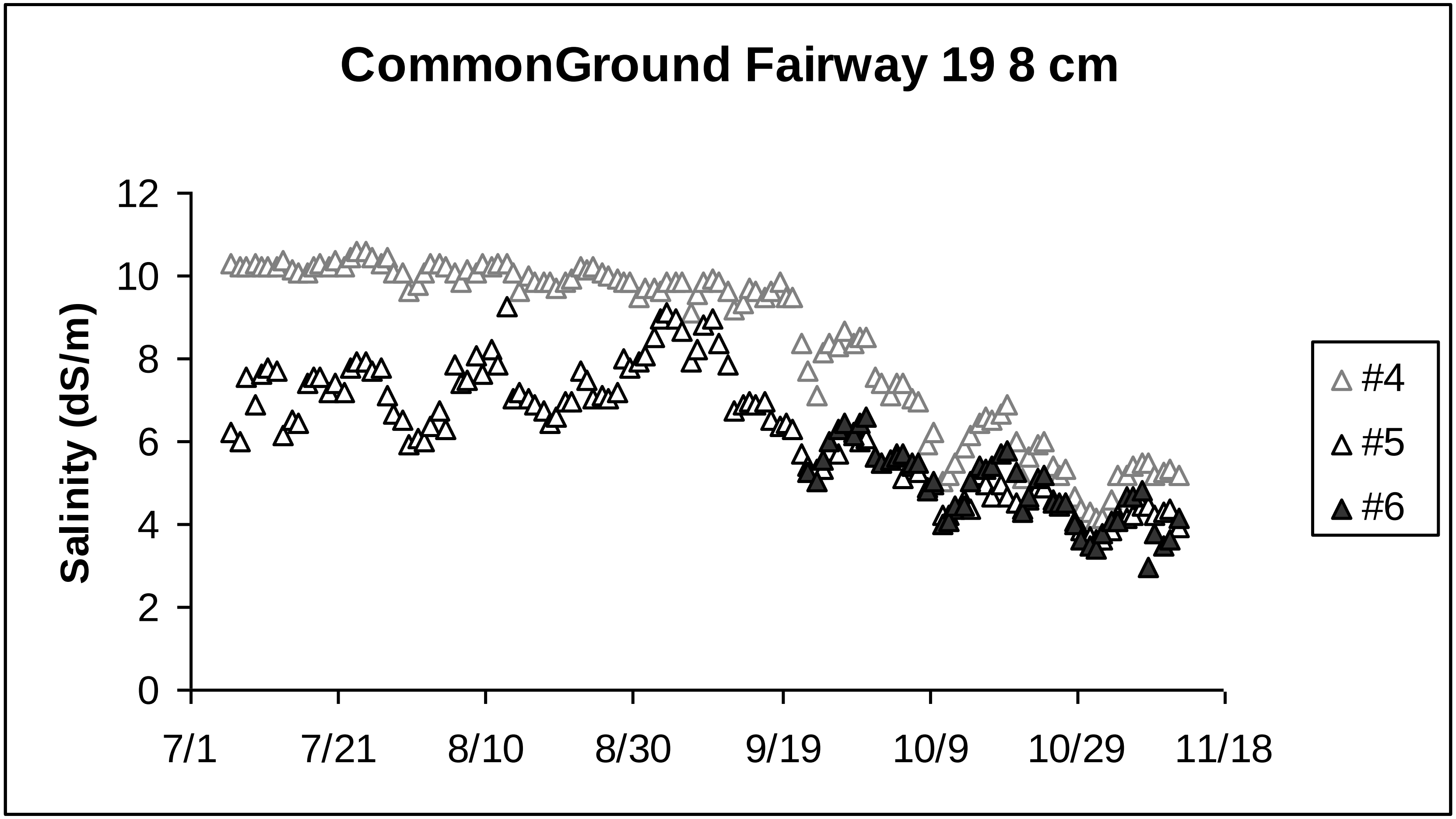

Figure 1.13 C Salinity accumulation patterns of individual sensors from Common Ground fairway 19.TG2 sensor 6 experienced some error.

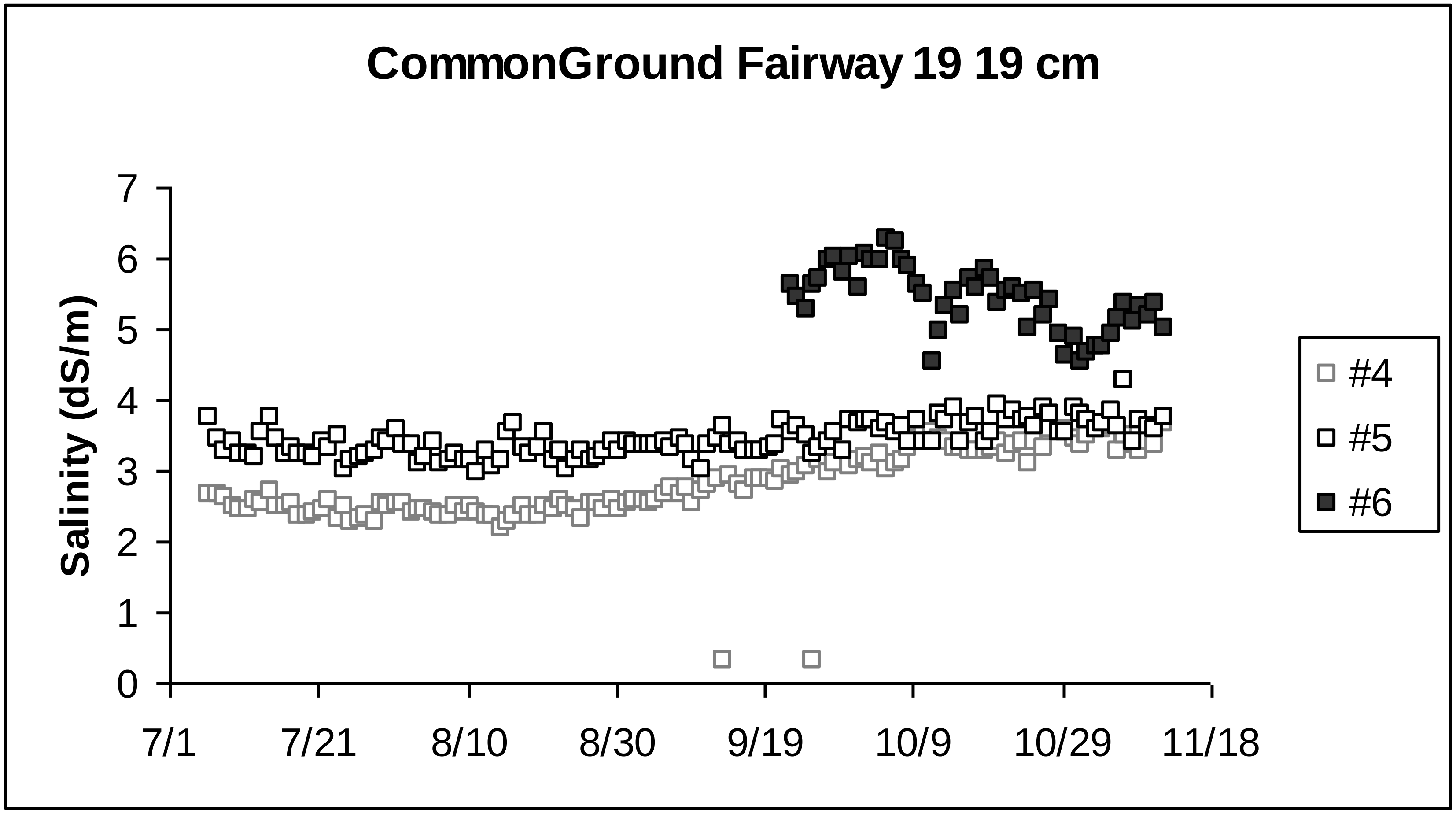

Figure 1.13D Salinity accumulation patterns of individual sensors from Common Ground fairway 19.TG2 sensor 6 experienced some error.

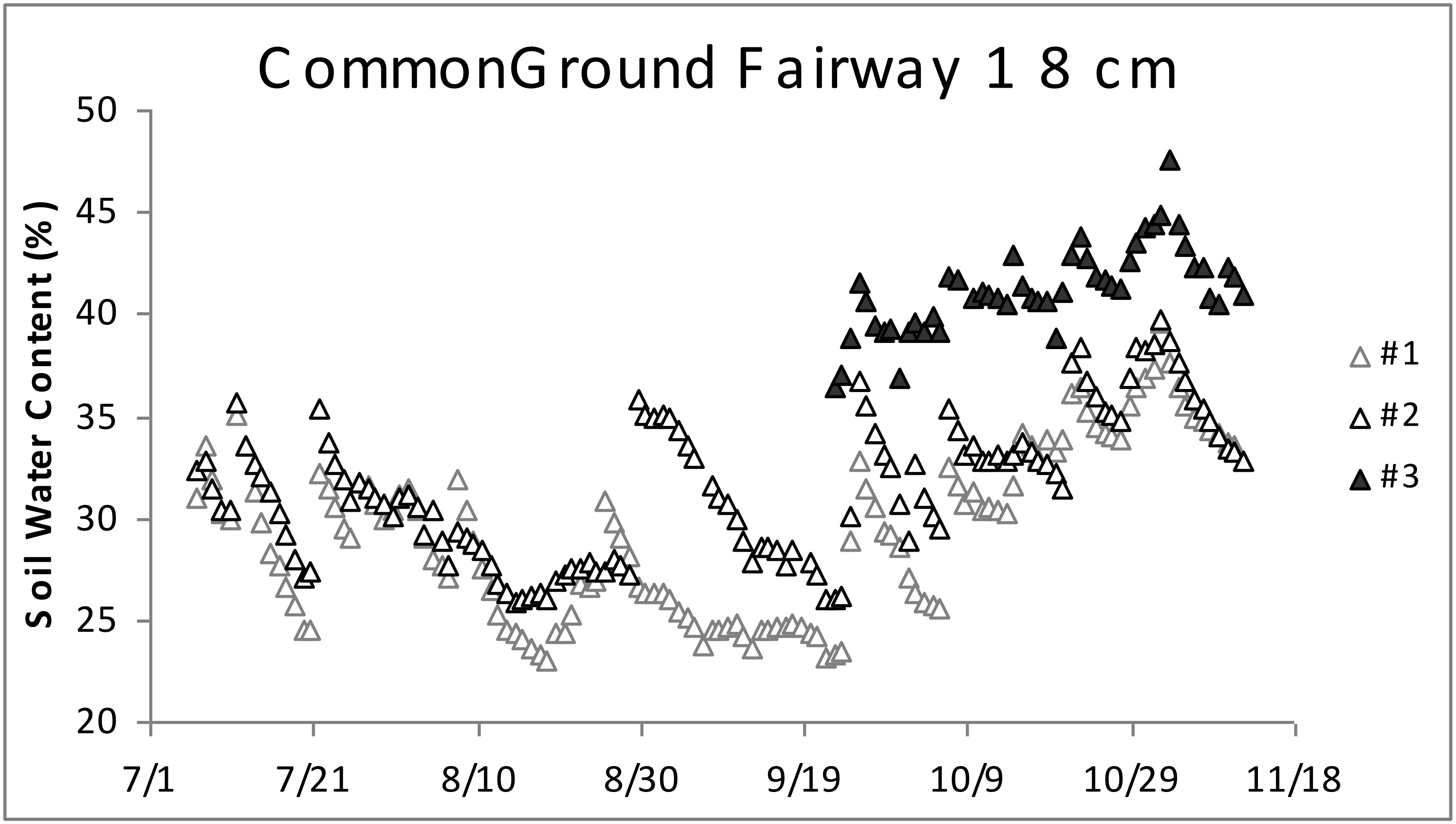

Figure 1.14A Soil water content patterns of Common Ground fairway 1's individual plots. TG2 sensor 3 experienced some error.

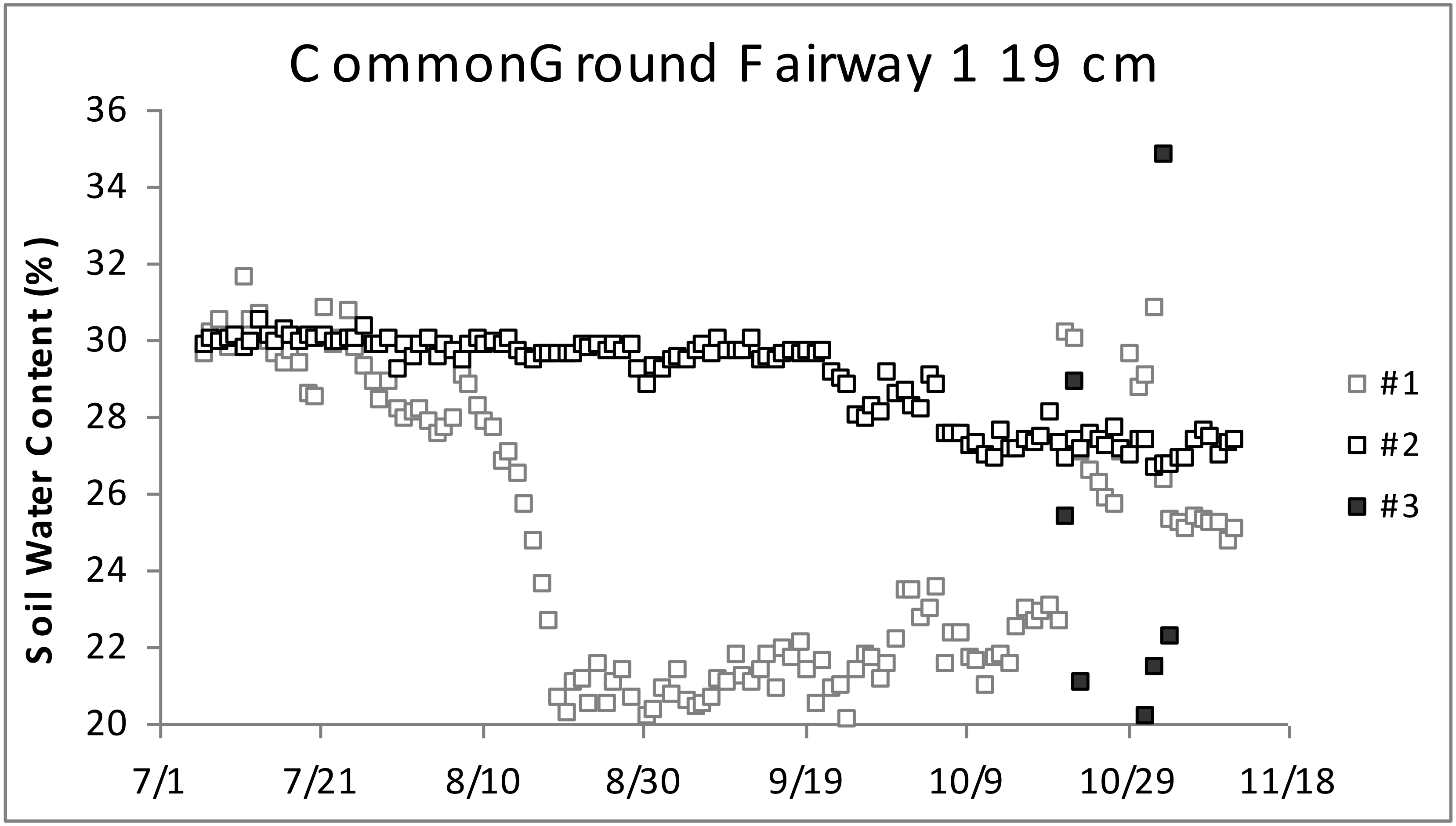

Figure 1.14B Soil water content patterns of Common Ground fairway 1's individual plots. TG2 sensor 3 experienced error.

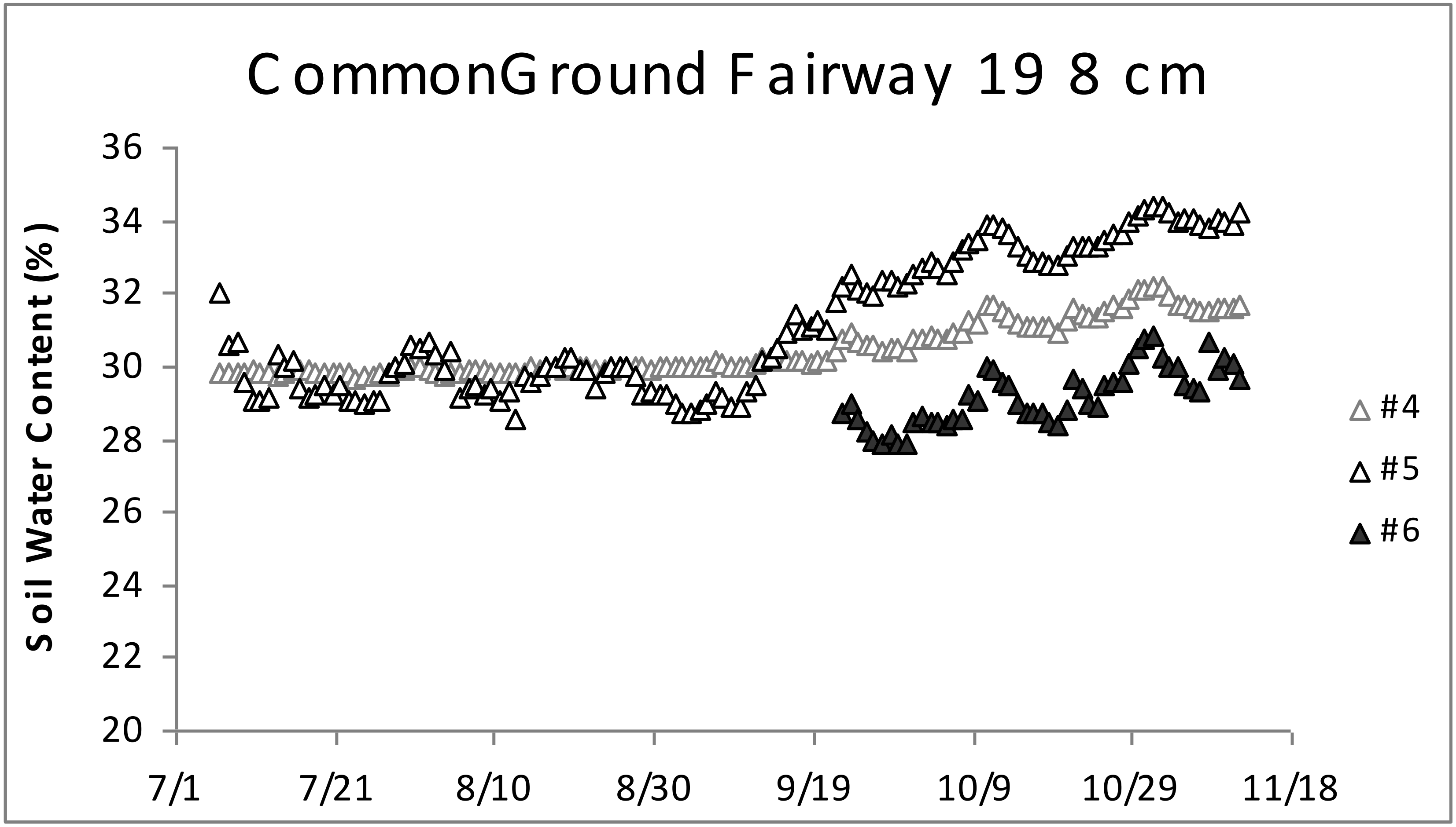

Figure 1.14C Soil water content patterns of Common Ground fairway 19's individual plots. TG2 sensor 6 experienced some error.

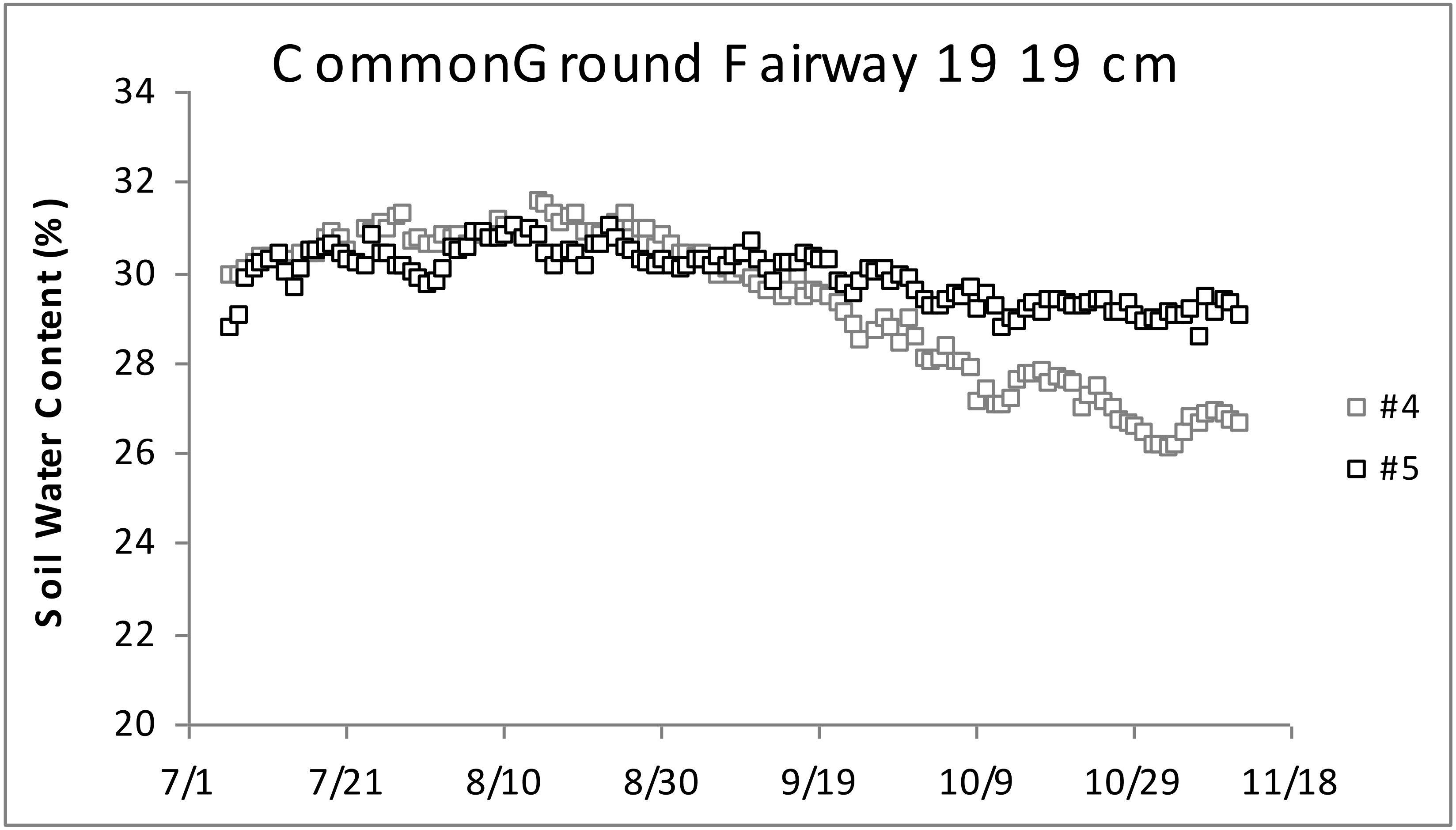

Figure 1.14D Soil water content patterns of Common Ground fairway 19's individual plots. TG2 sensor 6 failed to measure at the 19 cm depth.

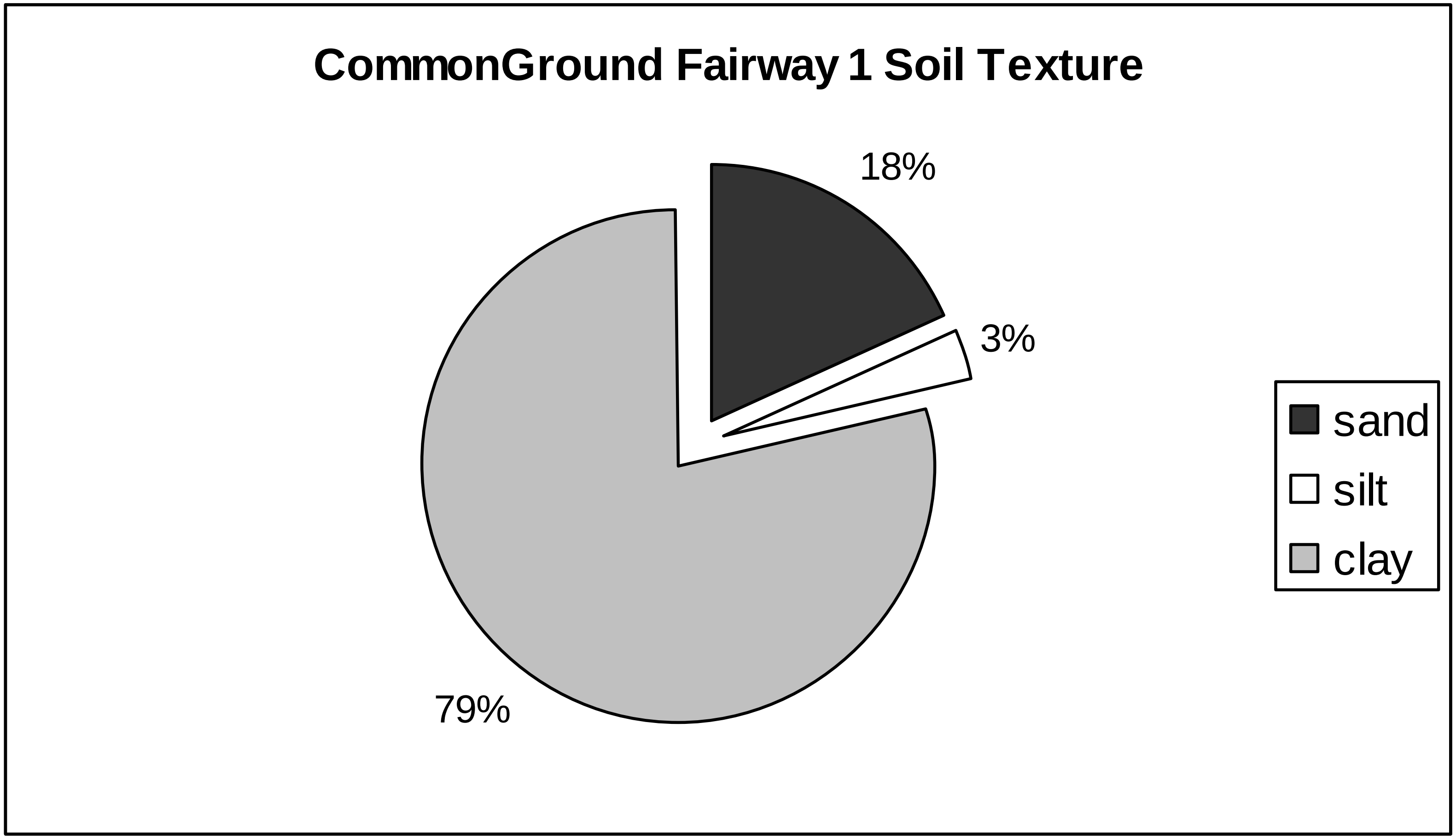

Figure 1.12A Common Ground fairway 1 soil texture data. Texture analysis by rudimentary jar tests (Sammis, 1996).

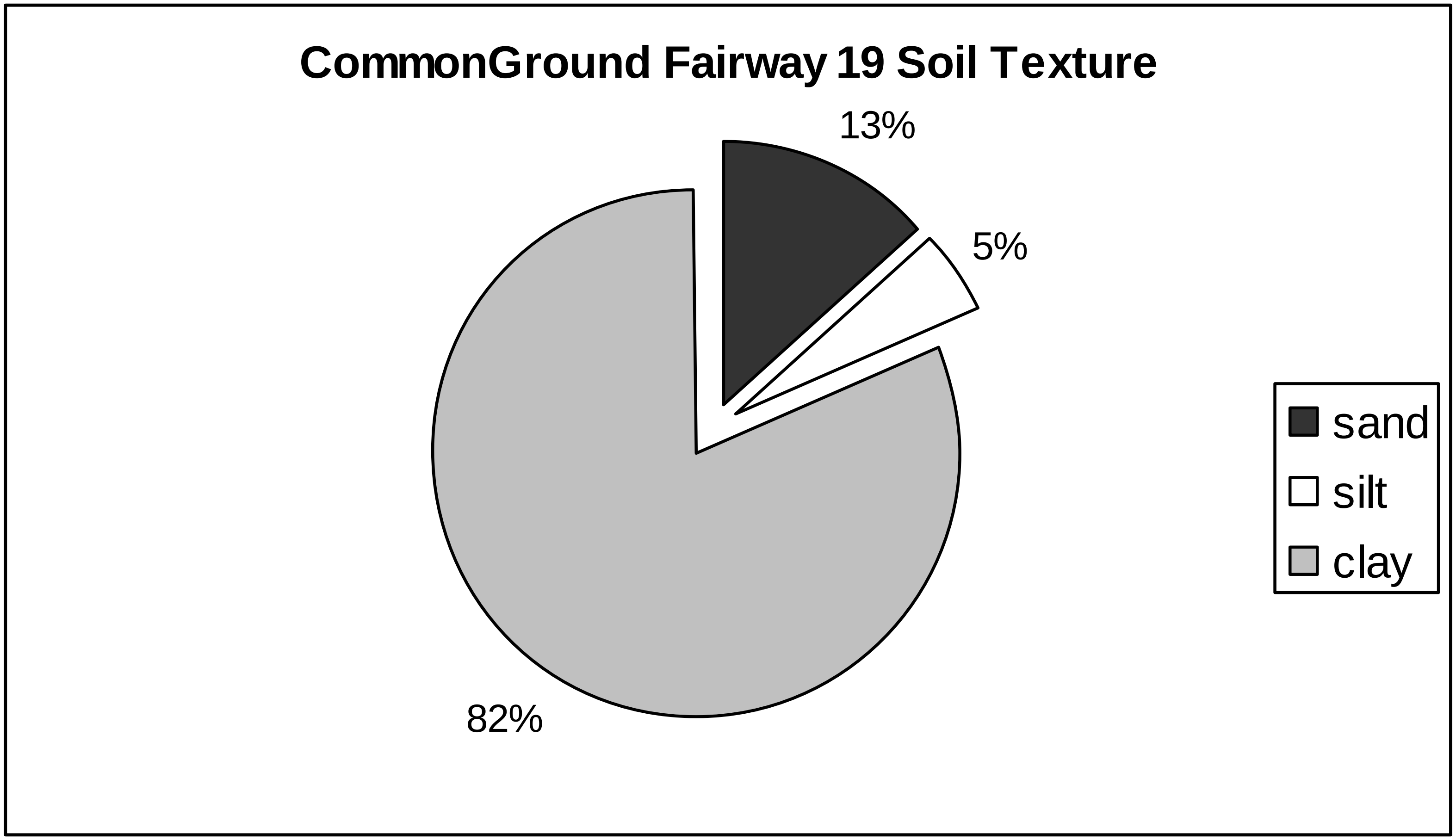

Figure 1.12B Common Ground fairway 19 soil texture data. Texture analysis by rudimentary jar tests (Sammis, 1996).

Table 1.4A Basic descriptive statistics of soil salinity at the 8cm depth at Common Ground Golf Course.

Sensor	1	2	3	4	5	6
Fairway	1	1	1	19	19	19
Mean	2.1276	3.2627	0.4442	8.4765	6.3185	4.8810
Standard Deviation	0.5901	0.9556	0.0521	2.0367	1.4635	0.8961
Coefficient of Variation	0.2773	0.2929	0.1172	0.2403	0.2316	0.1836

Table 1.4B Basic descriptive statistics of soil salinity at the 19cm depth at Common Ground Golf Course.

Sensor	1	2	3	4	5	6
Fairway	1	1	1	19	19	19
Mean	1.3451	1.9686	0.3825	2.7879	3.4253	5.4114
Standard Deviation	0.3344	0.3148	0.0303	0.5272	0.2358	0.4481
Coefficient of Variation	0.2486	0.1599	0.0793	0.1891	0.0688	0.0828

Table 1.4C Basic descriptive statistics of SWC at the 8cm depth at Common Ground Golf Course (Percentage expressed in decimal format).

Sensor	1	2	3	4	5	6
Fairway	1	1	1	19	19	19
Mean	29.3486	31.5412	41.2464	30.4650	31.1516	29.1816
Standard Deviation	4.0982	3.4713	2.0996	0.7326	1.8750	0.8002
Coefficient of Variation	0.1396	0.1101	0.0509	0.0240	0.0602	0.027

Table 1.4D Basic descriptive statistics of SWC at the 19cm depth at Common Ground Golf Course (Percentage expressed in decimal format).

Sensor	1	2	3	4	5	6
Fairway	1	1	1	19	19	19
Mean	24.7879	28.9071	10.4934	29.2948	29.8895	N/A
Standard Deviation	3.6313	1.1560	7.5570	1.6487	0.5999	N/A
Coefficient of Variation	0.1465	0.0400	0.7202	0.0563	0.0201	N/A

CHAPTER 2

SOIL CHEMICAL PROPERTY CHANGES ON GOLF COURSE FAIRWAYS UNDER EIGHT YEARS OF EFFLUENT WATER IRRIGATION

Abstract

Effluent water used for landscape irrigation has the potential to change soil chemical properties over time. Changes in soil chemistry can be observed across a range of time scales and in a variety of soil conditions. The objective of this study was to determine long-term changes in soil chemistry in soils under effluent water irrigation on golf course fairways. Soil testing data was provided by the superintendent for the years of 1999, 2000, 2002, 2003, and 2009 for Heritage Golf Course in Westminster, Colorado. Soil samples were tested by Brookside Laboratories, Inc, New Knoxville, OH. Parameters of each soil sample tested included pH, extractable salt content (calcium, magnesium, potassium, sodium, iron, manganese, copper, zinc, phosphorus, and boron), base saturation percent of calcium, magnesium, potassium and sodium, soil organic matter (SOM), and cation exchange capacity (CEC). Regression analysis was used to evaluate the changes in individual soil parameters over time after the use of effluent water for irrigation. Soil pH, CEC, extractable aluminum, copper, manganese and iron

along with both base saturation percentages and exchangeable percentages of calcium and magnesium did not change over time. The strongest indications of change are seen for extractable boron ($R^2 = 0.56$), Bray II extracted phosphate ($R^2 = 0.56$), and sodium base saturation percentage ($R^2 = 0.44$). The regression analysis indicated that B, P, and sodium increased linearly during the 8 year's irrigation with effluent water. Further studies are needed to determine if these parameters would continue to increase or would stabilize. Continued accumulation of sodium could eventually result in loss of soil structure.

INTRODUCTION

Demand for water resources is increasing at a global scale. Issues surrounding the demand for water command persistent public attention since they are politically and economically sensitive. Water is no more sensitive an issue to any industry than it is to the golf industry where game surfaces are sustained by adequate water input. As freshwater resources are allocated for high priority uses, turf managers are faced with increasing concerns about the sustainability of the turf industry (Devitt et al., 2004).

A direct result of urban growth and increased municipal water use is an increase in the availability and volume of effluent water being produced as a byproduct of residential and industrial usage. Effluent waters are either discharged back into surface water systems, recharged into groundwater aquifers or can be distributed to customers as a source of landscape irrigation water.

Effluent water used for landscape irrigation has the potential to change soil chemistry over time. These changes to soil chemistry can be observed across a range of time scales and in a variety of soil conditions. Soil chemistry can change over a single season (Murakami and Ray, 2000) or over many years (Wallach et al., 2005; Qian and Mecham, 2005; Thomas et al., 2006) or even decades (Walker and Lin, 2008). Methods for observing such change often include some element of conventional soil sampling and chemical analysis, although in-situ soil sensors have also been employed for real time data acquisition (Lockett et al., 2008).

Preceding research into the sustainability of effluent water irrigation as a practice has found overwhelmingly that changes in soil chemistry do result under effluent water irrigation. The changes observed vary in intensities. A number of studies have observed changes in soil chemistry that do not harm the overall functionality, agronomic quality and sustainability of soils irrigated with effluent water (Walker and Lin, 2008; Mancino and Pepper, 1992; Coppola et al., 2004). Other studies have found that changes in soil chemistry do have the potential to affect agronomic quality and sustainability of soils systems irrigated with effluent water (Balks et al., 1998; Hayes et al., 1990; Wallach et al., 2005; Rattan et al., 2005; Schipper et al., 1996; Speir et al 1999; Miyamoto and Chacon, 2006; Qian and Mecham, 2005; Thomas et al., 2006; Toze, 2006).

Turf managers often rely on the results of soil testing to develop their annual fertilization budget, and other management programs and to identify the presence of problematic soil conditions. In some cases, courses use regional labs (commercial), along with consultants to perform soil testing and analysis. If standard methods of testing are used, soil chemical change over multiple years can be evaluated. These data are valuable in assessing changes over long time intervals and can be compared for different sites. By utilizing existing records and standard operating procedures; low cost research observations can be formulated to further understand soil heath and stability in response to effluent water irrigation.

The objective of this study was to determine long-term changes in soil chemistry in soils under effluent water irrigation on golf course fairways.

METHODS AND MATERIALS

The study was conducted at Heritage Golf Course in Westminster, Colorado located north of metro Denver, Colorado. Soil testing data was provided by the superintendent for the years of 1999, 2000, 2002, 2003, and 2009. The course started to use effluent water for irrigation in 2000. Heritage Golf Course sampled odd numbered fairways in odd number years and even numbered fairways in even number years. Sampling locations within individual fairways remained approximately stationary from year to year. Sampling was performed by the golf course maintenance staff. The principal soil series found from the previous study included Renohill, Ulm and Platner with soil texture varying from clay loam to loam (Qian and Mecham, 2005).

Soil samples were analyzed by Brookside Laboratories, Inc, New Knoxville, OH. Soil samples were analyzed for pH, extractable salt content (Ca, Mg, K, Na, Fe, Mn, Cu, Zn, P, and B), base saturation percent of Ca, Mg, K and Na, soil organic matter (SOM) , and cation exchange capacity (CEC).

Brookside soil-testing lab provided information on analytical methods. Soil pH was analyzed using a saturated paste extract. Sieved soil samples were extracted using the Mehlich III extractant (0.015 M NH4F + 0.20 M CH3COOH + 0.25 M NH4NO3 + 0.013 M HNO3 + 0.0005 M EDTA chelating agent) to determine Ca, Mg, K, Na, Fe, Mn, Cu, Zn, B, and P by inductively-coupled plasma-emission spectrophotometry instrumentation. Mehlich III extracted Ca, Mg, K and Na plus soil buffer pH data are used to calculate CEC. Base saturation percent of Ca, Mg, K and Na was calculated by dividing the extracted Ca, Mg, K and Na by the calculated CEC, respectively. Base saturation percent of Na is considered the exchangeable sodium percentage (ESP). Soil organic matter was determined by reaction with $Cr_2O_7^{2}$ and sulfuric acid. The remaining unreacted $Cr_2O_7^{2-}$ is titrated with FeSO4 using ortho-phenanthroline as an indicator, and oxidizable organic matter was calculated by the difference in $Cr_2O_7^{2-}$ before and after reaction (Nelson and Sommers, 1982). Estimated nitrogen release is a calculated estimate of the nitrogen potentially released annually by decomposition of organic matter.

Regression analysis was used to evaluate the changes in individual soil parameters over time after the use of effluent water for irrigation.

RESULTS AND DISCUSSION

Accumulations of certain elements could be explained by conventional golf course management in general. Change in other elements may be directly attributed to the chemistry of effluent water. Effluent water chemistry was dominated by sulfate, bicarbonate, chloride and sodium (Table 2.1).

Data over ten years showed no statistical change in CEC (Figure 2.1) and pH (Figure 2.2). Soil organic matter (SOM) data revealed accumulation over ten years at an average rate of 0.26% per year ($R^2 = 0.53$, Figure 2.3). The rate of SOM accumulation in this study was higher when compared with previous work on SOM accumulation and the carbon sequestration potential of turfgrass systems (Qian and Follett, 2002). The estimated nitrogen available for release showed an increase over ten years ($R^2 = 0.30$, Figure 2.4). This increase was likely attributed to conventional golf course fertility management practices. Estimated nitrogen release is an estimate of nitrogen potentially released annually by decomposition of organic matter; increases in this category are most likely not the direct result of cumulative fertilization but rather as a secondary result of increased biomass production that has translated to increases in SOM and eventually releasable nitrogen from organic decomposition.

Soluble sulfur data over ten years showed increases in the amounts of soluble sulfur ($R^2 = 0.29$, Figure 2.5). The Heritage installed a sulfur burner after transitioning to effluent water. Sulfur burner units heat elemental sulfur to create sulfurous acid for injection into irrigation water to reduce the bicarbonate content and pH of irrigation water (Qian and Mecham, 2005). Increases in sulfur content in the soil over time were likely a direct result of the sulfur burner. The fact that we did not see an increase in soil pH suggested that the sulfur burner was effective in controlling soil pH. Soil pH changes have been observed by others in soils under effluent irrigation use (Miyamoto and Chacon, 2006).

Mehlich III extracted phosphates increased linearly at an average rate of 29 mg/kg/year ($R^2 = 0.48$) during the eight-year-period after the beginning of effluent water irrigation. Bray II extracted phosphates revealed a pattern of phosphate accumulation over time ($R^2 = 0.56$, Figure 2.6). Increases in phosphates with multiple years of effluent irrigation have also been observed by previous researchers (Bond, 1998).

No pattern indicating change was seen for exchangeable calcium (Figure 2.7) or for exchangeable magnesium (Figure 2.8). Exchangeable potassium data suggested a slight accumulation over a decade ($R^2 = 0.16$, Figure 2.9). Exchangeable sodium data showed that sodium accumulated over years at 45 mg/kg per year during the 8 years of irrigation with effluent water ($R^2 = 0.28$, Figure 2.10). The average sodium concentration of the effluent water used on the study site was 101 mg L^{-1} (Table 2.1).

No clear changes occurred for calcium and magnesium base saturation percentage (Figure 2.11, Figure 2.12). Potassium base saturation percentage increased over time ($R^2 = 0.20$, Figure 2.13. Likewise, exchangeable sodium percentages increased after eight years of effluent water irrigation at an average rate of 0.5% per year ($R^2 = 0.44$, Figure 2.14). Elevating exchangeable sodium percentages observed over several years of effluent irrigation can be of concern with regards to the preservation of soil structure and agronomic viability (Halliwell et al., 2001). Increased occurrence of clay dispersion has been associated with increased soil exchangeable sodium percentage and fine textured soils (Balks et al., 1998). Other factors, such as electrolyte levels and composition, organic matter, pH, negative charge density have been shown to affect clay dispersion (Chorom et al., 1994).

Extractable boron data showed gradual accumulation from years of effluent irrigation ($R^2 = 0.56$, Figure 2.15). Boron accumulated in fairway soils. Previous investigation into boron toxicity in perennial ryegrass found symptoms at levels of 39-42 mg B/kg (Sherrell, 1983). Boron toxicity in turfgrass under these conditions is unlikely given the frequency of mowing that removes boron accumulations in leaf tips (Mancino and Pepper, 1994). No pattern of change over time was indicated for extractable iron (Figures 2.16), extractable manganese (Figure 2.17), extractable copper (Figure 2.18), extractable zinc (Figure 2.19) or extractable aluminum (Figure 2.20).

Conclusions

Soil chemistry changed over time in response to effluent water irrigation. A total of eight chemical parameters have data indicating change over eight years of effluent irrigation, of varying statistical significance. The strongest indications of change were seen within extractable boron ($R^2 = 0.56$, Figure 2.15), Bray II extracted -phosphates ($R^2 = 0.56$, Figure 2.6), and sodium base saturation percentage ($R^2 = 0.44$, Figure 2.14). Other data sets indicating notable changes: soluble sulfur ($R^2 = 0.34$, Figure 2.5), estimated nitrogen available ($R^2 = 0.30$ Figure 2.4), exchangeable sodium ($R^2 = 0.28$, Figure 2.10), potassium base saturation percentage data ($R^2 = 0.20$, Figure 2.13.A-C) and exchangeable potassium ($R^2 = 0.1645$, Figure 2.9).

Some changes in soil chemistry could be attributed to conventional golf course management practices of nutrition management. Increases in soluble sulfur can be attributed to the use of a sulfur burning unit. Increases in sodium based parameters can be attributed to effluent water use. Likewise, boron and phosphate increases may be the result of effluent water irrigation. There is a relationship between the chemical constituents of effluent water used for irrigation and the changes observed through several years of soil testing data

Sodium accumulation occurred under effluent irrigation, as well as boron accumulation. Further studies are needed to determine if these parameters would continue to increase or would stabilize. Continued accumulation of sodium could eventually result in loss of soil structure.

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Table 2.1 Average effluent water quality of 5 water samples for the Heritage study site

Water quality parameters	
pH	7.4
NH_4–N, mgL^{-1}	0.8
NO_3–N, mgL^{-1}	2.9
Total P, mgL^{-1}	0.63
Total dissolved salts	638
Conductivity, dS m^{-1}	0.99
Sodium absorption ratio (SAR)	3.05
Adjusted SAR	5.74
Na, mgL^{-1}	101
Cl, mgL^{-1}	120
Bicarbonate, mgL^{-1}	125
Ca, mgL^{-1}	66.96
Mg, mgL^{-1}	11.84
Sulfate, mgL^{-1}	182
B, mgL^{-1}	0.21
Fe, mgL^{-1}	0.31
K, mgL^{-1}	16.85
TSS, mgL^{-1}	9.1

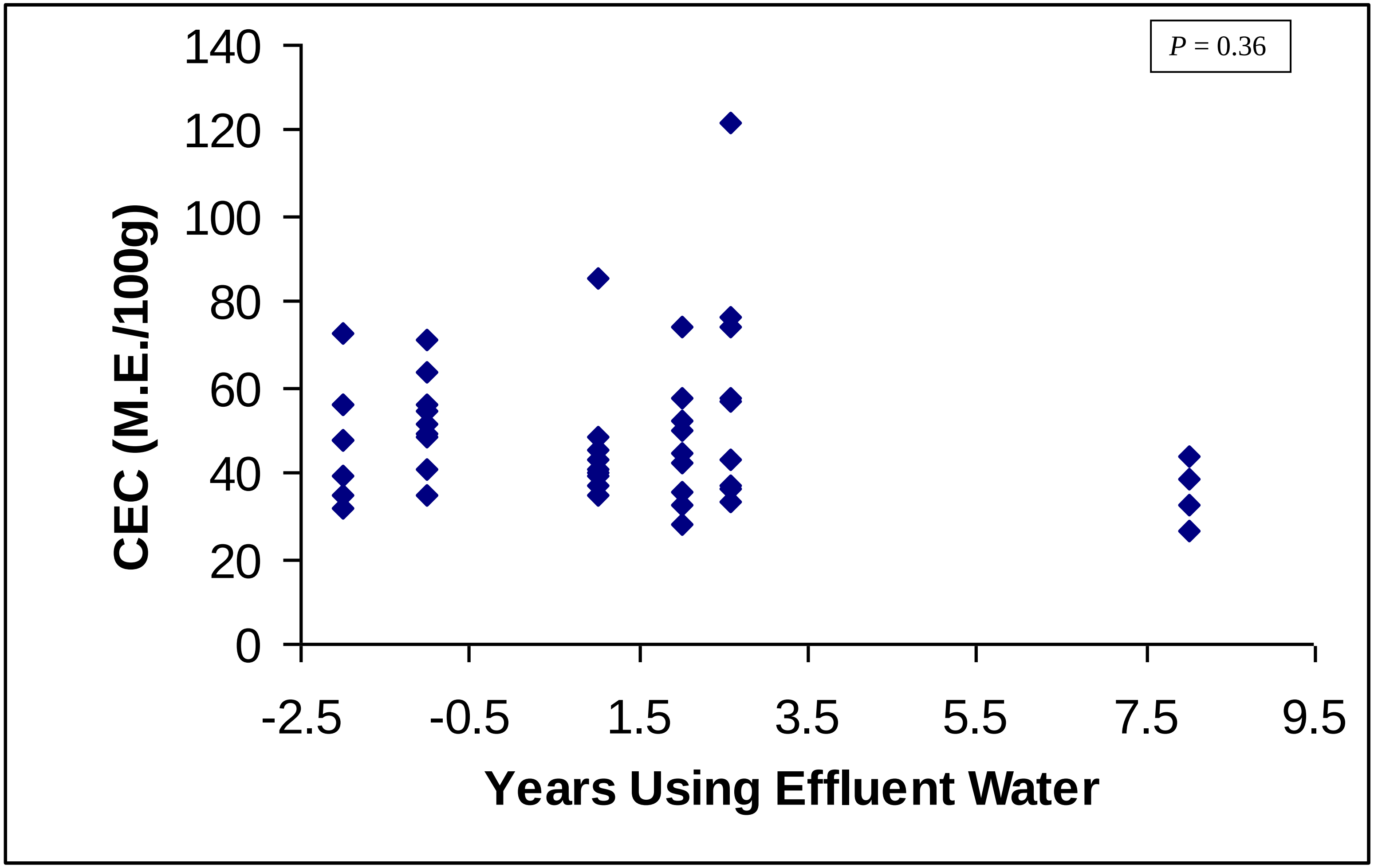

Figure 2.1 CEC data from Heritage fairways under eight years of effluent irrigation

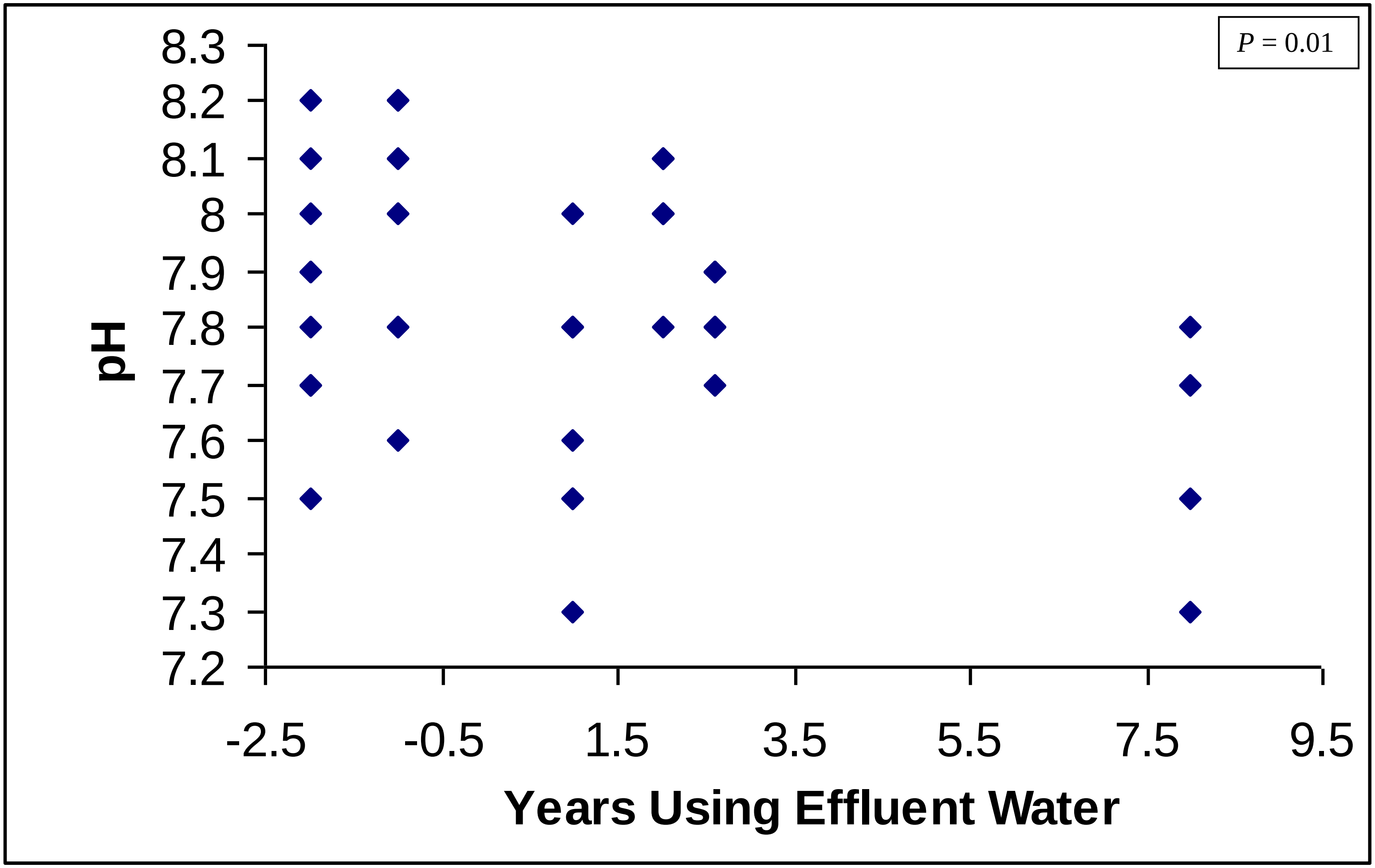

Figure 2.2 pH data from Heritage fairways under eight years of effluent irrigation.

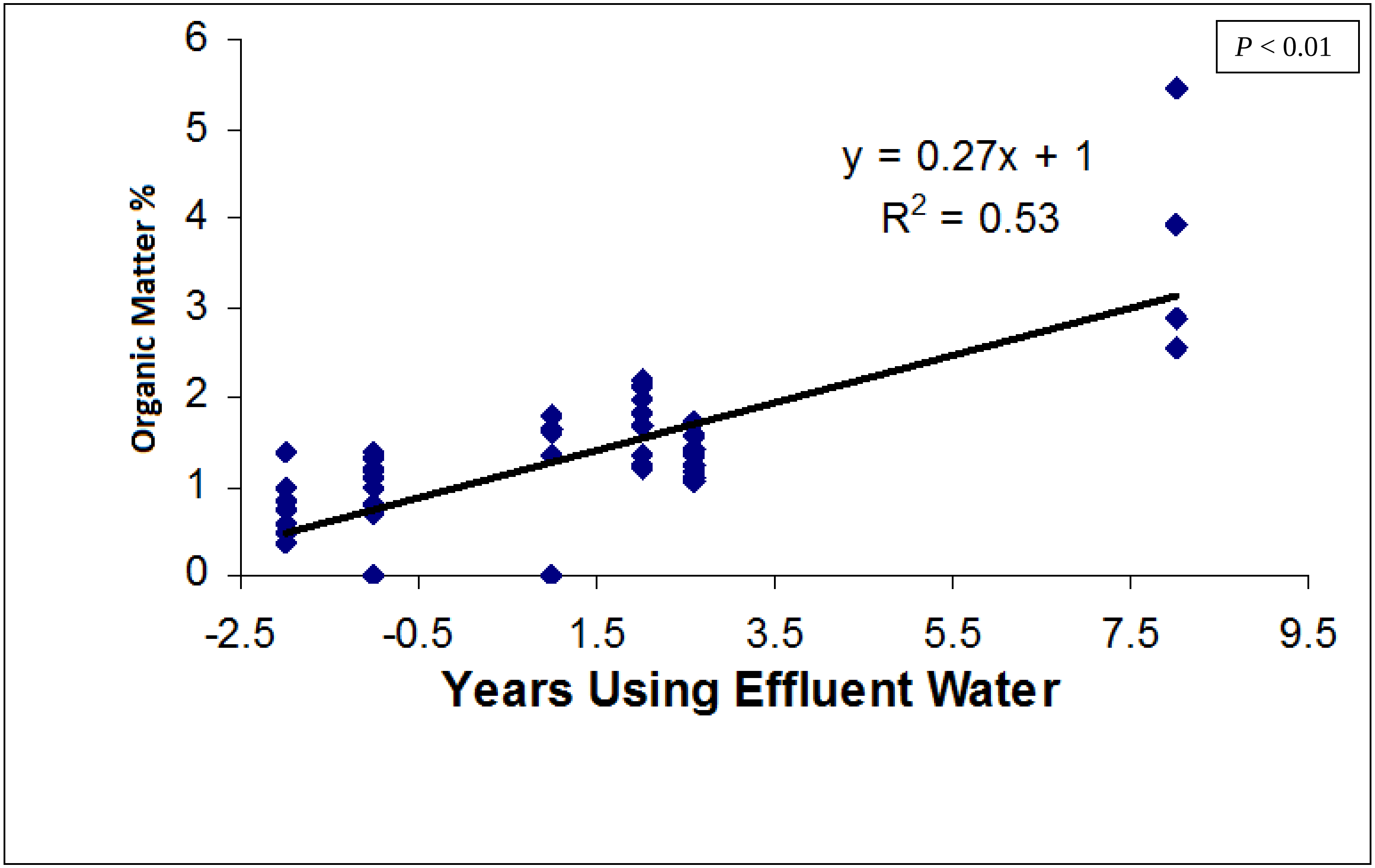

Figure 2.3 Organic matter data from Heritage fairways under eight years of effluent irrigation.

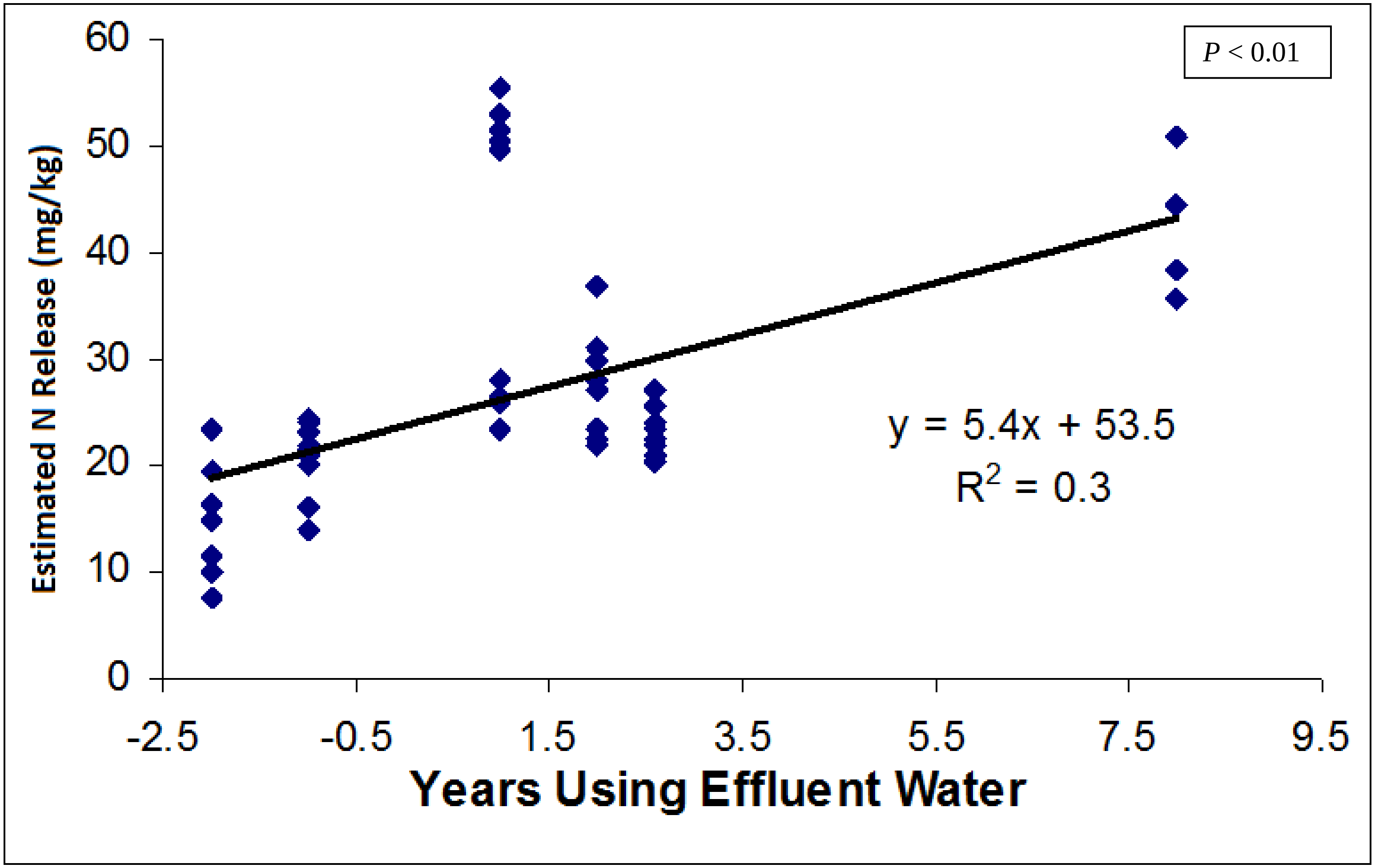

Figure 2.4 Estimated releasable nitrogen data from Heritage fairways under eight years of effluent irrigation.

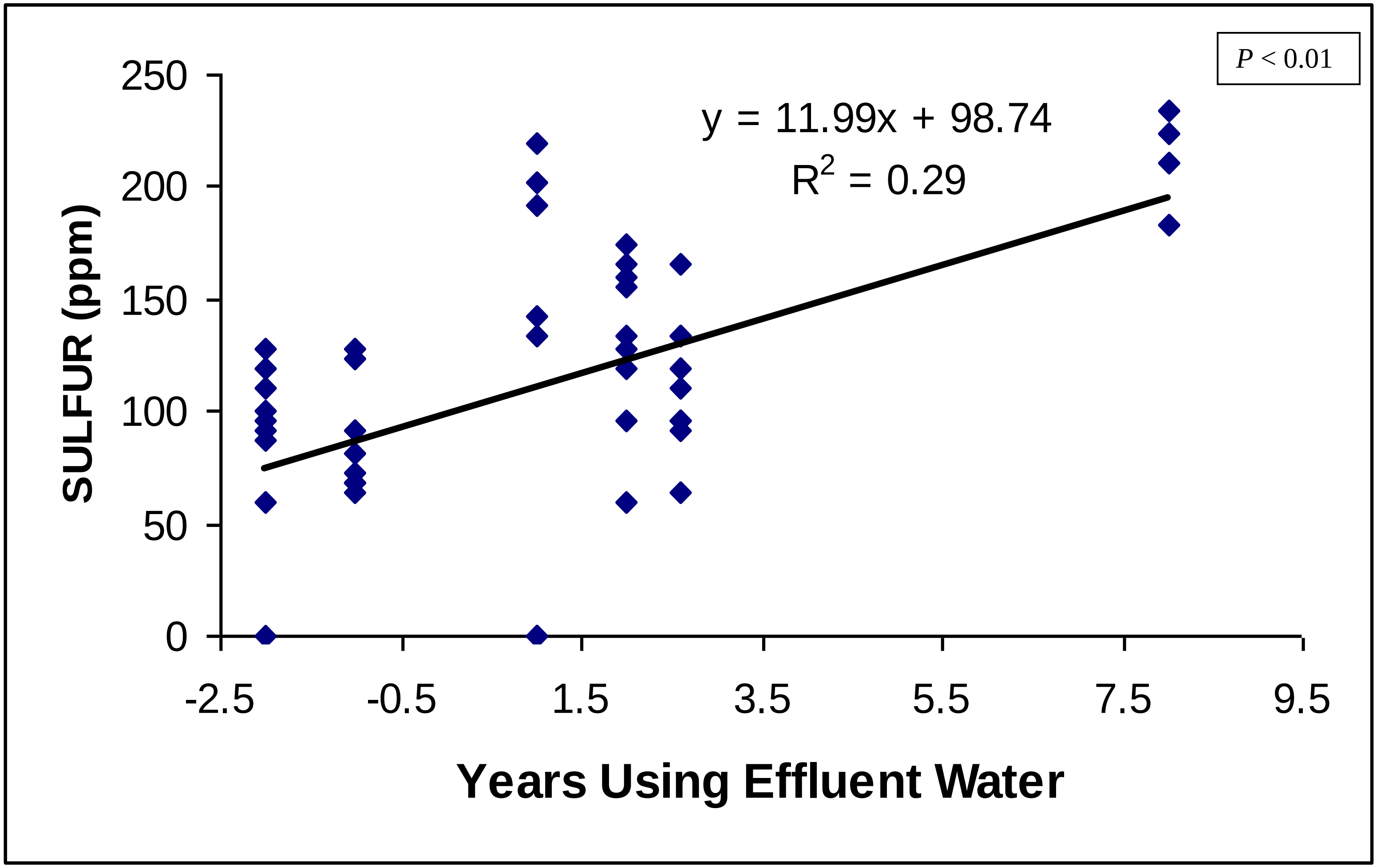

Figure 2.5 Soluble sulfur data from Heritage fairways under eight years of effluent irrigation.

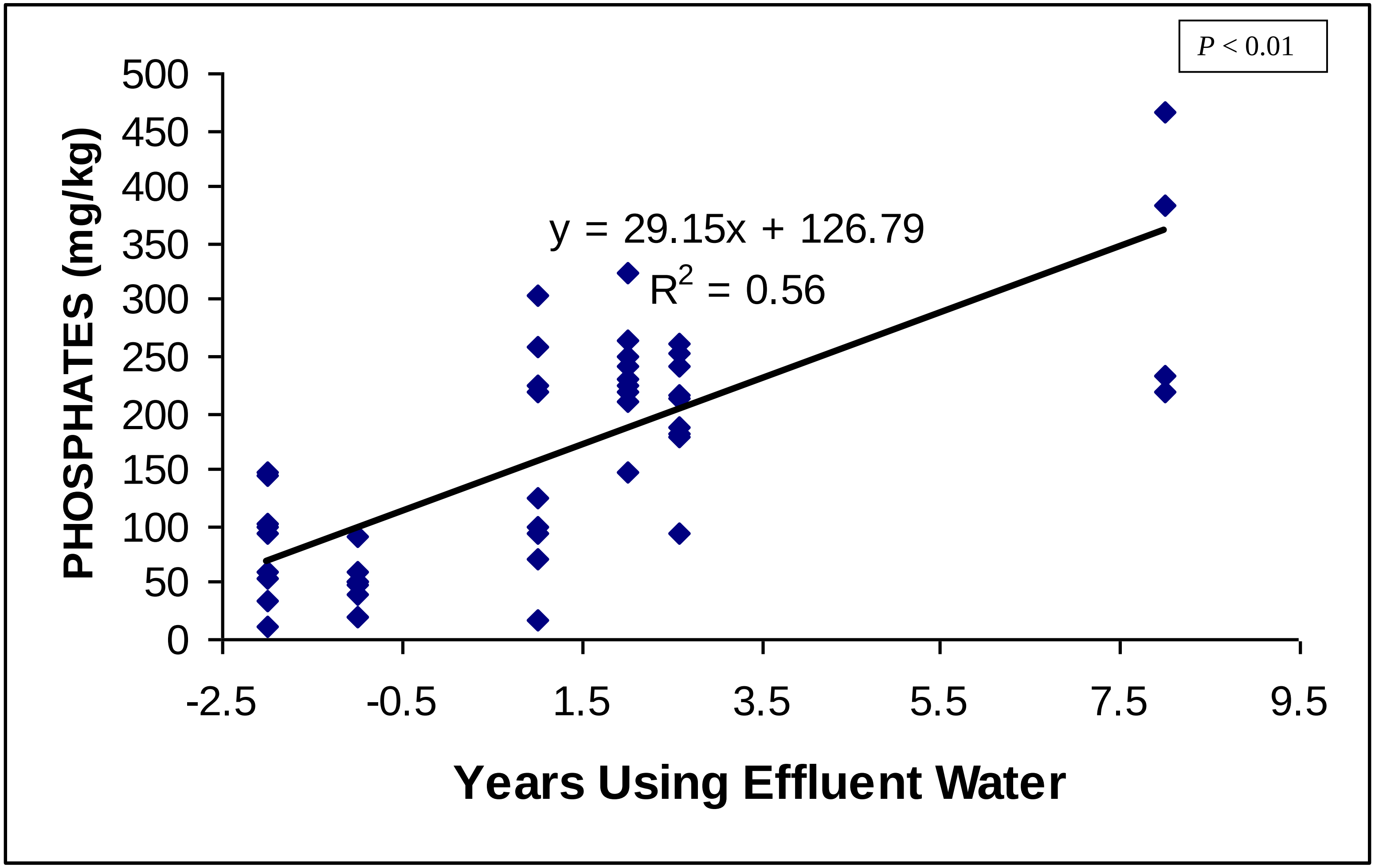

Figure 2.6 Phosphate data from Heritage fairways under eight years of effluent irrigation.

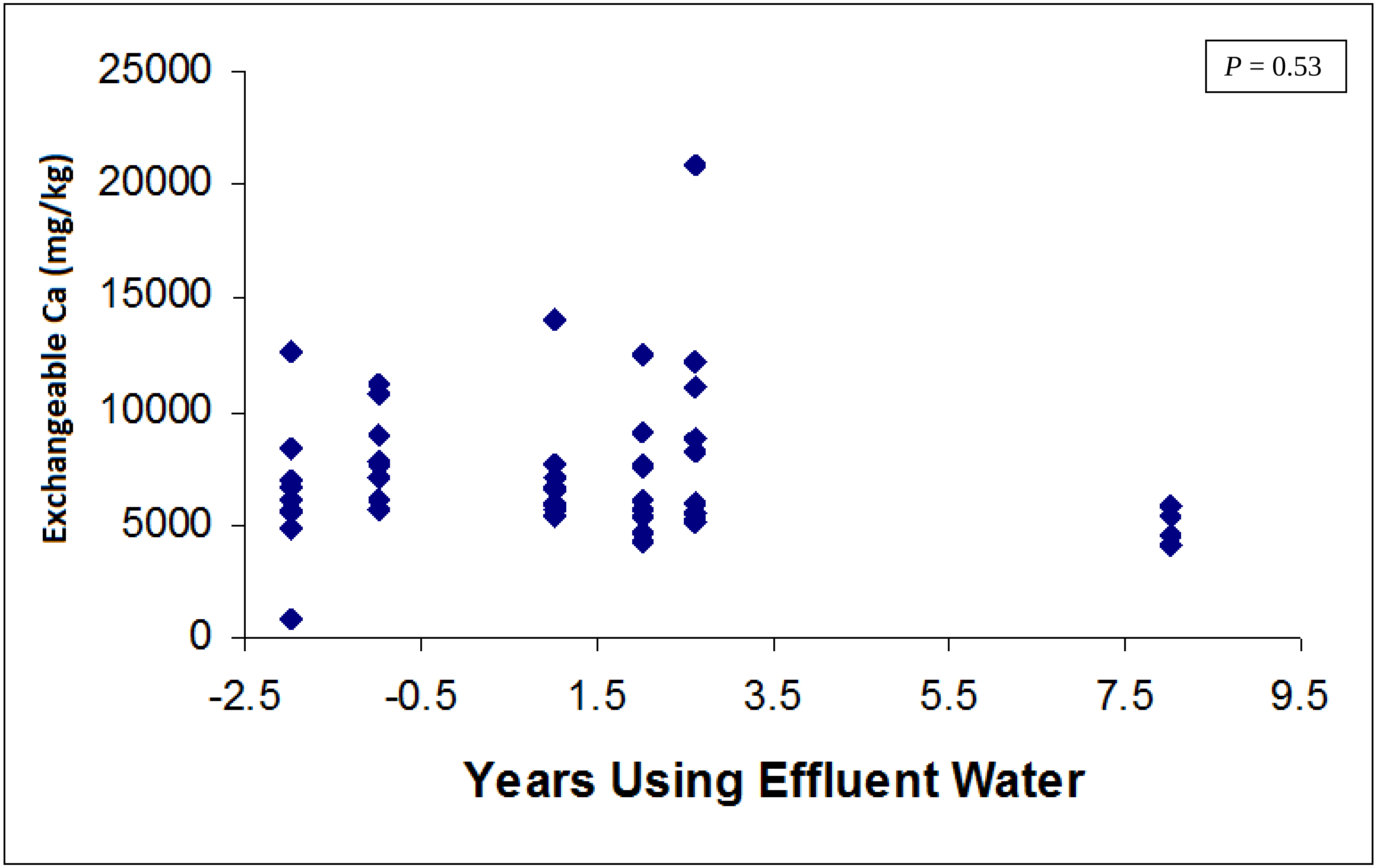

Figure 2.7 Exchangeable Ca data from Heritage fairways under eight years of effluent irrigation.

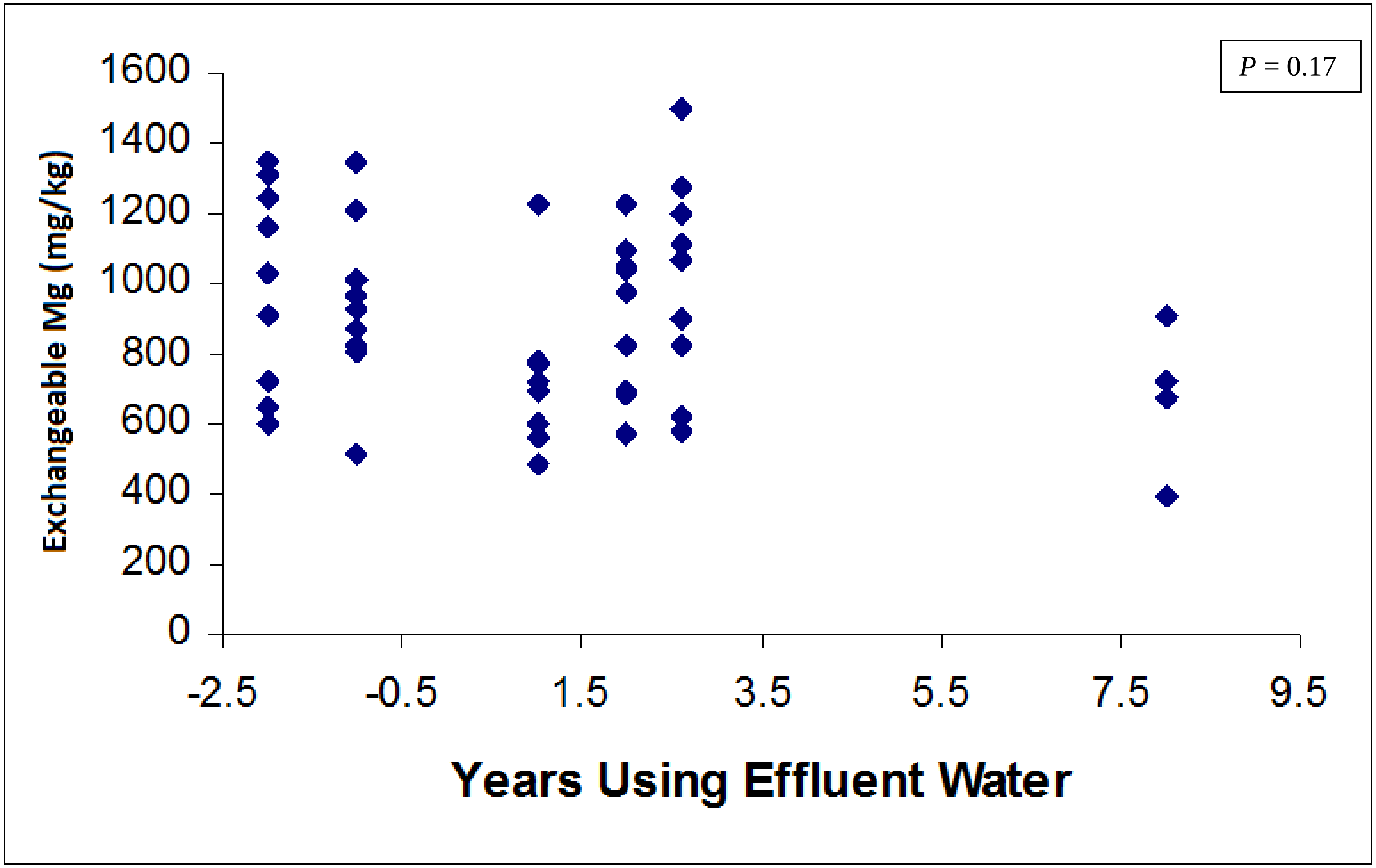

Figure 2.8 Exchangeable Mg data from Heritage fairways under eight years of effluent irrigation.

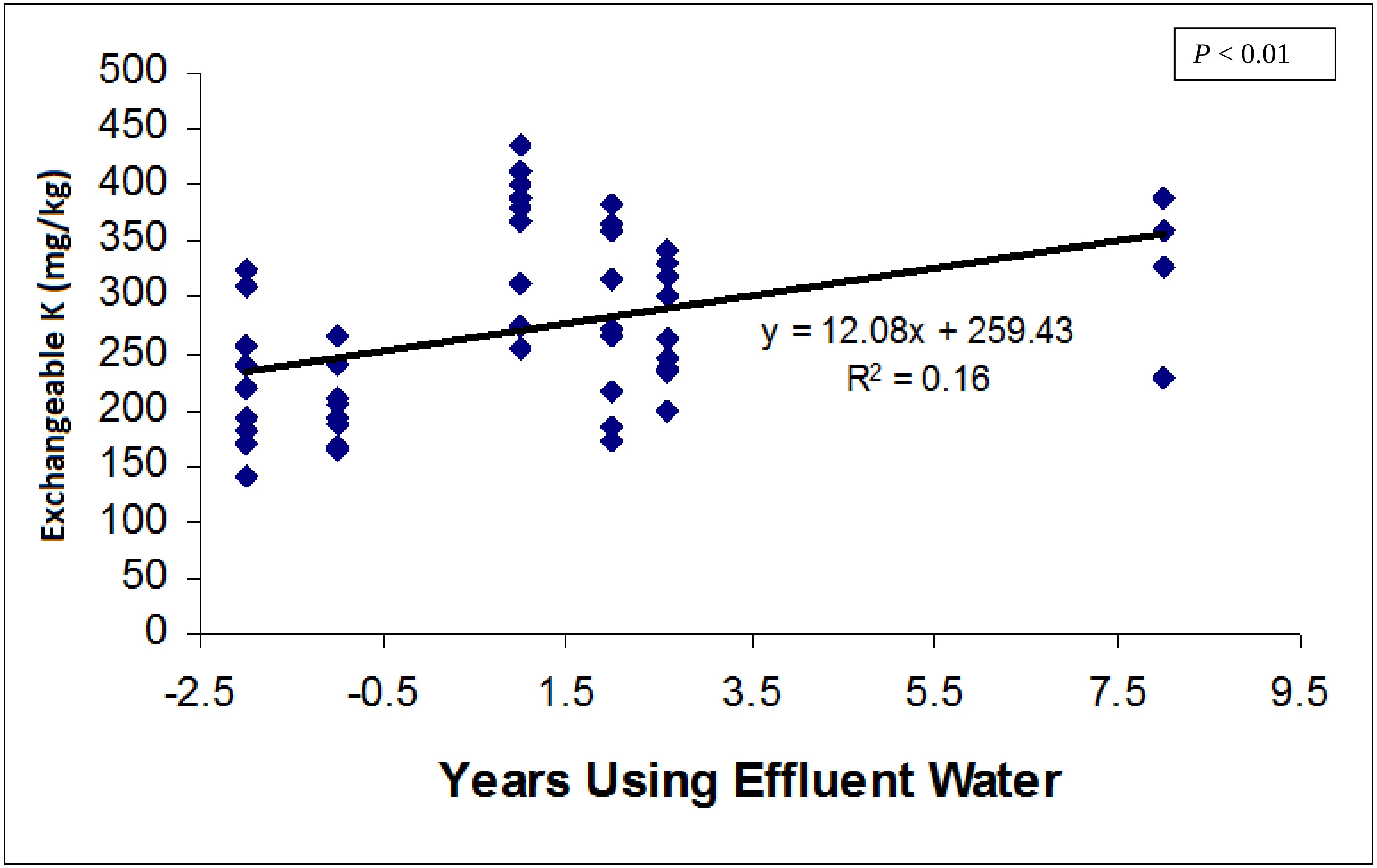

Figure 2.9 Exchangeable K data from Heritage fairways under eight years of effluent irrigation.

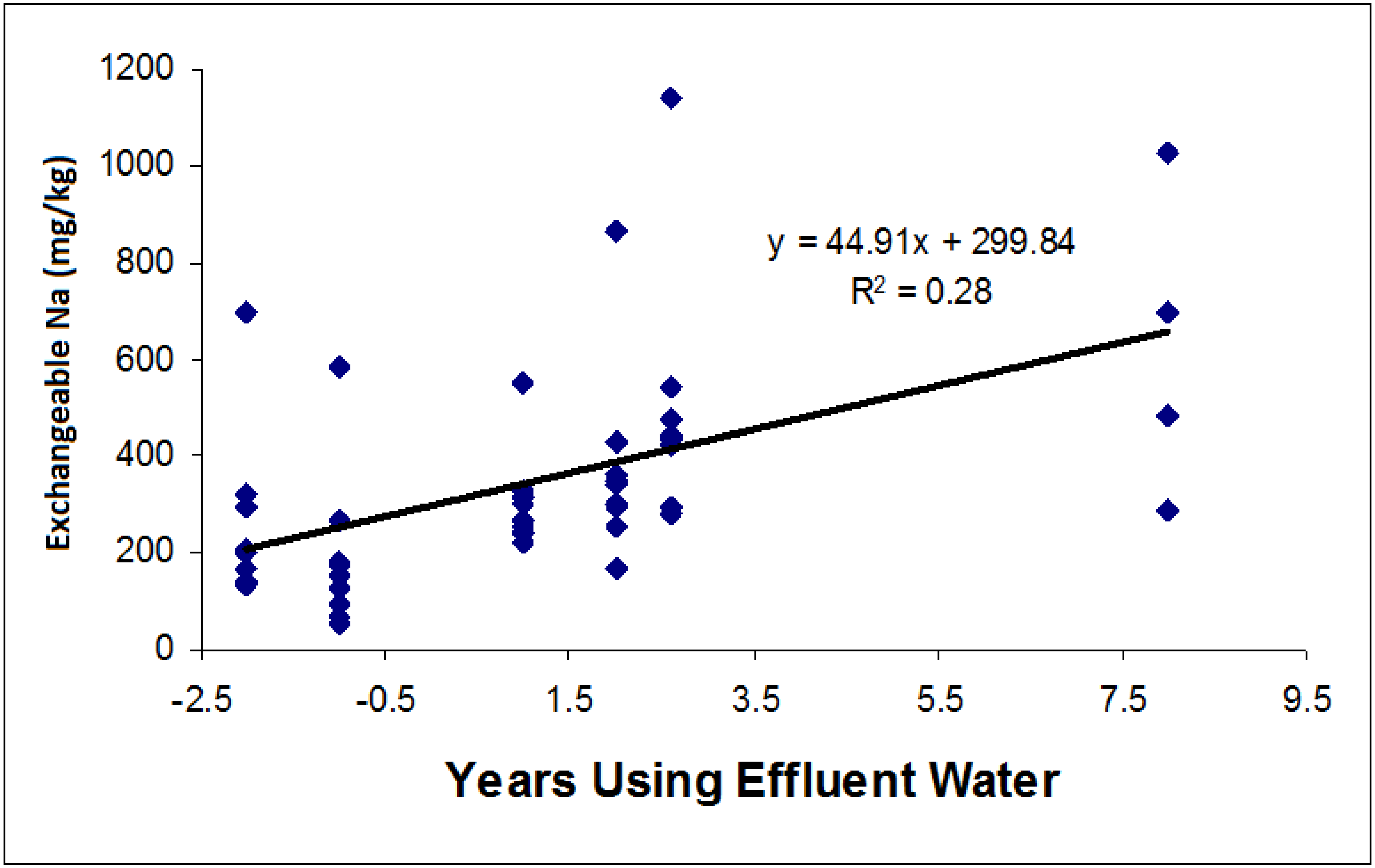

Figure 2.10

Exchangeable Na data from Heritage fairways under eight years of effluent irrigation.

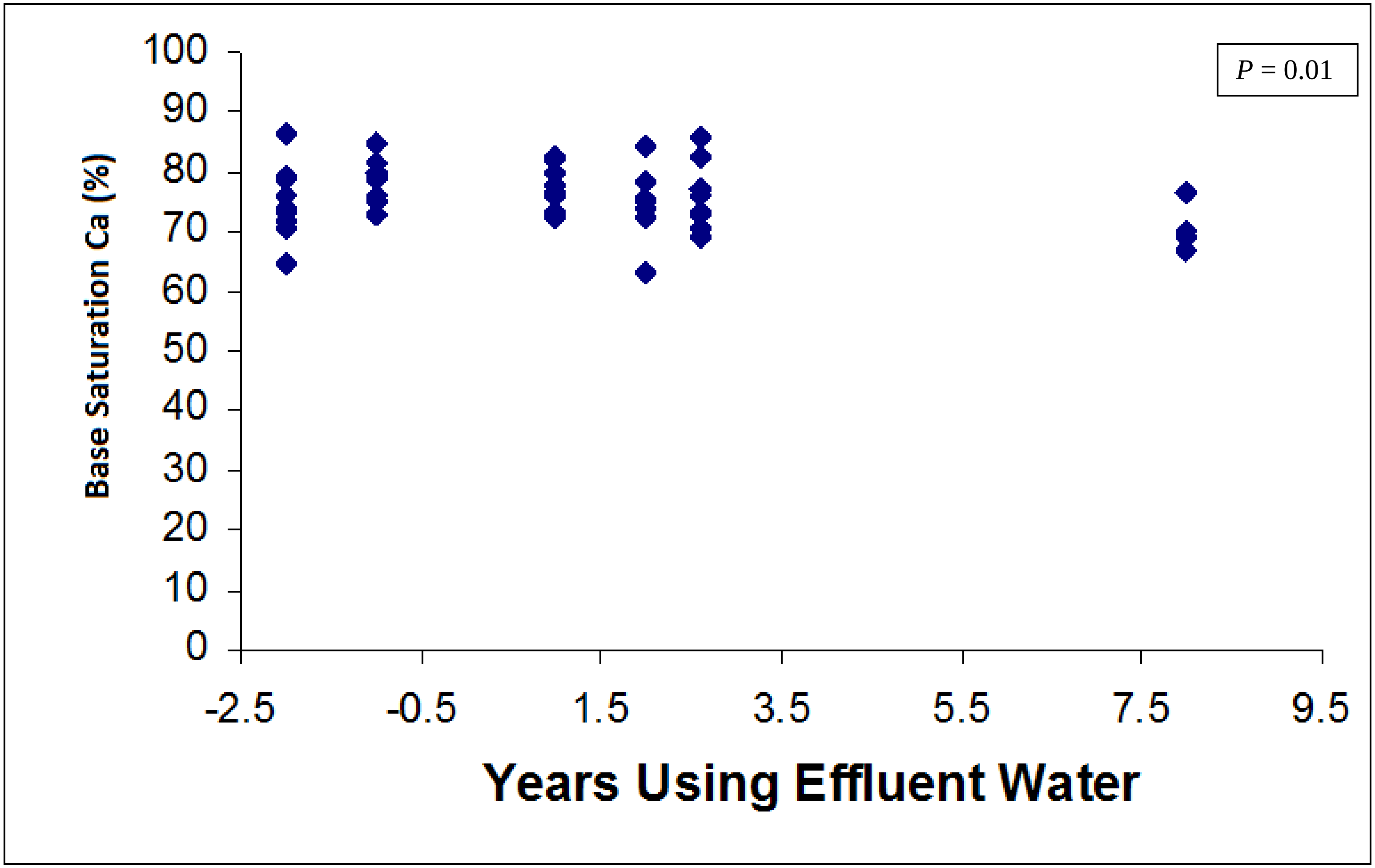

Figure 2.11 Base saturation Ca percentage data from Heritage fairways under eight years of effluent irrigation.

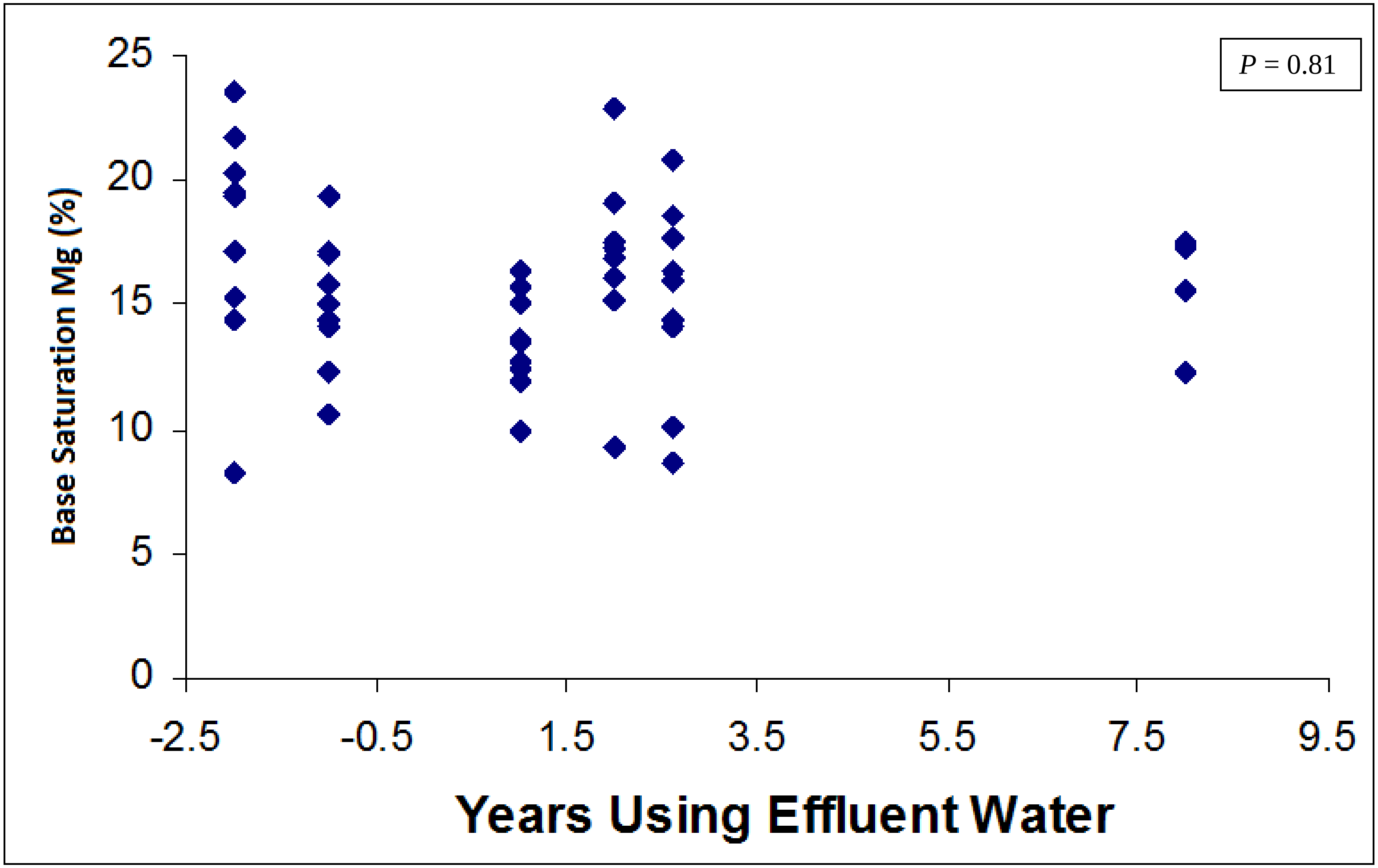

Figure 2.12 Base saturation Mg percentage data from Heritage fairways under eight years of effluent irrigation.

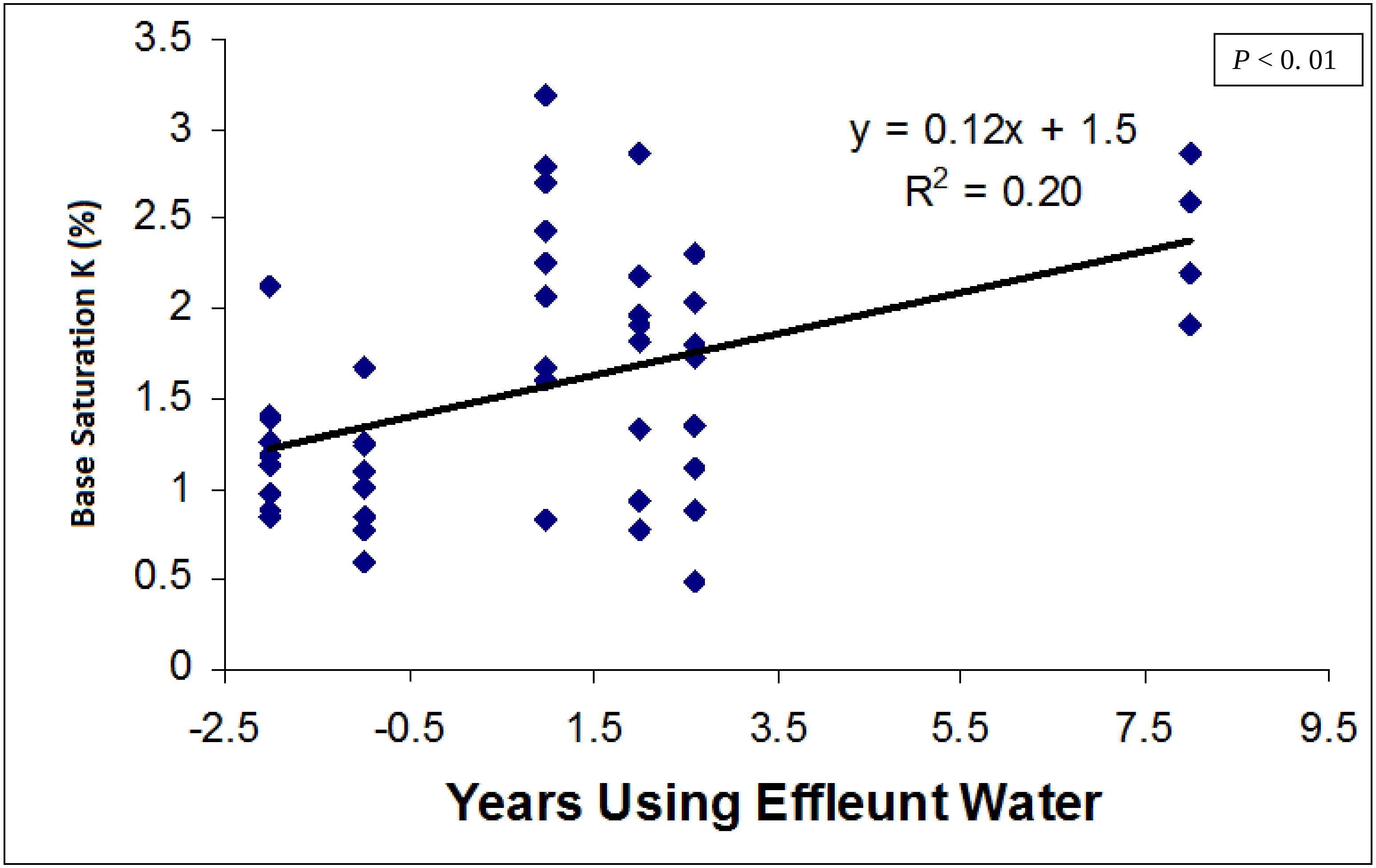

Figure 2.13 Base saturation K percentage data from Heritage fairways under eight years of effluent irrigation.

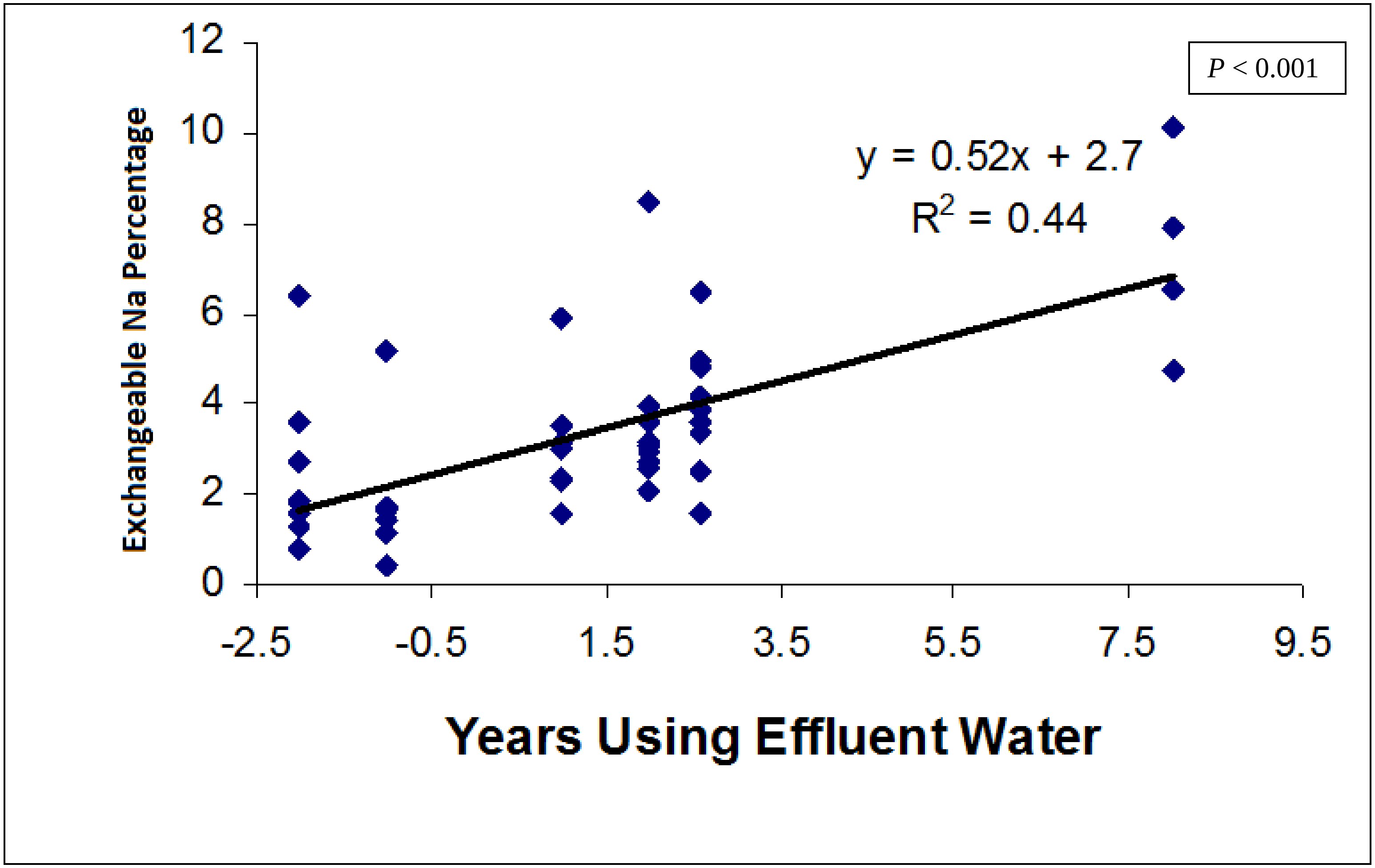

Figure 2.14 Base saturation Na percentage data from Heritage fairways under eight years of effluent irrigation.

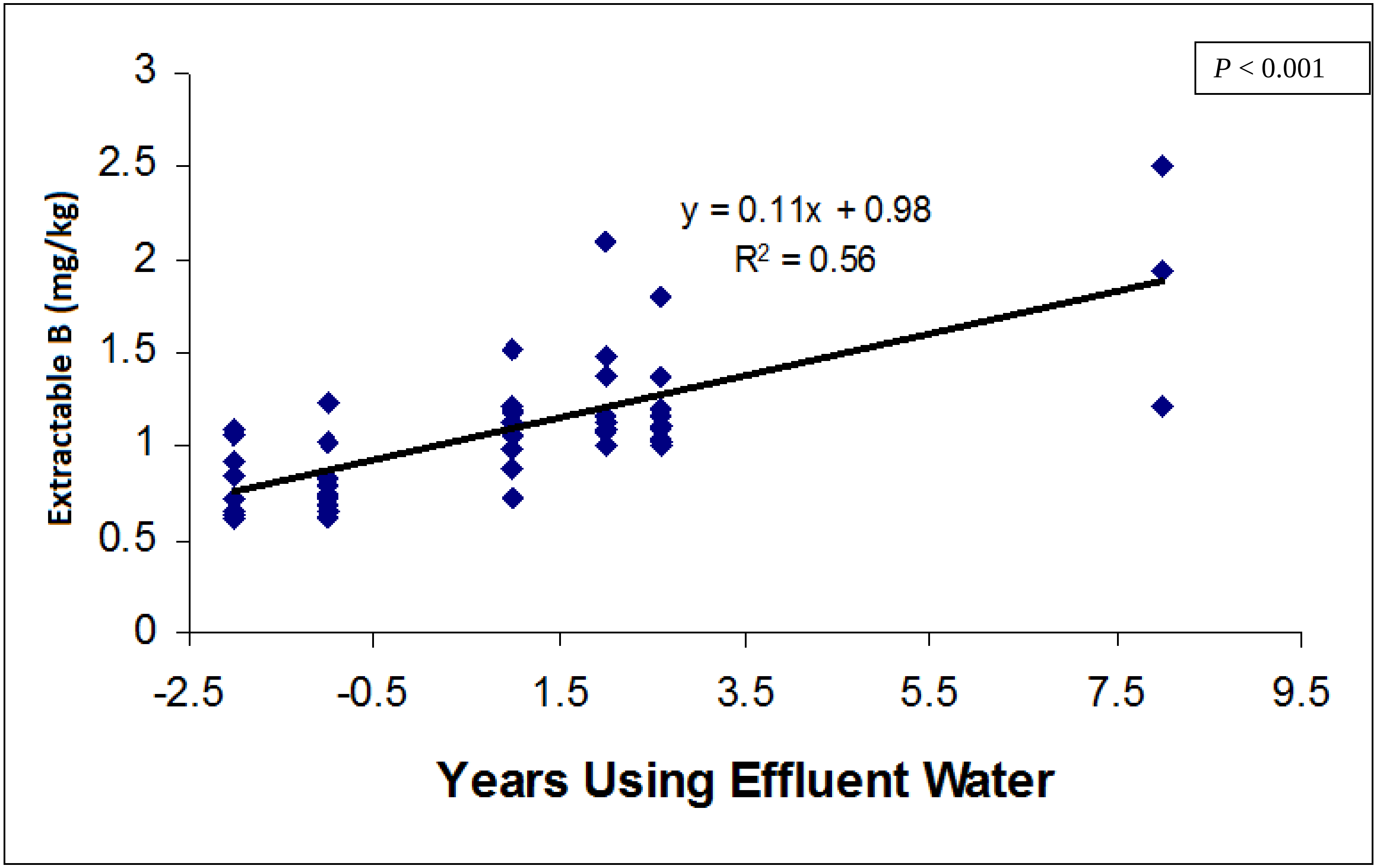

Figure 2.15 Extractable boron data from Heritage fairways under eight years of effluent irrigation.

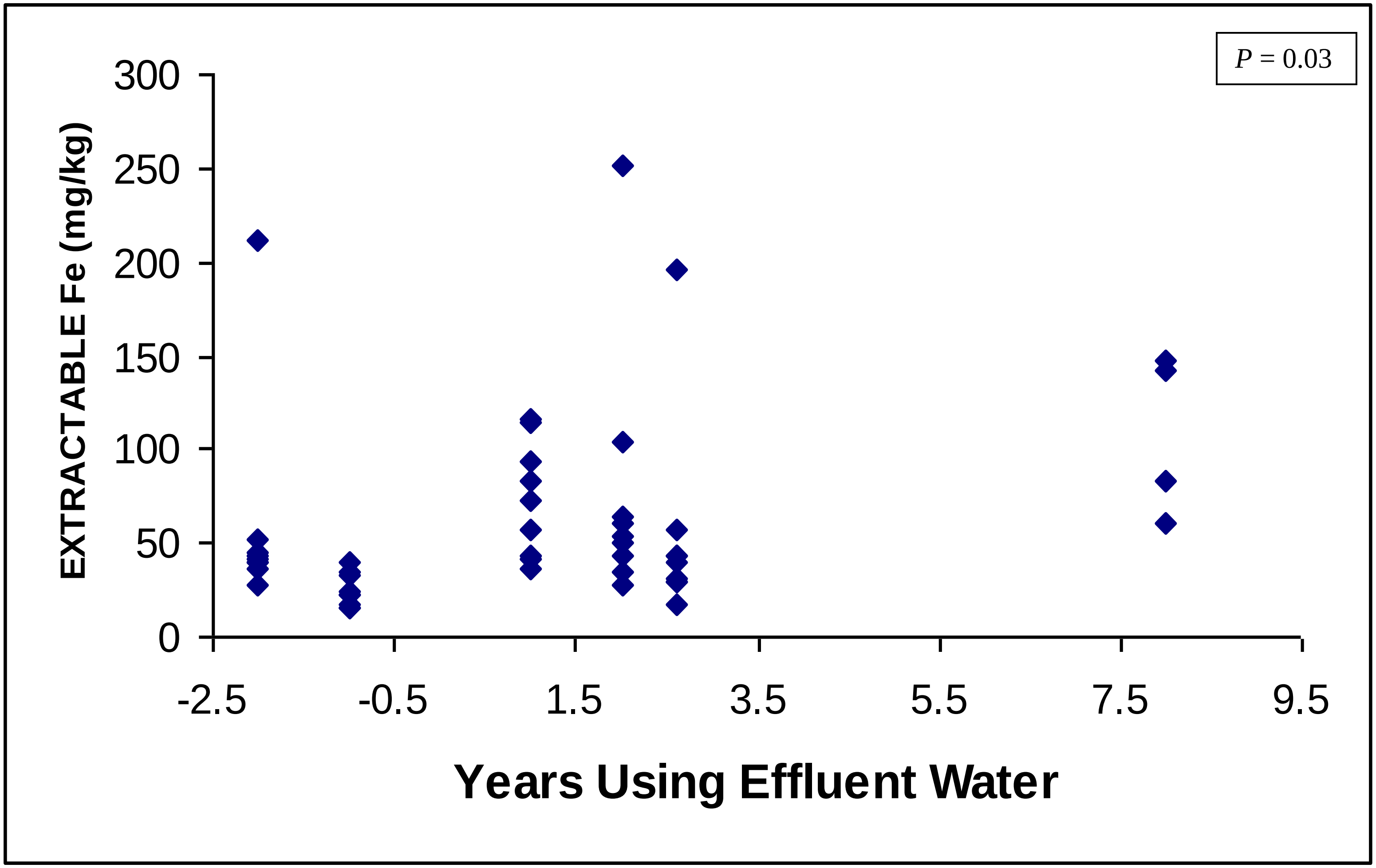

Figure 2.16 Extractable Fe data from Heritage fairways under eight years of effluent irrigation.

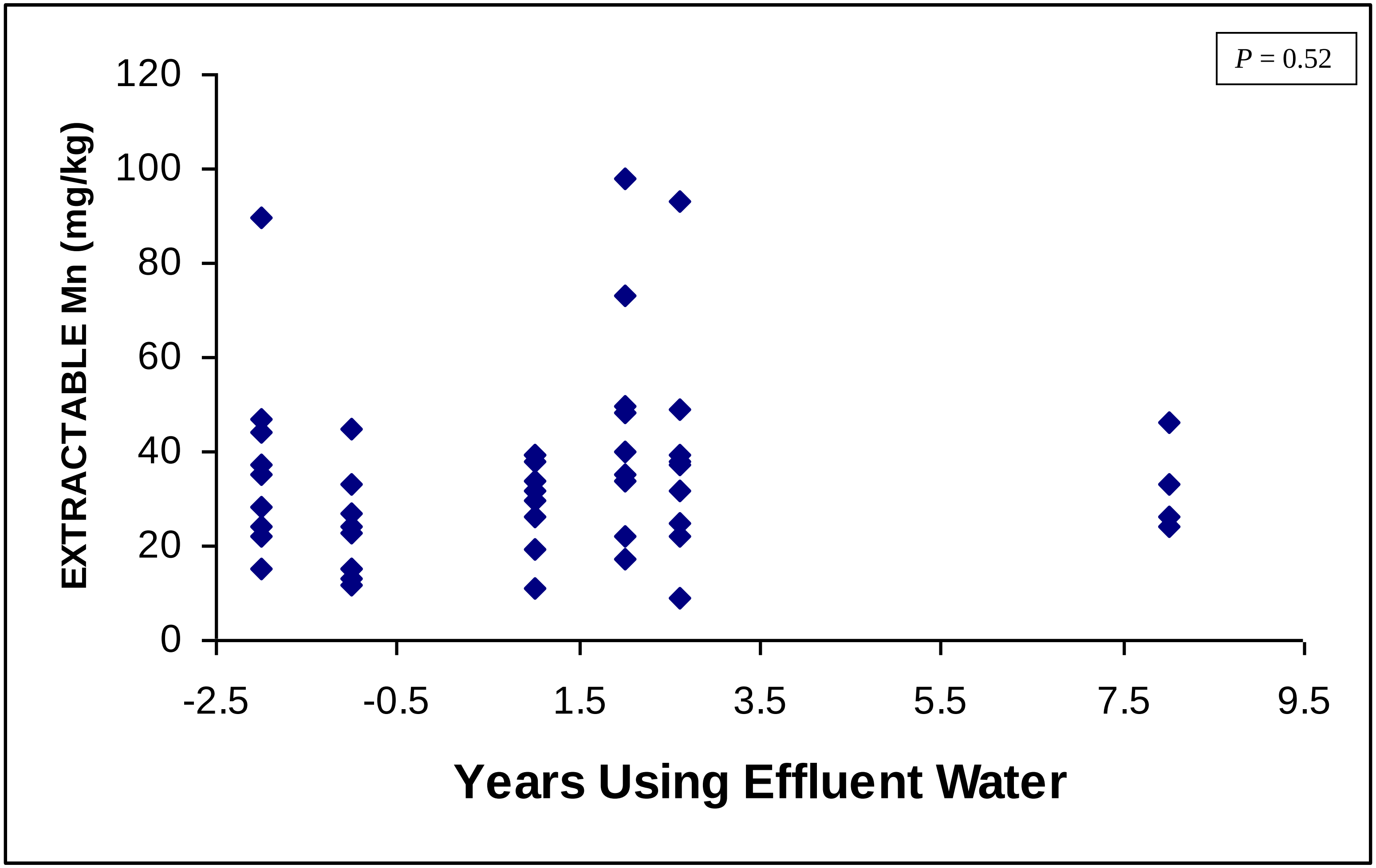

Figure 2.17 Extractable Mn data from Heritage fairways under eight years of effluent irrigation.

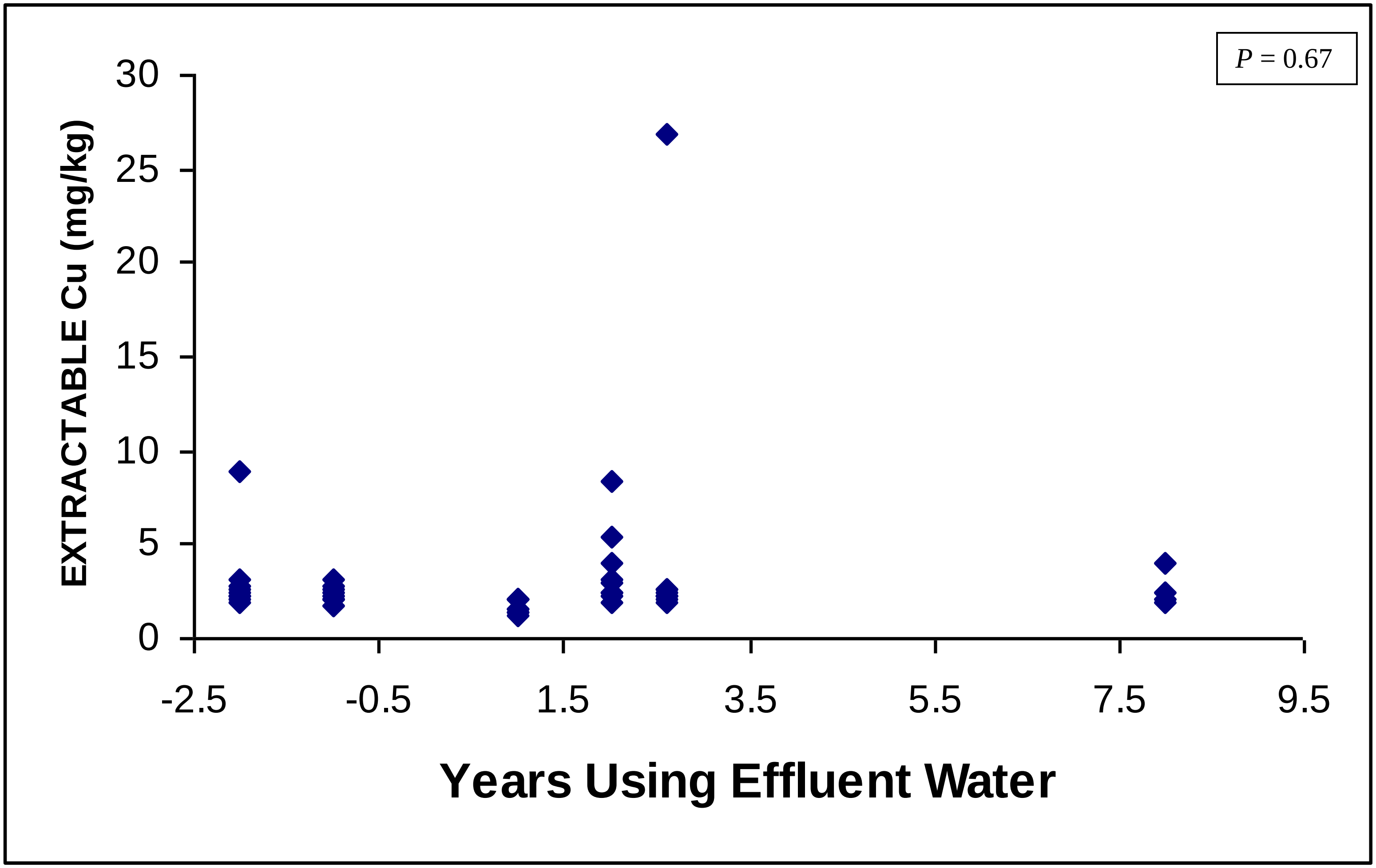

Figure 2.18 Extractable Cu data from Heritage fairways under eight years of effluent irrigation.

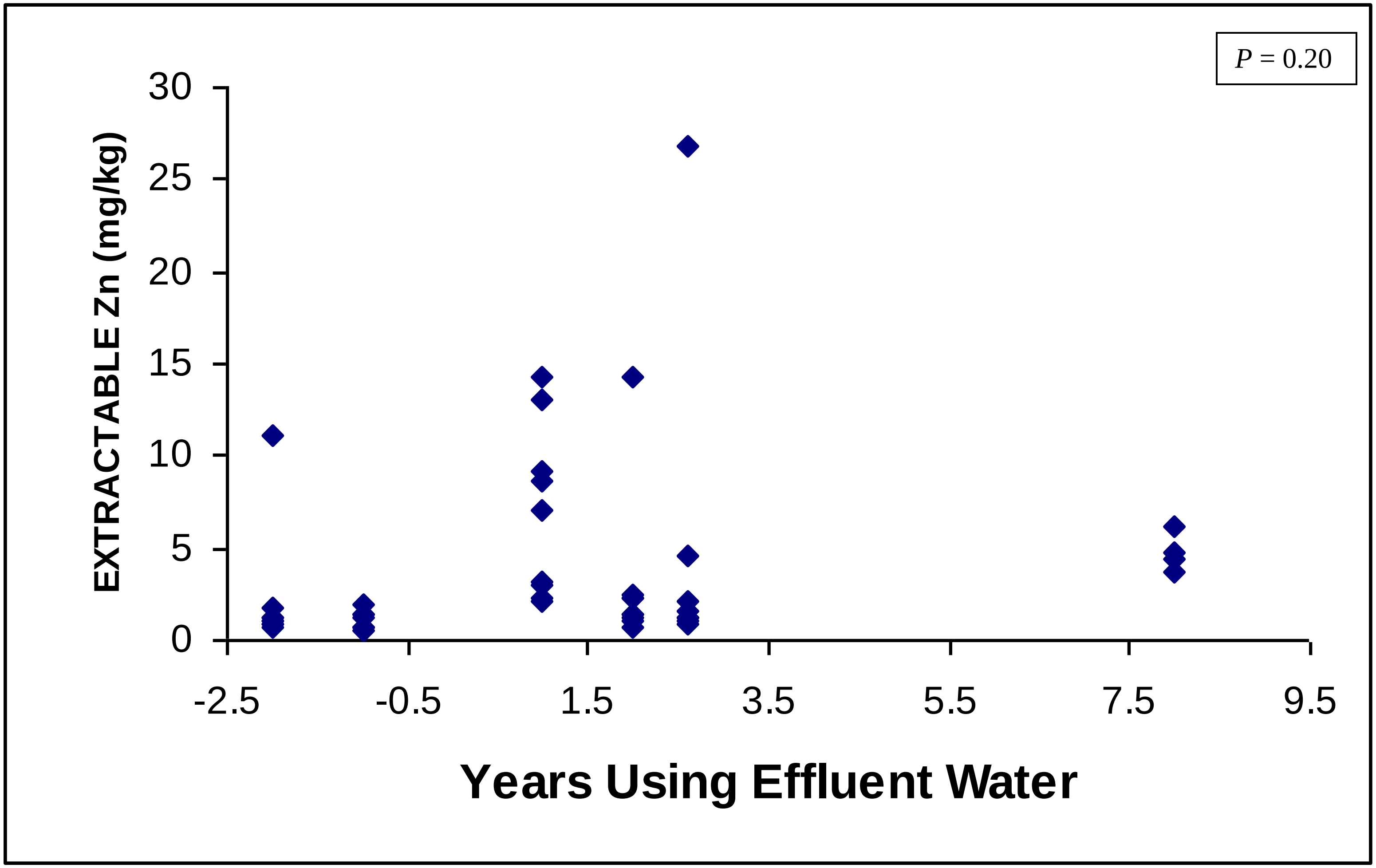

Figure 2.19 Extractable Zn data from Heritage fairways under eight years of effluent irrigation.

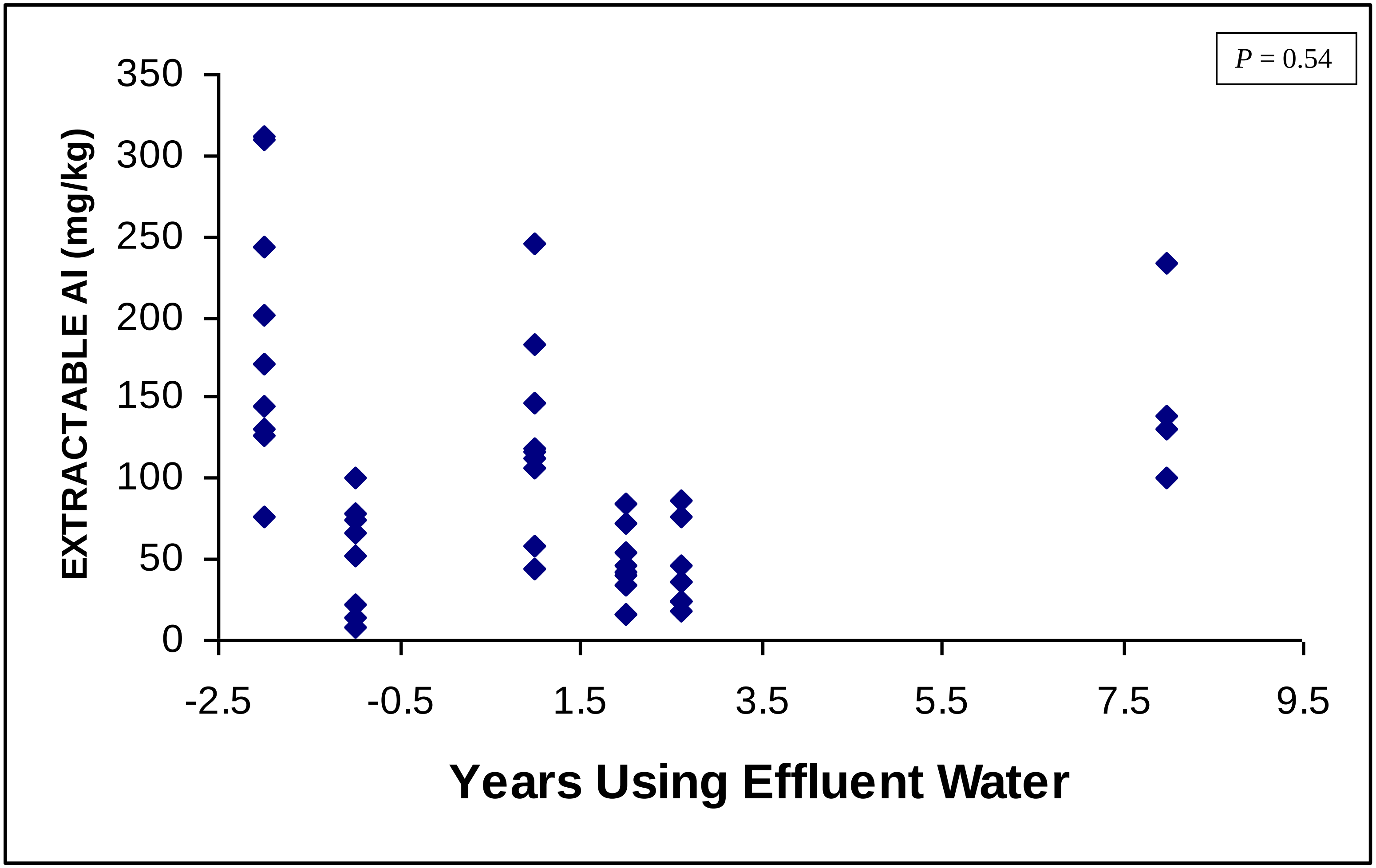

Figure 2.20 Extractable Al data from Heritage fairways under eight years of effluent irrigation.