Alaska North Slope Tundra Travel Model and Validation Study

Final Report

For project period 12/16/05 through 03/15/06

Authored by:

Harry R. Bader, Northern Region Land Manager- Alaska DNR

Jacynthe Guimond, Contract Consultant- Alaska DNR

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3700 Airport Way

Fairbanks, AK 99709-4699

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Jonathan Fiely, University of Alaska; Sherri Wall, University of Alaska;
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DISCLAIMER

ABSTRACT

The Alaska Department of Natural Resources (DNR), Division of Mining, Land, and Water manages cross-country travel, typically associated with hydrocarbon exploration and development, on Alaska's arctic North Slope. This project is intended to provide natural resource managers with objective, quantitative data to assist decision making regarding opening of the tundra to cross-country travel. DNR designed standardized, controlled field trials, with baseline data, to investigate the relationships present between winter exploration vehicle treatments and the independent variables of ground hardness, snow depth, and snow slab thickness, as they relate to the dependent variables of active layer depth, soil moisture, and photosynthetically active radiation (a proxy for plant disturbance). Changes in the dependent variables were used as indicators of tundra disturbance. Two main tundra community types were studied: Coastal Plain (wet graminoid/moist sedge shrub) and Foothills (tussock). DNR constructed four models to address physical soil properties: two models for each main community type, one predicting change in depth of active layer and a second predicting change in soil moisture. DNR also investigated the limited potential management utility in using soil temperature, the amount of photosynthetically active radition (PAR) absorbed by plants, and changes in microtopograhy as tools for the identification of disturbance in the field. DNR operated under the assumption that changes in the abiotic factors of active layer depth and soil moisture drive alteration in tundra vegetation structure and composition.

Statistically significant differences in depth of active layer, soil moisture at a 15 cm depth, soil temperature at a 15 cm depth, and the absorption of photosynthetically active radiation were found among treatment cells and among treatment types. The models were unable to thoroughly investigate the interacting role between snow depth and disturbance due to a lack of variability in snow depth cover throughout the period of field experimentation. The amount of change in disturbance indicators was greater in the tundra communities of the Foothills than in those of the Coastal Plain. However the overall level of change in both community types was less than expected. In Coastal Plain communities, ground hardness and snow slab thickness were found to play an important role in change in active layer depth and soil moisture as a result of treatment. In the Foothills communities, snow cover had the most influence on active layer depth and soil moisture as a result of treatment. Once certain minimum thresholds for ground hardness, snow slab thickness, and snow depth were attained, it appeared that little or no additive effect was realized regarding increased resistance to disturbance in the tundra communities studied.

DNR used the results of this modeling project to set a standard for maximum permissible disturbance of cross-country tundra travel, with the threshold set below the widely accepted standard of Low Disturbance levels (as determined by the U.S. Fish and Wildlife Service). DNR followed the modeling project with a validation study, which seemed to support the field trial conclusions and indicated that the standard set for maximum permissible disturbance exhibits a conservative bias in favor of environmental protection. Finally DNR established a quick and efficient tool for visual estimations of disturbance to determine when investment in field measurements is warranted. This Visual Assessment System (VAS) seemed to support the plot disturbance measurements taking during the modeling and validation phases of this project.

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INTRODUCTION

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EXECUTIVE SUMMARY

Tundra Travel Modeling Project

Note: this summary is included in the Tundra Travel Modeling Project component.

This project is intended to provide natural resource managers with objective, quantitative data to assist decision making regarding cross-country tundra travel, typically associated with hydrocarbon exploration and development on the North Slope of the Alaskan arctic. The analyses contained herein make no recommendations concerning the environmental conditions that should be present before such travel is deemed appropriate. That determination is an issue of policy balancing left to the discretion of land managers. The analyses contained herein employed data, generated by the first-ever standardized, controlled field trials with baseline data, to empirically investigate the effects of winter tundra travel in Alaska.

The project found interacting relationships among ground hardness, snow depth, and snow slab thickness with various types of exploration vehicles, which affected the subsequent active layer depth, soil moisture, and photosynthetically active radiation (a proxy for plant disturbance) in various tundra communities. These results are not inconsistent with anecdotal field observations and the few available published articles in the scientific literature. Statistically significant differences in depth of active layer, soil moisture at a 15 cm (5.91 in) depth, soil temperature at a 15 cm (5.91 in) depth, and the absorption of photosynthetically active radiation were found among treatment cells and among treatment types. In addition to descriptive analyses, four models were constructed to address physical soil properties. For the purposes of this study, DNR assumes that changes in the abiotic factors of active layer depth and soil moisture drive alteration in tundra vegetation structure and composition.

Validation Study and Management Recommendations

Note: this summary is included in the Validation Study component below.

In October 2004, the Alaska Department of Natural Resources published a model that used experimental plots to predict changes in important environmental variables caused by winter oil and gas exploration on tundra surface resources. The objectives of this report are to:

1. Validate the study results in real-world conditions;
2. Continue monitoring the experimental plots to determine if degradation or recovery trends change over time;
3. Design a Visual Assessment System to assist staff in making preliminary determinations of disturbance, during summer field inspections of exploration activity; and
4. Make recommendations regarding management standards.

First, observations from this final validation phase of the project indicate that the standard, derived from the model prediction, resulted in preventing significant environmental change as a consequence of overland vehicle travel, pursuant to hydrocarbon exploration under actual working conditions. Indeed based upon the 2005 validation results, it appears the standard may exhibit a conservative bias in favor of environmental protection. This conservative bias in the results is consistent with the “precautionary principle”, which is an appropriate strategy for decision making in the context of arctic management.

Second, no delayed effects, nor trends toward increasing disturbance intensity, were observed the second year after treatment on the experimental plots. Indeed the trend seems to be toward a return to the natural range of variation among the key indicator variables used in the study. This would suggest rather robust resiliency at the relatively low levels of disturbance recorded as a result of the experiments.

Third, a quick and efficient tool for visual estimations was successfully developed for use by DNR staff. This system employs 250-meter (820.21 ft) segments of trail, to ascertain disturbance not readily detected by the more quantitative and objective measurement approaches.

Finally the report recommends that prior to approval of overland tundra travel by vehicles, the soil temperature within the first 30 cm (11.81 in) of depth be no warmer than –5 degrees Celsius (23F), a minimum of 15 cm (5.91 in) of snow cover be present in wet sedge tundra environments, and a minimum of 23 cm (9.06 in) of snow cover be present in tussock tundra environments.

Under these conditions, tundra disturbance should be minimal. For those disturbance effects that do transpire, the resiliency of the tundra ecosystem, as indicated by the plot monitoring (as well as reported in the scientific literature), is likely to be such that recovery towards pre-disturbance conditions is expected to be relatively rapid.

EXPERIMENTAL

Please refer to the Study Methods and Techniques, pages 30-48, of the Tundra Travel Modeling component of this report for a discussion of experimental methods and material and equipment used. Also refer to Measurement Methodology, pages 6-7, and Visual Assessment System, pages 13-16, of the Validation Study and Management Recommendations.

RESULTS AND DISCUSSION

Please refer to Results and Discussion, pages 47-58, of the Tundra Travel Modeling component of this report. Also refer to Winter Measurements (p. 8), Validation Study Analysis and Results/Summer Measurements (p. 8), Post Treatment Monitoring Program Results (pp. 9-12), and Visual Assessment System (pp. 13-16) of the Validation Study and Management Recommendations.

CONCLUSION

Please refer to Conclusion in the Tundra Travel Modeling Report (pp. 61-62) and Conclusions and Recommendations (p. 17) of the Validation Study and Management Recommendations.

REFERENCES

Please see Reference Citations, beginning on page 63 of the Tundra Travel Modeling Report.

Tundra Travel Modeling Project

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The project found interacting relationships among ground hardness, snow depth, and snow slab thickness with various types of exploration vehicles, which affected the subsequent active layer depth, soil moisture, and vegetation productivity in various tundra communities. These results are not inconsistent with anecdotal field observations and the few available published articles in the scientific literature. Statistically significant differences in depth of active layer, soil moisture at a 15 cm (5.91 in) depth, soil temperature at a 15 cm (5.91 in) depth, and the absorption of photosynthetically active radiation were found among treatment cells and among treatment types. In addition to descriptive analyses, four models were constructed to address physical soil properties. For the purposes of this study, DNR assumes that changes in the abiotic factors of active layer depth and soil moisture drive alteration in tundra vegetation structure and composition.

Two models, one predicting change in depth of active layer and a second predicting change in soil moisture, were created for the wet graminoid/moist sedge shrub communities of the Coastal Plain. Two more models for change in depth of active layer and soil moisture were constructed for the tussock tundra communities that dominate the more rolling terrain typically found in the Foothills. In addition to the four models, this report discusses the limited potential management utility in using soil temperature, the amount of photosynthetically active radiation absorbed by plants, and changes in microtopography as tools for the identification of disturbance in the field.

Because of the lack of variability in snow depth cover throughout the period of field experimentation, these models were unable to thoroughly investigate the interacting role between snow depth and disturbance. Therefore these models can only be employed after a minimum threshold snow depth of 15 cm (5.91 in) has been attained on wet graminoid/moist sedge shrub tundra and 23 cm (9.06 in) on tussock tundra.

The amount of change in disturbance indicators associated with the treatments was found to be greater in tussock tundra than in wet graminoid/moist sedge shrub tundra. However the overall level of change in both community types was generally less than expected. The project found that in the wet sedge tundra characteristic of the Coastal Plain, ground hardness and snow slab thickness were the most important environmental ameliorators of disturbance regarding active layer depth and soil moisture. In tussock tundra, only snow cover appeared to play an important role in ameliorating the level of change in active layer depth and soil moisture as a result of treatment. Once certain minimum thresholds for ground hardness, snow slab thickness, and snow depth are attained, it appears that little or no additive effect is realized regarding increased resistance to disturbance in the tundra communities studied.

The project recommends that further monitoring of the plots continue, to determine if the changes detected within the study sites increase or decrease over time. If unanticipated change occurs, the model should be altered to take new information into account. In addition the project recommends that a rigorous program of in-field monitoring of tundra travel activity be instituted to verify if disturbance changes materialize, consistent with model predictions. Finally the project recommends DNR institute an adaptive management approach, anticipating an iterative process as new data is collected and the model is improved.

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I. INTRODUCTION AND PURPOSE

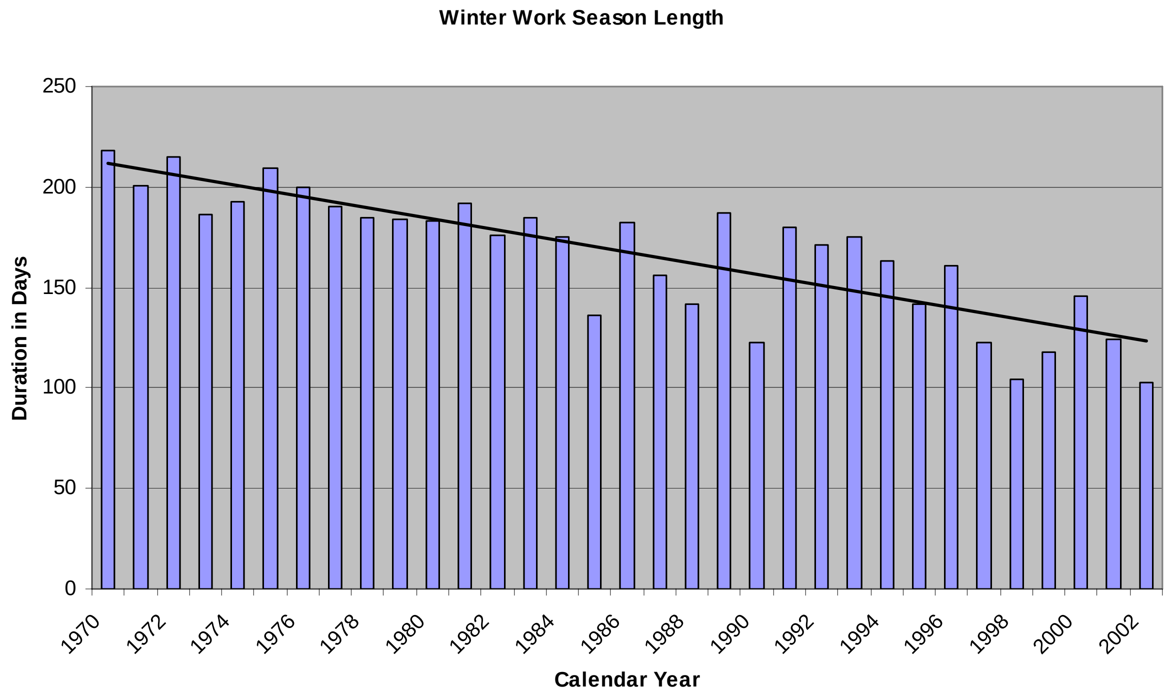
A. Introduction

On Alaska's North Slope, the oil and gas industry requires off-road travel across the tundra during winter for seismic exploration and to build ice roads for exploratory drilling, for construction activity, and for routine maintenance of remote infrastructure. The Alaska Department of Natural Resources (DNR) authorizes travel across the tundra on state land, which includes the Prudhoe Bay Area and most of the surrounding areas being developed and explored.

DNR authorizes winter travel across the tundra after it determines that the tundra is sufficiently frozen and protected by ample snow cover that travel will not have major environmental effects. The length of the winter work season imposes a profound limitation on exploration activity and has declined markedly over the past 30 years along a pronounced downward trend. The number of days between opening and closing of the tundra for exploration activity has decreased from over two hundred days in 1970 to only about one hundred days in 2003, as a result of progressively later openings (see Figure 1). The degree to which this trend can be attributed to climate change or to changing management strategies cannot easily be discerned.

The reduction in season length is not symmetrically distributed between a later beginning of the season and an earlier end of the season. Rather most of the shortening of the winter work season occurs as a result of a later onset of winter. According to DNR data, the opening of tundra travel (to start the winter work window) is now 85 days later than in the 1970's, while the closure of tundra travel (ending the winter work window) is now 15 days earlier than in the 1970's (Appendix A). This pattern is consistent with available scientific literature observing a significantly later freeze-up of the active layer in autumn (Romanovsky, Sergueev, and Osterkamp 2003) and a slightly earlier disappearance of snow from the tundra in spring (Foster 1989). Therefore this project concentrates on a model to predict the disturbance consequences of tundra opening, beginning the winter work window, in order to gain maximum benefits from the effort.

Figure 1. Length of winter work season from 1970-2002.



Land managers need a thorough understanding of the ecological disturbance effects generated by winter tundra travel to ensure the effectiveness of long term resource management decisions. However both the National Research Council (NRC) and the Arctic Research Commission (ARC) recently reported a paucity of studies investigating the impact of winter cross-country travel on tundra ecosystems (NRC 2003; ARC 2003). Noting that data do not now exist describing the effects of overland exploration activity on tundra under varying snow and soil conditions, the NRC stated that, "Studies are needed to determine the amount of snow and the frost penetration required to adequately protect the tundra from the effects of seismic exploration," (NRC 2003). The NRC then commented that, "The current regulations governing minimum snow depth and frost penetration to allow [exploration] activities on the tundra are not based on research." Seconding this opinion, the ARC emphatically called for immediate quantitative field investigations to address such issues (ARC 2003).

This DNR modeling project represents a scientific research attempt to integrate (1) real time environmental variables such as snow depth and ground hardness (at time of disturbance) with, (2) controlled and standardized experimental field treatments of known type and intensity with, (3) baseline ecological characteristics to, (4) identify disturbance associated with winter travel on arctic tundra under varying conditions. Because DNR does not currently take into account the interactive effect of varying snow characteristics and ground frost penetration depths (Hazen 1997), the project develops models designed to describe the integration of these variables and thereby enhance DNR decision making.

Understanding the properties of frozen ground and snow is essential to prevent environmental disturbance and costly damage to the oil and gas infrastructure. The need for such knowledge is particularly great today as increased exploration and development is expected on the North Slope as the search for gas reserves accelerates (NRC 2003). Improved information regarding anthropogenic disturbance of tundra ecosystems, directly and indirectly associated with resource development, is a critical emerging need (Forbes 1992), especially in light of the debate concerning the effects of winter vehicular travel and the sensitivity of tundra under the current information vacuum (Kevan et. al. 1995).

The purpose of the study is to provide DNR with objective and quantitative information to understand the extent of environmental change associated with different management choices regarding the timing of tundra opening. With this understanding, DNR can design approaches that may minimize disturbance while facilitating exploration. This project is a response to the findings of the National Research Council and the U.S. Arctic Research Commission.

B. Description of Tundra Travel and Oil/Gas Exploration

Oil and gas production industries require off-road travel across the tundra in winter to accomplish three distinct tasks: (1) seismic exploration activity, (2) ice road construction for exploratory drilling, and (3) routine maintenance of infrastructure such as pipelines. Without the opportunity to travel across the tundra, the exploration for oil and gas resources in the Alaskan arctic would come to a halt.

The most extensive use of off road tundra travel over the past ten years has occurred during 3D seismic exploration. The 2003 National Research Council report describes seismic activity as a survey using sound waves that travel underground and bounce off various geological formations, creating an image from the echo that can then be mapped and evaluated for hydrocarbon potential. Seismic camps involve a variety of activities and vehicles that travel across the winter snow as a slow moving city on sleds, housing up to 100 workers.

A set of microphones (geophones) connected by miles of cable, are laid out on the surface of the ground in a rectilinear grid of parallel lines, spaced about 0.40 km (0.25 mi) apart. These lines receive the echo. Rubber tracked vehicles called Tucker Snowcats are most often used for this phase of the operation. After an area has been set out, tracked vehicles called vibrators travel in parallel lines perpendicular to the receiver lines, forming the grid. Vibrators are very heavy and often move in tandem to generate coordinated sound waves. The vibrator lines are termed, “source lines”. Once an area has been surveyed, the Tuckers are sent back down the lines to retrieve the receivers. The process repeats in an adjacent area, until the entire survey is complete. Each line can measure over 9.66 km (6 mi) long, and a single winter survey project can cover over 777 sq. km (300 sq. mi).

Supporting the survey is a whole community, with workshops, kitchen facilities, dormitories, laboratories, power generation plants, and sewage facilities built upon huge sleds and pulled by steel tracked D-7 dozers and rubber tracked Challengers. During the period 1990 to 2001, an estimated 25,750 km (16,000 mi) of seismic lines were traveled across the tundra (NRC 2003).

After seismic surveys have been completed, the next phase of exploration involves drilling test wells. Because of the size and weight of drill rigs and the need for continual traffic to maintain logistical support for the operations, ice roads are constructed to access and maintain the drilling operations. Ice road use, and the potential environmental disturbance that may accrue, is not the subject of this study. However ice road construction does require a level of off-road tundra travel.

Ice road construction first requires that the snow be packed down to form a firm bed, to assist in the penetration of cold deep into the ground. Water is then broadcast over the packed snow trail to freeze in a solid layer. The process is repeated several times, and the ice is smoothed between broadcasts to build up a road to the required thickness.

Once the road is built, all vehicular travel takes place on the ice roadway. During the winter of 2001-2002, over 402 km (250 mi) of ice road were built.

Maintenance crews also take advantage of winter conditions to travel across the tundra for repair of infrastructure in remote locations. Tuckers and Challengers are the general method of transport for off-road, cross-country travel for both crews and equipment.

C. History of DNR Tundra Travel Management

DNR regulation of tundra travel has evolved over the past 30 years. While the Department has increased its sophistication over that time, it has relied, for the most part, upon subjective standards and an anecdotal sampling system to predict tundra resistance to disturbance. (A comprehensive history describing DNR tundra travel management on the North Slope was prepared for the agency in 2004 and is included as Appendix D of this report.) At first, natural resource managers used their general familiarity with the North Slope to estimate when frost depth and snow cover conditions were adequate to prevent tundra damage. Under this system, the tundra was generally opened for cross-country travel and exploration if it appeared that at least 15.24 cm (6 in) of ground cover snow was found and the ground was determined to be hard to a depth of at least 30.48 cm (12 in). Ground frost was estimated by driving a metal rod into the ground with a sledgehammer and by boring holes into lake ice. By 1995 measurement of ground hardness was accomplished with a slide hammer that was physically pounded into the ground by personnel. This ad hoc approach, adopted in the 1970's without the benefit of prior scientific investigation, appears to have provided a high degree of tundra protection during oil exploration, although occasional severe tundra disturbance has been documented (Felix and Raynolds 1989a,b).

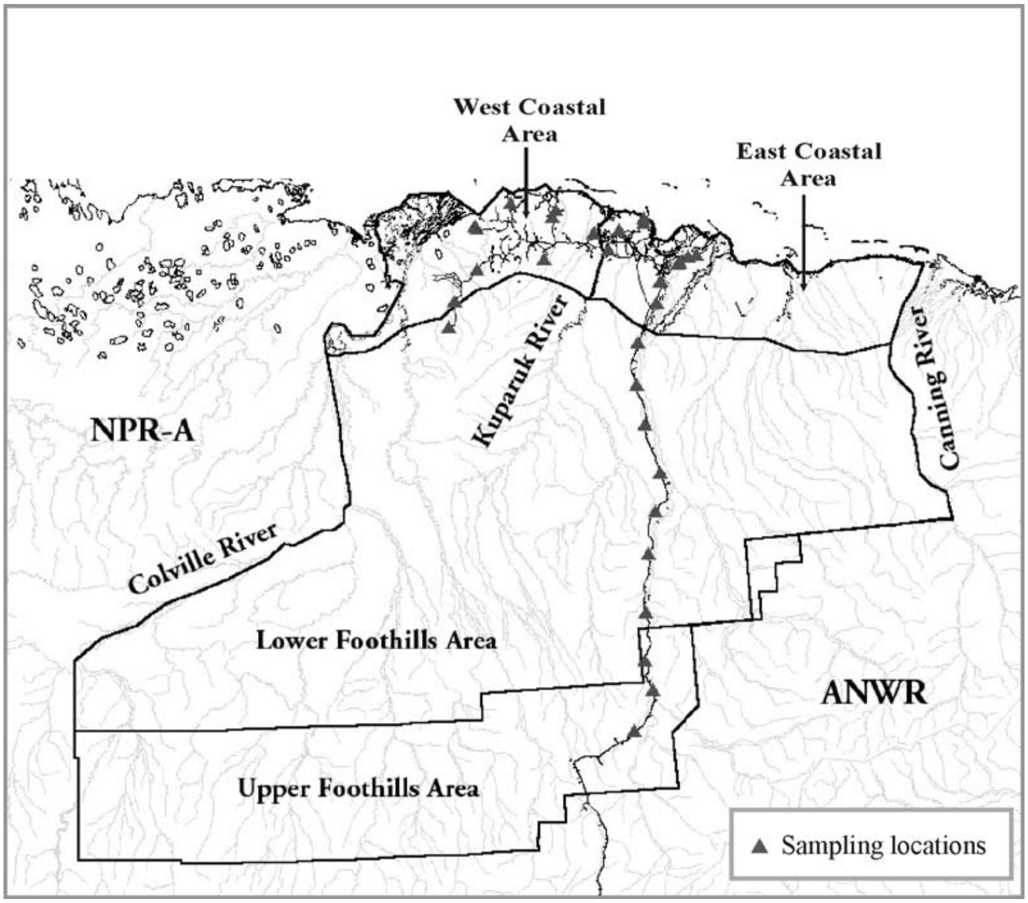
In response to the need for a more objective and quantitative approach toward tundra travel management, DNR initiated a number of reforms starting in the year 2002. The first reforms standardized measurement techniques. DNR created 30 permanent measurement stations in 2002. These stations serve as the locations for measuring snow depth and ground hardness on a periodic basis starting in November of each year. Ten of these 30 measurement locations are distributed along a 161 km (100 mi) north-south transect along the Dalton Highway from Deadhorse to Slope Mountain, at approximately 16 km (10 mi) increments. The remaining measurement locations are distributed within the oil field complex, spanning approximately 64 km (40 mi) from east to west (Figure 2).

A second reform divided state lands on the arctic North Slope into four geographically distinct management subunits (named Tundra Opening Areas, or TOA's). The TOA's replaced the earlier practice that considered the entire North Slope as a single ecological region. Relying on topo-climatic differences, as well considering infrastructure and administrative concerns, the North Slope is now separated into an Upper Foothills TOA, Lower Foothills TOA, East Coastal TOA, and West Coastal TOA (Figure 2). The division between the Coastal and Lower Foothills TOA's follows the Alaska Coastal Zone Management administrative boundary, which approximates the maritime temperature influenced ecological boundary that extends about 32 km (20 mi) inland from the Arctic Ocean. The demarcation between Upper Foothills TOA and Lower Foothills TOA approximates the 152 m (500 ft) contour, which follows another climo-topo-edaphic boundary (Spetzman 1959). DNR manages each TOA as an independent unit.

Another reform redesigned the slide hammer probe for measuring ground hardness. Previous slide hammers required DNR staff to exert energy to pound a 1.43 cm (9/16 in) diameter probe into the ground. In addition to the variation in measurement attributable to personnel strength and fatigue, each hammer employed was slightly different in weight and drop distance. In 2003 the slide hammer was redesigned. It is now a true "drop" hammer with standard drop weight and drop distance, employing no assistance from the operator. Each new drop hammer uses a 0.95 cm (3/8 in) diameter probe for easier penetration into the ground. Variability in measurement due to the individual operator and equipment has been eliminated. The new drop hammer was field tested in January of 2003 and calibrated to assist with comparison to prior data sets.

Despite these improvements, DNR still lacks scientific information linking snow and ground hardness characteristics with tundra resistance to disturbance by vehicles traveling off-road. This modeling project represents an effort to provide information necessary to improving DNR management of the North Slope environment regarding tundra travel.

Figure 2: Tundra Opening Areas and Snow and Ground Sampling Stations



D. Description of Alaska North Slope – General

Alaska's arctic North Slope covers an area of 230, 509 sq. km (89,000 sq. mi), about the size of the state of Minnesota. The North Slope can be divided into three general geographic areas: (1) Brooks Range, (2) Foothills, and (3) Coastal Plain (Gallant et al 1995; Walker and Acevdeo 1987). The southern boundary of the North Slope is formed by the Brooks Range. North of these mountains is an 81-121 km (50-75 mi) wide band of rounded hills and broad valleys, the Foothills. Between the Arctic Ocean and the Foothills lies a nearly level plain, with a width ranging from 161 km (100 mi) in the west to less than 19 km (12 mi) in the east. The North Slope is sparsely populated with about 8,000 residents, approximately 70% of whom are Alaska Native peoples of Inupiat descent (NRC 2003).

1. Climate

The Brooks Range is steeply sloped and heavily dissected with deep gorges. South of the continental divide, separating those waters that flow north to the Arctic Ocean and those that flow into the Bering Sea via the Yukon River system, the mountains exhibit the continental climate of the interior boreal forest. North of the divide, the mountains are dominated by vegetation characteristic of arctic tundra. Mean annual temperature is approximately –6 degrees Celsius (21.2F) with about 375 mm (14.76 in) of precipitation, 60% of which occurs as rain during the growing season (Mull and Adams 1989). During an average year, there are approximately 4,000 cumulative freezing degree-days, punctuated by a 110 day growing season (Mull and Adams 1989). Since little or no hydrocarbon exploration is expected in this region, the modeling project does not address travel in these rugged mountains.

The Foothills lie just north of the Brooks Range and vary in width from over 201 km (125 mi) in the west to just 16 km (10 mi), before tapering out east of the Canning River in the Arctic National Wildlife Refuge. They vary in elevation from 1,000 m (3280.84 ft) in the south, at the base of the Brooks Range, to about 160 m (524.93 ft) in the north, forming a low border with the Coastal Plain. Irregular buttes, bluffs, and east-west trending ridges characterize the southern margin of the Foothills. The northern Foothills are also dominated by east-west trending ridges but are lower, broader, and more rounded. Mean annual temperature in the Foothills is –9 degrees Celsius (15.8F), with a 120 day growing season; an average year accumulates nearly 5,500 freezing degree-days (Mull and Adams 1989). A little over 210 mm (8.27 in) of precipitation falls over the Foothills, evenly divided between winter snow and summer rain.

The Coastal Plain is heavily influenced by the maritime margin and the adjacent ice cap on the Arctic Ocean. This broad, flat, wetland plain has a mean annual temperature of –11 degrees Celsius (12.2F) and a 100 day growing season (Mull and Adams 1989). Maximum annual cumulative freezing degree-days can reach 8,000 (Brewer 1958). Total precipitation is typically less than 200 mm (7.87 in), the majority of which is in the form of snowfall.

2. Ground Characteristics

a. Permafrost

The entirety of both the North Slope Coastal Plain and Foothills are underlain with continuous permafrost (Brown 1997). Permafrost is most commonly defined as that ground which remains continuously frozen for at least two consecutive years (NRC 2003, ARC 2003); though some researchers have defined it as requiring much longer periods in a frozen state (Lunardini 1995). Permafrost is generally regarded as having four main, interacting constituents that affect its mechanical properties: (1) solid mineral or organic grains, (2) ice, (3) liquid water, and (4) gases (Ladanyi 1985).

The Prudhoe Bay area is known to have anomalously deep permafrost compared to the rest of the North Slope, with a maximum depth of about 650 m (2,132.55 ft) (Lachenbruch et. al. 1982). The great depth of Prudhoe Bay area permafrost is attributed in part to the high thermal conductivity of the fine grained, siliceous parent material (Lachenbruch et. al. 1982). Formation of the permafrost in Alaska is believed to have begun about 2.5 million years ago, and has undergone periods of warming and cooling during that time (Osterkamp and Gosink 1991).

Temperatures in the uppermost portion of permafrost, typically the top 20 m (65.62 ft), fluctuate with annual seasonal variation, warming in summer and cooling in winter, but always remaining below freezing (Romanovsky, Sergueev, and Osterkamp 2003; Williams and Smith 1989; Brewer 1958). The point in the permafrost profile at which there is no seasonally affected temperature change is called the level of “zero annual amplitude” (Burn and Smith 1988). Permafrost temperatures are often at their coldest at this point. On the North Slope, the minimum permafrost temperature ranges between –8 and –11 degrees Celsius (17.6 and 12.2F) (Osterkamp 1988; Lachenbruch et. al. 1982; Brewer 1958). The permafrost bottom (maximum depth) is determined by heat flow escaping upward from the earth’s interior and interacting with the long term climate effects that cool the ground from the surface down (Williams and Smith 1989). Over time, permafrost temperatures fluctuate in response to long term climate trends. It appears that the temperature of permafrost in Alaska has been increasing slightly over the past 100 years (Romanovsky, Sergueev and Osterkamp 2003; Osterkamp and Gosink 1991).

While it may appear incongruous, permafrost contains substantial quantities of liquid water locked within the particle and ice matrix (Hinkel et. al. 1996; Smith 1985). Indeed, volumetric liquid water can reach 20% at near 0 degrees Celsius, dropping to about 5% at –12 degrees Celsius (10.4F) (Romanovsky and Osterkamp 2000). Liquid water in frozen permafrost exists in two forms: as films strongly bound to mineral particles and as weakly bound liquid water in soil pore spaces (Ladanyi 1985). The finer grained the soil and the warmer the temperature of the permafrost, the more liquid water will be present in the permafrost (Williams and Smith 1989).

The varying amounts of liquid water within permafrost have profound consequences on the characteristics of frozen ground. Liquid water can retard temperature change in permafrost during seasonal fluctuation in early winter through latent heat (Romanovsky and Osterkamp 2000) and alter the mechanical strength of the permafrost (Williams and Smith 1989). As a result of the presence of liquid water in frozen ground, one may encounter slight mud streaking on equipment penetrating into permafrost, even though the ground is thoroughly frozen.

While permafrost obstructs the downward percolation of surface water into the ground, contributing to the abundant standing water characteristic of tundra environments (Lachenbruch et. al. 1982), the liquid water fraction within the permafrost is capable of movement through the frozen ground (Hinkel et. al. 1996; Smith 1985). The movement of liquid water in frozen ground allows for the formation of lenses of pure ice, expanding the volume of frozen soil significantly (Williams and Smith 1989). Ice segregation and differential frost heave contribute to the unique landforms found in the arctic.

The mechanical strength of frozen ground surpasses the sum of independent strengths for ice and unfrozen soil combined (Williams and Smith 1989). The rather remarkable strength is the product of four factors: (1) pore ice strength, (2) soil inter-particle friction, (3) adhesion ice bond resistance to dilation, and (4) the synergistic strengthening between soil and the ice matrix (Ladanyi 1985). Affecting these four factors are soil grain size and temperature. The finer the soil grain, the stronger the permafrost; and the warmer the temperature of the ground, the more liquid water is present in the frozen soil, and thus the weaker the permafrost (Williams and Smith 1989). Strength of frozen ground such as permafrost increases quickly as the temperature drops from 0 to –10 degrees Celsius (32 to 14F) (Ogata et. al. 1982). After a temperature of –10C (14F) is reached, the rate of increasing strength drops off precipitously (Williams and Smith 1989). Permafrost also increases in strength with increasing ice content up to a certain point, after which higher ice contents can generate brittleness and lead to failure.

Frozen ground displays two very different strengths: resistance to deformation and resistance to shear failure (Williams and Smith 1989). Resistance to deformation and compression (ductile failure) is weakest between –2 and 0 degrees Celsius (28.4 and 32F) (Joshi and Wijeweera 1990). At temperatures below –10C (14F), shear failure may be more common due to the tendencies of frozen ground to become brittle with cold temperatures (Davis 2001; Joshi and Wijeweera 1990).

b. Ice

In addition to abnormally deep permafrost, the segregated ice content in the permafrost found in state lands on the North Slope between the Canning and Colville Rivers is inordinately high (Hazen 1997). Segregated ice is often referred to as excess ice, because the volume of ice present exceeds the volume that would have been present within the soil pore spaces had the ground not been frozen. This excess ice can constitute almost 50% of the total volume of permafrost (Williams and Smith 1989). It is the movement of liquid water through the pore spaces of frozen ground along a thermal and hydrostatic gradient that creates segregated ice formations, such as ice lenses (Williams and Smith 1989). Once an ice lens is established, liquid water vacates the adjacent frozen ground pores; and water flows up through the soil to replenish the vacated pores, thus fostering continued growth of the segregated ice (Henry 2000).

Intrusive ice is quite different from segregated ice. Intrusive ice forms when water percolates downward into frost cracks in the permafrost to form vertical wedges. Ice wedges can constitute 10% of total permafrost volume in the top three meters (Davis 2001). In sum, there are three primary forms of ice found in permafrost: (1) massive ice, which is water frozen within the pore spaces of the soil; (2) segregated ice, which forms horizontal lenses as the result of liquid water movement in the frozen ground moving toward the ice front; and (3) intrusive ice, which forms vertical wedges as a result of percolation down open cracks in the ground. Together these three forms of ice greatly alter the strength, thermal properties, and susceptibility to disturbance of the permafrost environment.

c. Active Layer

Above the permafrost is the active layer. The active layer is that portion of the ground that thaws and refreezes in an annual cycle in response to seasonal temperature change (Hinkel et. al 1996). On state lands of the North Slope, active layer thickness varies between 20 cm (7.87 in) and 100 cm (39.37 in). Factors affecting the depth of the active layer include: (1) winter and summer air temperature; (2) depth, duration, and temporal deposition patterns of snow; (3) the type of minerals and grain size of the parent material; (4) the vegetative canopy; (5) peat layer thickness; and (6) moisture content (Paetzold et al 2000; Luthin and Gwymon 1974).

Because of this complex interaction of many variables, thickness of the active layer can change markedly over very short distances (Nelson et. al 1997). Indeed active layer thickness can differ by as much as 300% along a single short transect (Hinkel et. al. 1996). There is also great inter-annual variation in active layer thickness, changing as much as 100% from year to year (Romanovsky, Sergueev, and Osterkamp 2003; Osterkamp and Romanovsky 1997). On the Coastal Plain near Prudhoe Bay, active layers of 40-50 cm (15.75-19.69 in) are typically encountered, while in the Foothills, active layer depths can vary from 28-60 cm (11.02-23.62 in) (Brown 1997; Brown and Grave 1979).

Each winter, the active layer freezes both from the top down and the bottom up (Romanovsky, Sergueev and Osterkamp 2003). Freezing in the active layer first starts in the autumn from the bottom, along the permafrost interface, and moves up, followed approximately two weeks later by freezing from the ground surface down (Osterkamp and Romanovsky 1996; Romanovsky and Osterkamp 1997). The process of bottom up freezing starts when the ground surface temperature drops below +2 degrees Celsius (35.6F) (Osterkamp and Romanovsky 1996; Romanovsky and Osterkamp 1997). Along the Coastal Plain near Prudhoe Bay, active layer freeze-up tends to start in mid September and is complete sometime during the second half of November. In all, freeze-up typically requires 65-70 days from inception to completion, with about 64% of the frozen active layer resulting from bottom up freezing (Osterkamp and Romanovsky

1997). Once complete freeze-up has occurred in the active layer, the drop in temperature stalls at about –1 degree Celsius (30.2F) due to the latent heat effect of liquid water in the frozen soil (Hinkel et. al. 1996). This point, called the zero curtain effect, may last for about 20 days, after which the drop in temperature throughout the active layer is quite rapid (Hinkel et. al. 1996). During the time of the zero curtain effect, moisture migrates vertically to the frost front, desiccating parts of the active layer. Once completely frozen, the active layer temperature becomes considerably colder than the temperature of the permafrost below, due to its nearer proximity to the extremely cold ambient air temperatures.

Just as the depth of the active layer possesses a high degree of natural variation within a short spatial distance, the date of freeze-up is also highly variable (Romanovsky, Sergueev and Osterkamp 2003). Depending upon prevailing weather conditions, complete freeze-up may occur any time within a 40 day range. However a distinct trend toward a later active layer freeze-up has been documented: from 1987 to 2001, the complete freeze-up date has shifted later in the season by approximately 30 days (Romanovsky, Sergueev and Osterkamp 2003).

Because the active layer is a critical component of the arctic ecosystem- it is the zone within which almost all biological, hydrological, and chemical activity takes place (Hinzman et. al. 1991)- this project attaches great attention to changes in the active layer. Organic material is also transported through the active layer and sequestered in permafrost through percolation into ice wedges and through ground mixing by cryoturbation (Bockheim et. al. 1999). Disturbance that affects the thermal regime, influencing the active layer and its thickness, may have the potential to trigger important ecological consequences such as thermokarst, alteration of biological productivity, and carbon release.

3. Snow

The temporal and spatial pattern of snow depth and density exerts an important influence on permafrost and active layer dynamics (ARC 2003). Large interannual variation in total snow depth, variation in intra-seasonality of snowfall events, and the moisture content of the snow all make understanding the influence of snow a complex undertaking. Snow depth and density at any one geographic location change greatly over time due to weather events that can erode existing snow, redeposit new snow in drifts, or form hard crusts. In general snow tends to persist on the ground for approximately 9 months per year, usually dry in moisture content and wind packed with a firm crust (Benson and Sturm 1993). The International Commission on Snow and Ice of the Association of Scientific Hydrology, in collaboration with the International Glaciology Society, issued a uniform international classification system for seasonal snow on the ground, which standardized descriptions of snow based upon density, grain shape and size, liquid content, impurities, hardness, temperature, and strength (Colbeck et. al. 1990). The project relies upon this classification system to define a slab layer.

Two primary types of snow are found on the North Slope Coastal Plain and Foothills: veneer facies that interact with the tundra surface and drift facies that form deep deposits. These two types of snow possess profoundly different properties (Benson and Sturm 1993). About half of all deposited snow is eventually redistributed by wind, creating a very dynamic snow environment (Benson and Sturm 1993). Snow is an efficient insulator and can protect the ground from heat loss, contributing to a late freeze-up if heavy snow deposition occurs early in the season and generating a warmer thermal regime in the frozen active layer that may persist throughout the winter season (Stieglitz et. al. 2003; Romanovsky and Osterkamp 2000). Maximum average end of year snow depths range from 35 cm (13.78 in) on the Coastal Plain to over 70 cm (27.56 in) in the Foothills (Romanovksy, Serbueev and Osterkamp 2003).

4. Vegetation

Microtopography, climate, moisture regime, and soil chemistry interact to strongly influence local vegetation composition and distribution on a very small scale, creating a complex mosaic of tundra vegetation community types on the North Slope (Walker et. al. 2002). Ecologists have classified these complex patterns employing a number of approaches, identifying as many as 30 distinct communities or as few as 5 primary community types. The project relies on a system that recognizes 6 broad vegetative community types: (1) wet sedge meadows, (2) sedge/dwarf shrub, (3) sedge tussock, (4) shrub tussock, (5) shrub, and (6) Dryas terraces (Modified from Muller et. al. 1999). The first three community types are found on the Coastal Plain, which is dominated by sedge communities; while the latter three community types are found in the Foothills, which are dominated by tussock and shrub communities. (A list of plant species found at the two modeling sites is attached to this report as Appendix C.)

Wet sedge meadows are frequent on the Coastal Plain and represent poorly drained areas of low relief and ice rich permafrost (Jorgenson, T. et al. 2003). Associated with either non-patterned ground or low centered polygons, wet sedge meadows are dominated by *Carex aquatilis* and *Eriophorum angustifolium*. Attending the dominant sedges are abundant bryophytes and *Salix* species.

Table 1. North Slope Vegetation Community Types by Percent Terrestrial Cover (Modified from Muller et. al. 1999)

Vegetation Community	**Coastal Plain** (Approximate % cover)	**Foothills** (Approximate % cover)
Wet Sedge	31	4
Sedge/Dwarf Shrub	30	22
Sedge Tussock	15	3
Shrub Tussock	12	41
Shrub	7	28
Dryas Terraces	5	2
Total	100	100

Sedge/dwarf shrub tundra is found on patterned ground with high center polygons, or a mix of high centered and low centered polygons, in moderately drained areas with moderate to high ground ice content. Dominant plant species include *Carex bigelowii* as well as *C. aquatilis, Eriophorum angustifolium* and dwarf shrubs such as *Betula nana, Salix reticulata, Cassiope tetragona* and *Vaccinium vitis-idaea* (Jorgenson, T. et. al. 2003). Bryophytes such as *Hylocomium* and *Dicranum* are also prevalent.

Tussock tundra exhibits a low mounded physiognomy, comprised principally of *Eriophorum vaginatum* and containing such woody species as *Ledum decumbens, Vaccinium vitis-idaea, Salix planifolia,* and *Salix phlebophylla*. Because tussock tundra tends to be moderately to well drained, lichen serve as a major constituent of the community. Hummocks are a frequent topographical feature, providing drier microsites that host vascular forb species. Ice content tends to be low to moderate at these sites.

Shrub communities are those dominated by low willows such as *Salix lanata* and *Salix planifolia,* as well as *Betula nana* and *Vaccinium.* These well drained communities are often found along riparian margins or upland side slopes and contain lower volumes of segregated and intrusive ground ice than the other vegetation communities.

Dryas terraces are relatively infrequent, dry sites located along well drained riparian benches, upland crests, and sandy side slopes in areas that typically lack patterned ground. These areas are dominated by *Dryas integrifolia* and co-dominants of lichen and *Salix reticulata*.

Plant communities are not only affected by abiotic factors, but they also influence the abiotic environment. Evapotranspiration from living plants, especially mosses, can lower soil surface temperatures considerably (Williams and Smith 1989). Various plant communities also exert an influence through their different insulating properties. Bryophytes, for example, impede the development of deep active layers: they promote low temperatures through efficiently conducting heat under wet summer conditions and then become an effective insulator later in winter when the moss becomes dry (NRC 2003).

According to some investigators, it can be argued that tundra vegetation communities are not fragile at all but are quite resistant and resilient as a necessary adaptation to an inherently unstable physical environment dominated by continual natural disturbance processes (Crawford 1997). This study only addresses the potential resistance of abiotic tundra characteristics to different types and intensities of anthropogenic disturbance, so that managers may learn to avoid disturbance or anticipate the level of disturbance from exploration activities. At this time, DNR leaves the important issue of ecological resiliency for further investigation by others.

5. Frequent Terrain Landforms

Cryoturbation, solifluction, segregated ice formation, intrusive ice, and the near surface presence of permafrost combine to generate a suite of topographic features that distinguish arctic tundra ecosystems. These various physical forces mark the arctic as the epitome of a stressed, disturbance driven ecosystem of great instability (Crawford

1997). Cryoturbation involves the churning of soil associated with freezing and thawing ground and is the primary force in creating characteristic arctic topographic features (Williams and Smith 1989). Solifluction is the down slope creep of soil located in the permafrost as a result of frost heave expansion and the force of gravity in association with subsequent thaw (Davis 2001).

a) Patterned Ground Polygons

Patterned ground is the product of ice wedge formation and is the dominant landform feature on the Coastal Plain. Polygons form as a result of cooling contraction cracks in the ground, as a sharp temperature gradient develops in early winter when ground surfaces are rapidly cooled prior to snowfall (Davis 2001). Water percolates down these cracks, which penetrate into the permafrost, and freezes, creating intrusive ice. As the process repeats itself over time, wedges of pure ice, oriented vertically with the wide end at the top, develop. These wedges can be a meter wide at the top and taper to a point 3 m (9.84 ft) below the surface. Wedge formation along interconnecting contraction cracks form the polygons, much as drying mud forms cracks.

b) Hummocks

Hummocks form bumpy ridges and small mounds where permafrost is overlain by a relatively deep active layer (Mackay 1980). Hummocks appear to be composed of fine grained parent material, overlying a bowl shaped thaw bulb depression on the surface of the permafrost/active layer margin (Mackay 1980). The freeze-thaw cycle produces a circulation pattern within the thaw bulb, in which the upper portion is extremely active early in the summer and the lower portion most active with the onset of autumn (Mackay 1980). Soil movement is downward at the margins of the bulb and upward at its center, creating the irregular bumpy surface so indicative of the arctic. Hummocks tend to form slowly in mesic environments and are thus usually vegetated, offering a small, well drained micro-climate and a terrain feature that absorbs solar radiation along its elevated, though small, slopes. Hummocks form in both the Coastal Plain and Foothills.

c) Frost Boils

Frost boils, sometimes called frost scars, are circular mounds 1-5 m (3-16 ft) in diameter that rise about 0.35 m (1.15 ft) in height above the surrounding terrain and are often void of vegetation. Found in silt rich substrate in poorly drained areas, they form above thaw bulbs as a result of a combination of forces, including differential frost heave, excess pore pressure, and cryostatic pressure (Davis 2001; Shilts 1978).

d) Thermokarst

Thawing of permafrost containing excess ice results in ground subsidence and is called thermokarst (Williams and Smith 1989). Usually, thermokarst subsidence is the result of some modification in the heat flux that increases melting at the subsurface. Because excess ice can constitute more than 50% of permafrost volume, the ground collapses into the vacant whole left by the melted ice, making a sinkhole-like feature (ARC 2003). Thermokarst is very unstable. Even a small subsidence can expand substantially along the margins. If water begins to pool in the depression, thermokarst will usually accelerate due to the greatly efficient thermo-conductivity of water and its ability to infiltrate deep into any permafrost cracks.

E. Description of Tundra Travel Ecological Effects

There is surprisingly little data published in the scientific literature addressing the environmental conditions that either exacerbate or mediate disturbance impacts associated with winter tundra travel. The reported research has been primarily retrospective in nature. As a consequence, most studies on the subject lack baseline data for controls, standardized experimental design for identifying type and intensity of disturbance, and measurements of the existing suite of environmental conditions present at the time the activity occurred. These previous studies also rely predominantly upon qualitative and subjective measures of disturbance.

The earliest studies addressed the disturbance effects associated with <u>summer</u> tundra travel (Bliss and Wein 1972; Hernandez 1973; Gersper and Challinor 1975; Abele, Brown and Brewer 1984; Chapin and Shaver 1981). These studies found significant, severe disturbances with long term changes in soil temperature, depth of the active layer, soil bulk density, soil pH, microbial activity, ground subsidence, and soil moisture regimes. As a result of these findings, state and federal agencies moved to limit most tundra travel to winter months only (see Tundra Travel Management History in Appendix D).

A few vehicles are permitted by DNR to travel on the tundra in summer. Such permission, however, is limited to those vehicles that use very low surface pressures, such as rolligons and flat track Tucker Snowcats. All summer travel is subject to total closure for wildlife protection purposes during key periods in migration and reproduction cycles.

Nearly all knowledge of seismic winter activity disturbance on tundra resources is the result of a long term study, conducted by the U.S. Fish and Wildlife Service in the Arctic National Wildlife Refuge, started in the mid 1980's (NRC 2003). Limitations in study design limit applicability of the results of the USFWS work (NRC 2003). However, the USFWS study represents pioneering work and makes a substantial contribution to the effort to understand the effects of winter tundra travel (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992; Felix and Raynolds 1989a; Felix and Raynolds 1989b). It is therefore relied upon by DNR for guidance.

The USFWS researchers adopted a system defining different levels of disturbance, ranking from low to high on a subjective numerical scale of 0-3 (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992). Under this system, disturbance was classified as low if less than 25% of total vegetation was "damaged" and less than 5% of the trail surface had exposed mineral soil. The studies defined moderate disturbance as 25-50% vegetation "damage" and 5-15% of the track surface with exposed mineral soil; high disturbance levels were defined as those plots with greater than 50% vegetation "damage" and greater than 15% of soil surface exposed. Tussock disturbance was likewise ranked subjectively, with a numerical value of 0 if no disturbance was observed, 1 if the tussock was slightly scuffed, 2 if the tussock was crushed but still living, and 3 if the tussock was shattered and dead.

According to the USFWS study, all vegetation community types exhibited little resistance to disturbance from winter tundra travel activities (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992). However, at low levels of disturbance, most community types were capable of demonstrating resiliency (Emers, Jorgenson, and Raynolds 1995; Felix et al.1992). Dryas terraces and tussock communities seemed to have the least resistance to change (Emers, Jorgenson and Raynolds 1995; Felix and Raynolds 1989a,b; Raynolds and Felix 1989). Wet graminoid communities demonstrated the greatest resistance to disturbance (Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992; Felix and Raynolds 1989 a,b; Raynolds and Felix 1989). These studies found that changes, especially in highly disturbed sites, could continue long after the initial disturbance event (Emers and Jorgenson 1997; Emers, Jorgenson, and Raynolds 1995). In one case study, the investigators found that at high levels of disturbance, the resilience amplitude may have been exceeded, resulting in the replacement of one community by another (Felix et. al. 1992).

In most cases, these studies indicate that shrubs are disproportionately affected, with significant decreases in overall relative vegetative cover the first growing season after the passage of vehicles (Felix and Raynolds 1989a,b). Of the shrubs, evergreens seem to decrease the most as a result of disturbance (Emers and Jorgenson 1997; Emers, Jorgenson, and Raynolds 1995; Felix et. al. 1992). On most disturbed plots, a species composition change occurred, with increased dominance of those species associated with more mesic and hydric sites, favoring increased cover by graminoids and disfavoring lichens (Emers, Jorgenson, and Raynolds 1995; Felix and Raynolds 1989). While bryophyte and forb relative cover often did not decrease significantly, substantial changes did occur in species composition, favoring hydric and mesic genera within the life form classes.

Several studies describing the changes in physical environment as a result of summer tundra travel may be useful in explaining the mechanisms for some of the changes detected in vegetation communities following winter travel (Kevan et. al. 1995; Abele, Brown, and Brewer 1984; Chapin and Shaver 1981; and Gersper and Challinor 1975). Soil temperature was higher in disturbed areas, thaw depth of the active layer was deeper, soil density in tracks was higher, soil pH became higher, and microbial activity increased. These changes appear to have resulted in the degradation of underlying permafrost, causing significant alteration to the biological and physical environment (Brown 1997; Walker and Walker 1991).

II. STUDY DESIGN

The study is designed to link those environmental characteristics that influence tundra resistance to disturbance (and which can be easily field measured) to the environmental effects associated with off-road tundra travel. DNR tested vehicles that are commonly used in oil and gas exploration activity and represent a range of drive mechanisms and weight. The study evaluated a Tucker, Challenger, Front End Loader, and D7 Tractor. Measurements were taken to identify disturbance and include change in depth of active (thaw) layer, soil temperature, change in soil moisture, soil microtopography related to rutting and track depressions, vegetation productivity, and change in vegetation life form composition and cover.

A. Study Sites

The study approach used standardized field trial tests conforming to a randomized design. Two test locations were selected to generate a model for each of the two primary ecosystems found on the North Slope. These two areas are the Coastal Plain and the Foothills. The coastal case study area is located near the Prudhoe Bay oil field infrastructure about four miles south of Deadhorse; the Foothills case study area is located near Happy Valley, adjacent to the Dalton Highway road corridor, 100 km (62 mi) south of Deadhorse.

Each case study location had to satisfy five selection criteria. First the area had to be free from previously recorded seismic exploration or other disturbance generating anthropogenic activity. Second, the study area needed to be within one mile of the long term soil and water temperatures and snow monitoring data arrays set up by the National Science Foundation through the University of Alaska, so that study measurement results could be evaluated in context with long term climate trends. Third, the areas had to be located next to the existing road system. Fourth, an area suitable for staging had to be located within 0.40 km (0.25 mi) for ease of unloading and loading heavy equipment from trailers pulled by large semi-truck tractors. Fifth, the road surface between the staging area and the study location had to be a gravel surface, as the equipment would shatter hardened roads such as asphalt at anticipated winter temperatures. Both study areas were sited on the basis of these criteria.

B. Treatment Cell Configuration

Each study area was divided into rows of treatment cells, each cell measuring 100 by 50 m (328.08 ft by 164.04 ft). To the extent practicable, the treatment cells were configured to form blocks of ten cells formed by two adjacent rows of five cells. These blocks were then spaced and oriented to allow vehicle access to each cell in order to perform the treatments, without affecting the other cells in the vicinity (Figures 3 and 4). Each study area contained 30 treatment cells.

Within each cell, three 5 m (16.40 ft) transects were created. One transect was located at each end of a cell, oriented with the length of the cell. A third transect was located in the center of the cell, oriented perpendicular to the length of the cell (Figure 5). The ends of each transect were marked by metal survey arrows, driven into the ground. Further marking was accomplished with wood stakes driven into the ground 1 m (3.28 ft) beyond each survey arrow, in line with the transect. These stakes extended approximately 1 m (3.28 ft) above ground and had both reflector tape and steel shiners attached. These wooden markers served as “gates” measuring 7 m (22.97 ft) wide, within which treatment vehicles would pass, ensuring consistent driving over the transects.

In the study area, the rows of treatment cells were oriented parallel to the hillside contour. An elevation reading was taken at the middle transect of the center cell in each row and recorded.

Figure 3: Foothills Study Site Treatment Cell Configuration

(Shaded cells show those plots used in the first treatment date; one for each treatment, for purpose of example.)

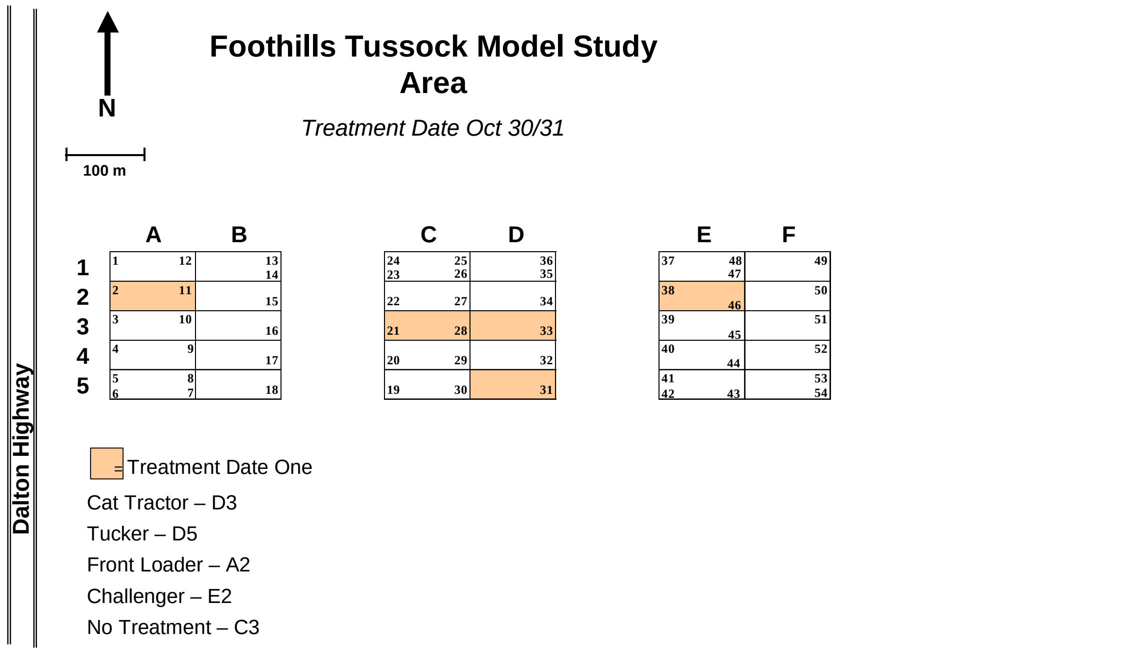


Figure 4: Coastal Plain Study Site Treatment Cell Configuration

(Shaded cells identify those treatments tested on the first treatment date, for purpose of example.)

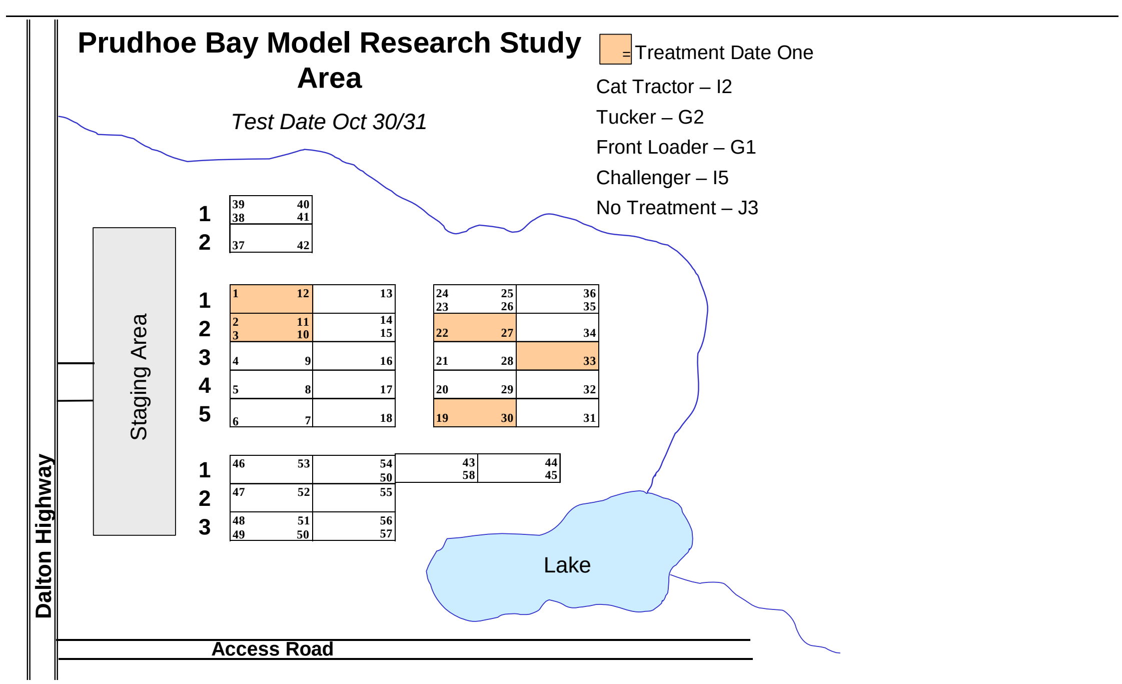
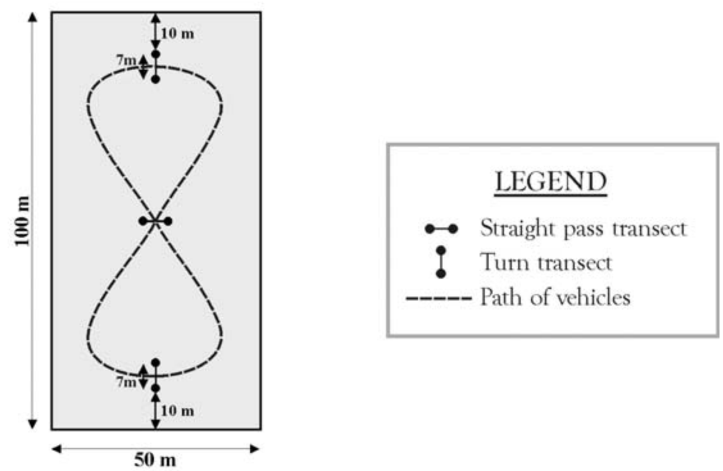


Figure 5: Treatment Cell Design with Transect Placement



After staff located all transects and gates for the treatment cells, a helicopter was chartered to fly staff above each study area, searching for indications of past anthropogenic disturbance not originally detected at ground level. Of particular note, the search focused on finding “green trails” that denote past tundra travel activity (Chapin et. al. 1988). If found these green trails were to be marked by tossing rocks marked with blue flagging tape from the helicopter, following the trail in a “bread crumb” style. Any transects affected would be moved slightly to avoid the disturbance. As a result of these overflights, trails were noted in two cells, requiring location adjustment of three transects in the Foothills study area and one cell, with one transect affected by prior disturbance, in the Coastal Plain study area.

C. Treatment Cell Measurements

Prior to the winter field tests, each of the 60 cells (30 for each study area) was sampled to create baseline data along each of the three transects in each cell, during July-August, 2003. Baseline measurements included: (1) depth of active (thaw) layer; (2) vegetation community type; (3) vegetation composition by genera, established with a hybrid “point frame”/ “intersect” sampling system; (4) vegetation life form cover, using the same hybrid sampling system; (5) soil temperature at a depth of 15 cm (5.91 in); (6) soil moisture at a depth of 15 cm (5.91 in); (7) soil microtopography; (8) tussock frequency and condition; (9) shrub frequency and condition; and (10) vegetation productivity as measured by chloroplast density, estimated with the percent of photosynthetically active radiation (PAR) absorbed[1].

Each cell within a particular study area was then randomly assigned one of six treatment dates and one of five treatment types (see Appendix B for the complete assignment of treatment type and treatment date by cell for each study area).

The day before each treatment date, winter measurements were taken along each transect within the treated cells for that date. Winter measurements included: (1) snow depth, (2) ground hardness, (3) snow slab presence, and (4) snow slab thickness.

D. Treatment Design

Treatments consisted of an assigned vehicle type making five consecutive figure-8 passes within an assigned cell on an assigned date, passing over each of the three transects within the cell. Each treatment cell, therefore, had only a single vehicle type pass through its transects on a single date.

Five treatment vehicle types were used on each test date. The five vehicle type treatments are as follows: (1) cleat tracked Snowcat; (2) wheeled front-end loader; (3) rubber tracked Challenger; (4) Caterpillar D-7 dozer; and (5) a “No Treatment” treatment. Vehicle types were selected upon the basis of equipment availability and transportability and type of equipment frequently used in cross-tundra travel for seismic exploration and ice road construction (Figures 6a-d). Vehicle types were also chosen to represent a range of weight, drive types (wheel and track), and steering mechanisms. (Vehicle specifications are discussed in Appendix I.)

[1] PAR measurements were taken only during the second summer field season after the winter treatments.

Treatment dates were designed to span a suite of environmental conditions potentially present during tundra travel. Treatment dates were established for: (1) October 30, 2003; (2) November 14, 2003; (3) December 4, 2003; (4) December 16, 2003; (5) January 5, 2004; and (6) January 20, 2004.

A specific vehicle made five passes in a figure-8 pattern in each cell designated for a particular test date. In each cell, a transect was located to bisect each turning point at each end of the figure-8, to provide data on left and right turns. A third transect bisected the middle “thoroughfare” of the figure-8, to provide data on straight travel (Figure 5).

The summer following the winter field season, DNR returned to the two study areas July-August, 2004, to re-measure each transect in each treatment cell for change detection. Natural ecological disturbance and change was accounted for, and calibrated, by referencing to change detected within the “No Treatment” cells, using the summer 2003 measurements with the subsequent summer 2004 measurements. In this fashion, **disturbance is defined as a change from baseline exceeding that observed for natural inter-annual variation for each of the measurements**.

Figure 6: Treatment Vehicle Types

a. Tucker

b. Front End Loader

c. Challenger

d. D7 Dozer

Data from the 2003 and 2004 field seasons were integrated into a multiple regression model, enabling DNR staff to predict disturbance responses under differing combinations of environmental conditions with known types and intensity of tundra travel. This model will provide enhanced information and serve as an additional tool for DNR in deciding appropriate opening dates for winter tundra travel.

III. STUDY METHODS AND TECHNIQUES

A. Measurement Error Analysis

Measurement error is that difference among multiple readings of the same sample measurements that is attributed to the observer. It arises from inappropriate use of instrumentation, mistakes in taking readings, transcription error, and anticipatory bias. This project incorporated rigorous methods to reduce measurement error.

Prior to embarking upon field measurements, staff technicians underwent intensive training and testing to reduce measurement error. Each technician was required to complete, and repeat three times, the full suite of summer measurements for a set of six faux transects. Measurement error was calculated after completing each transect, and adjustments were made until each staff person's error was less than +/- 2%. If measurement error was not reduced to less than 2%, then that technician was not allowed to perform the particular measurement in the field on the actual plots. Two percent was the selected threshold because it represented the point of precision for most of the instrumentation.

In the field, measurement error continued to be monitored. Protocols required that 5 treatment cells within each study area be selected at random for measurement error analysis. Immediately following the recording of measurements for a cell, technicians would make a random draw to determine if the cell should be sampled again. This process was repeated after each cell, so that staff had no knowledge if a particular cell was a measurement error replicate. At the end of each summer field season, the measurement error was calculated for each study area (Table 2). Due to the inclement and dangerous conditions during winter measurements, no measurement error analyses were conducted. It is probable that the winter error rates would be considerably higher than the summer data, given the darkness, cold temperatures, and high winds encountered during the winter field season. However safety protocols precluded the additional time that replication would have required staff to be exposed to hypothermic/frost bite conditions.

Table 2: Measurement Error Analysis Results for Summer Data

	Coastal Plain 2003	Coastal Plain 2004	Foothills 2003	Foothills 2004
Active Layer Depth	+/- 1.0%	+/- 1.7%	+/- 1.9%	+/- 2.0%
Soil Temperature	N/A	+/- 1.3%	N/A	+/- 1.7%
Soil Moisture	+/- 0.9%	+/- 1.1%	+/- 1.3%	+/- 1.1%
Micro-topography	+/- 0.07%	+/- 0.03%	+/- 0.13%	+/- 0.09%
PAR	N/A	+/- 2.0%	N/A	+/- 2.3%

Transcription error was prevented using a detailed data entry check protocol. Data was entered from field data sheets into separate SAS files twice. Then the two files were compared cell by cell, pursuant to a software program, and inconsistencies identified for investigation. Inconsistent cells were corrected by reference to the original data sheets and errors eliminated. In addition all data entry was made on a separate computer that was not connected to the internet to prevent virus corruption. Finally any individual having contact with the data sheets or SAS files had to sign chain of custody forms to ensure protection of information.

B. Measurement Protocols- Summer

Before measurements could be taken, the study areas had to be divided into treatment cells with the desired configuration. This was accomplished through ground survey, using the traditional system with a transom level, rod, and chain. Once the cells were established, each of the four cell corners was marked with a metal survey arrow and wood stake sporting reflective tape, a coded numbered aluminum tag, and cell name inscribe on the wood with permanent black ink. GPS coordinates were taken at each of the four cell corner stakes, as well as at each of the transect end stakes, to assist in finding the cell and transect survey arrows in the event that animals, weather, or humans destroyed the identifying stake. Each transect had a single stake marked by a metal tag, demarcating it as the starting reference point for all measurements along the transect and identifying the left and right sides along the transect. Great care was employed in alignment and placement of the transect rod between the metal survey arrows, to ensure that the 2003 baseline measurements and the 2004 post treatment measurements were in nearly identical locations along the transect for maximum accuracy in change detection.

After the transects were established, measurement duties were divided among the field staff on the basis of which staff person had achieved the lowest measurement error rate for each measurement type. In order to avoid disturbing the transect, the observer always positioned him/her self on the right side of the transect and took measurements to the left side, reaching over the transect. This approach minimized trampling of the sampled area[2].

Because of both the rapid rate of phenological development within the vegetation community and the physical, abiotic changes due to the brief but intense arctic summer, all measurements should be taken during as short a temporal window as possible. This prevents encountering ecologically important changes near the end of the measurement window from that at the beginning. As a result, most researchers try to confine their measurement season to no more than a two week period, sometime from mid-July to early August (Vavrek et. al. 1999; Kevan et. al. 1995; Felix et. al. 1992; Chapin and Shaver 1981). Protocols for this project call for all summer measurements to be taken within a three-day window at each of the study areas (Table 3). All PAR absorption measurements were taken within a single day at each of the study areas because it was assumed that this measurement might be the most sensitive to phenological change during the critical time shift of inflorescence to senescence encountered in late July and early August.

So long as the measurement window duration remains the same, departure from the same window period between the 2003 and the 2004 field seasons should not constitute a confounding variable because the change in baseline is calibrated to take such variation into account through reference to the “No Treatment” cells and by the manner in which disturbance is defined.

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[2] The orientation of which side to sample on and which side to observe from was reversed on the Coastal Plain due to a miscommunication.

Table 3: Sampling Window- Summer Measurements

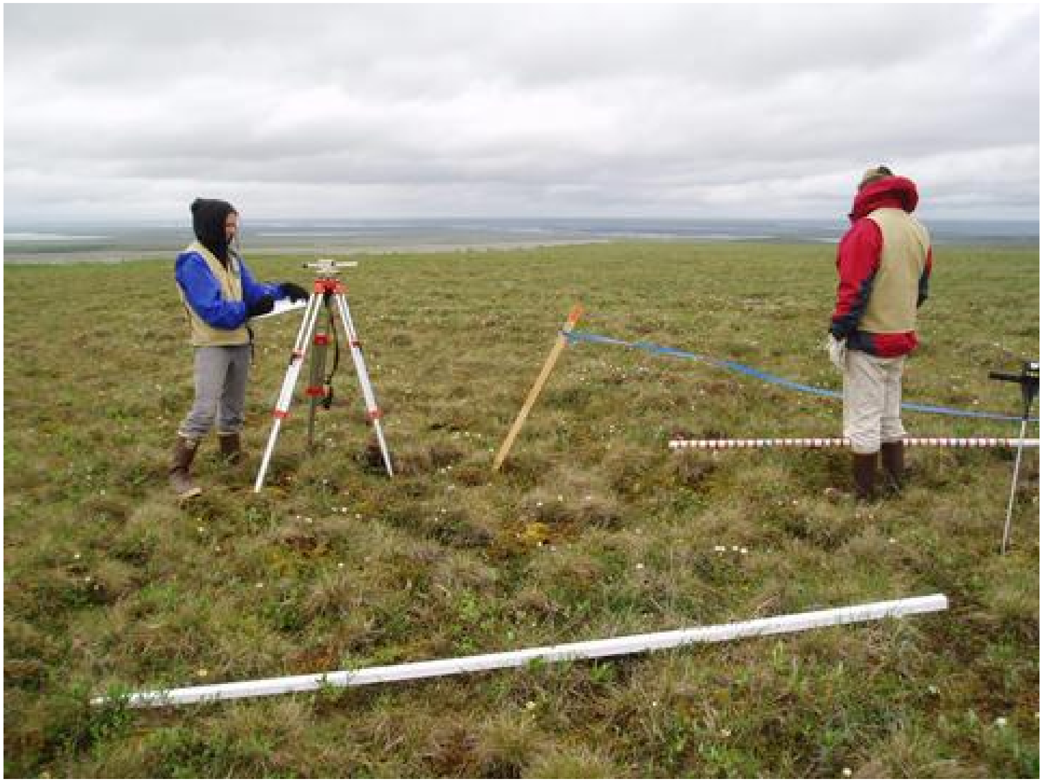
Location	Dates	Duration (Days)
Foothills 2003	July 17-July 19	3
Coastal Plain 2003	July 30-August 1	3
Foothills 2004	July 12-July 20	9*
Coastal Plain 2004	July 25-July 27	3
Foothills 2005	August 8-August 10	3
Coastal Plain 2005	August 13-August 15	3

*Deviation from protocol due to personal emergency.

To take measurements, a 5 m (16.40 ft) transect rod was placed snugly between the survey arrows identifying the transect location. This rod was divided into ten 50 cm (19.69 in) units, numbered 0 through 10. Measurements were taken and entered onto data sheets according to the following sequence:

1. Identify study site
2. Identify treatment cell number
3. Identify gate number and type (Left Turn, Straight, Right Turn)
4. Start with Right gate, then sample Straight gate, then end with Left gate
5. Place 5 m (16.40 ft) plant transect rod between transect survey arrows.
6. Note slope with clinometer and aspect of each gate transect
7. Note degree orientation of each gate transect with handheld compass
8. Note Right and Left side of transect, based upon orientation
9. Observer must remain on the **RIGHT** side of transect and make all measurements on the **LEFT** side of transect, as determined from the transect reference point.
10. Begin taking measurements.
11. Soil temperature
12. Soil moisture
13. Depth of active layer
14. Microtopography
15. Tussock frequency and disturbance level
16. Shrub frequency and disturbance level
17. PAR (performed only in summer of 2004)
18. After all transects have been measured in a study area, take transect photos from a height of 2.2 m (7.22 ft), with field of vision oriented lengthwise down the transect from the reference point.
19. Take aerial photos of each treatment cell from helicopter, at a height of approximately 40 m (131.23 ft).

Figure 7: Summer Measurements in the Field (Foothills Study Site)



C. Measurement Protocols- Winter

At the time of each test date, staff measured the appropriate five treatment cells and each of the three transects within the cells. These measurements were taken the day prior to vehicle treatments. In order to leave the actual transects unmolested by the measurement process, a proxy transect was established parallel to the transect at a distance of 2 m (6.56 ft). All snow depth, ground hardness, and slab presence measurements were taken along this second transect. Data collected along the second transect was assumed to be the same for the actual transect. This procedure prevented the altering of snow and ground properties prior to the treatments, due to the trampling of snow, the creation of snow pits to measure depth and ground hardness, and the use of the ratchet plunger for snow slab detection. Staff took all winter measurements at three locations for each transect. These locations were the two ends and the middle point.

Figure 8: Winter Measurements in the Field (Coastal Plain)

D. Measurement Methods

1. Output Variables

a) Depth of Active Layer

Technicians measured depth of active layer by steadily pushing a calibrated, pointed metal rod into the ground to the point of refusal (Affleck and Shoop 2001; Brown et. al. 2000; Vavreck et. al. 1999; Nelson et. al. 1997). While this is the most frequently used technique, it is understood that this system may involve some level of measurement error in finer grained soils, by overestimating depth if the rod penetrates into the softer, topmost layer of permafrost (Nelson et. al. 1997; Brown and Grave 1979). Depth is measured by reading the increment measurement on the rod from the ground surface to the point. To reduce measurement error associated with the subjective determination of the ground surface in thick vegetation, DNR affixed a loose washer on the rod. After the rod had been inserted into the ground to the point of refusal, the washer was pressed downward to the point of resistance, marking the ground surface next to the appropriate increment on the rod. Active layer depth was read to the nearest 0.5 in (equivalent to 1.27 cm). All data was subsequently converted to cm.

b) Soil Temperature

Soil temperature was recorded with an insulated probe, with a thermister attached at its tip. The probe was pushed 15 cm (5.91 in) into the ground and left 30 seconds to equalibriate. Temperature was read to the nearest 0.1 Fahrenheit degree (equivalent to the nearest 0.056C). After the temperature probe malfunctioned for unknown causes, temperature was measured with a digital soil probe, which took an average temperature along the 15 cm (5.91 in) long probe length in the ground. The new instrument therefore introduced error by indicating a warmer reading than that at the appropriate depth. All temperature data was then converted to Celsius.

c) Soil Moisture

Soil moisture was recorded with a Spectrum soil moisture probe using magnetic resonance, which estimated percent of total volumetric water content between two probes. Moisture was recorded to the nearest one percent.

d) PAR (Photosynthetically Active Radiation)

In an effort to use a quantitative and objective measure of plant stress to replace the qualitative approaches used in earlier studies, DNR used instrumentation that measured the percent of ambient photosynthetically active radiation (PAR) absorbed by vegetation. The instrument was affixed to a standard height staff 1.3 meters (4.27 ft) above the ground, to ensure consistency across the measurement area. Ten evenly spaced measurements were taken along the transect, between each measurement mark on the transect. The instrument measured the average absorption of PAR within a 15.24 cm (6 in) diameter circle. Unlike all other measurements, PAR was performed without baseline data in 2003. Treatment cells were instead compared to No Treatment cells, which served as a control.

Due to a brief growing season and relatively low productivity rates, most initial growth by tundra plants is supported by stored nutrients, therefore reducing the effect of annual weather variation, or disturbance, on total community productivity in any one year (Chapin and Shaver 1981; Chapin et. al. 1988). Thus the productivity of a site, for which PAR is used as a proxy, reflects more an average of prevailing conditions over several preceding years rather than the most recent environmental conditions. PAR measurement may therefore systematically underestimate the extent of stress induced by the treatments.

e) Microtopography

Microtopography was measured along each transect with use of a transom and rod. Eleven measurements were taken at 50 cm (19.69 in) intervals, from 0 to 5 m (0 to 16.40 ft). All measurements were taken as a vertical departure from the reference reading at point 0 on the transect. Measurements were read to the nearest mm (equivalent to 0.04 in).

f) Life Form Description

Each transect was described subjectively in 10 increments by the dominant life form class, relying upon ocular estimates. Each increment was 50 cm (19.69 in) in length. Life form classes were (a) graminoid, (b) herbaceous forb, (c) woody shrub, (d) bryophyte, and (e) lichen. Other descriptors used, when dominant for an increment, were bare earth, water, rock, or trash.

g) Tussock Assessment

Tussock disturbance was based upon the subjective, qualitative scaled used in prior tundra travel disturbance studies performed by the U.S. Fish and Wildlife Service and the University of Alaska. This scale is fully described by Emers (Emers and Jorgenson 1997). The scale is 0 for no disturbance; 1 for low disturbance; 2 for moderate disturbance; and 3 for high disturbance. Tussocks were noted as present or absent at each of the 50 cm (19.69 in) marks along each transect. Those tussocks along the transect that did not lie at a 50 cm (19.69 in) mark were not counted.

h) Shrub Assessment

Shrub disturbance was another qualitative and subjective measurement employed from previous studies reported in the literature. At each 50 cm (19.69 in) mark along the transect, the presence or absence of a shrub was noted. Disturbance was described as Zero for none, Low if secondary or tertiary branches were broken, and High if the primary branch or stem was broken.

i) Inventory by Genera

A horizontal rod, with 100 increments spaced at 5 cm (1.97 in) intervals, was used to inventory each transect. At each increment, the plant at first intersect was recorded by genera. Thus each of the 3 transects within a treatment cell was described along 100 points, giving a relative cover by genera.

2. Input Variables

a) Ground Hardness

Ground hardness in winter is measured by use of a drop hammer that drives a 30.48 cm (12-inch) probe into the ground. A 6.80 kg (15 lb) weight is lifted by the operator and allowed to drop freely a prescribed 60.96 cm (24 in) along a shaft, striking a plate to which the probe is attached. This approach removes all influence of the operator from the measurement. Hardness is described by how many drops it requires to drive the probe into the ground to a depth of 30.48 cm (12 in). The 0.95 cm (3/8 in) diameter probe is scribed at 2.54 cm (1 in) increments to allow measurement of the number of drops at various depths, if such a measurement is desired. It must be pointed out that all ground hardness measurements, as expressed in terms of drops to penetrate 30.48 cm (12 in), are assumed to be an ordinal scale. No controlled laboratory tests have been conducted to ascertain how the number of drops relates to actual hardness. Thus while 12 drops is assumed to be harder than 11 drops, and 13 drops harder than 12, no inference is made as to how much harder 12 may be than 11 or how much harder 13 is than 12.

Ground hardness measurements were taken at three locations along a snow trench, dug parallel to each transect within a treatment cell at a distance of 2 m (6.56 ft) from the transect, so as to leave the transect unmolested prior to application of the treatment vehicle. Three ground hardness measurements were taken along each transect: one in the middle and one at each end of the trench. Measurements were taken the day before treatment was applied.

b) Snow Depth

A snow depth measurement was taken at each point along the snow trench where the ground hardness measurements were taken. Snow depth is measured to the nearest 0.5 inch (equivalent to 1.27 cm) and later converted to cm.

c) Snow Slab Presence and Thickness

DNR evaluated a snow slab by means of an objective and quantitative system. Staff determined the presence of a snow slab if the snow resisted penetration by a handheld, spring ratchet penetrometer, calibrated in the lab to equal the International Snow Classification System hardness index of “R4-High” (see Colbeck et. al. 1990). This laboratory-designed standard and test corresponded well to field measurements, indicating a snow slab density of 0.45-0.55 grams per cubic cm (0.016-0.019 oz per 0.06 cubic inch), which is consistent with published literature. If the observer was able to depress the ratchet penetrometer fully without breaking through the snow, a slab was recorded as present. The slab was then measured for thickness to the nearest 0.5 inch (equivalent to 1.27 cm) and later converted to cm.

3. Potentially Confounding Variables

The Foothills study area poses the possibility of confounding variables, due to a marked variation in topography influencing elevation, slope, and aspect. Regression analyses were run to identify if baseline conditions were correlated with changes in topography at the scale of the study area.

a) Elevation

A regression was performed with elevation as an independent variable and dependent variables as depth of active layer, soil moisture, and soil temperature. Only the depth of active layer was significantly related to change in elevation.

b) Aspect

No significant relationships were found as a result of aspect, due to the consistency of aspect in each study site across treatment cells.

c) Degree Slope

No significant relationships were found with slope, likely as a result of slope uniformity.

E. Determination of Whether to Have Separate Models for Each Study Area

An early question that had to be answered by DNR was whether the two study areas are sufficiently different in ecological characteristics to warrant management under separate models. Given the large sample sizes (n=990 for DAL, n=900 for PAR, n=540 for soil moisture and temperature), a z-test was used to compare means on untransformed data. Results found a highly statistically significant difference (at $p<0.01$) between the Foothills and Coastal Plain study areas for each of the four characteristics (Table 4). DNR acknowledges that it would be possible to build a unified model that could be used for both ecosystem types (tussock and wet graminoid). However, for purposes of management approach, DNR determined that separate models for each ecosystem would encourage manager recognition of the distinctive differences created by the heterogeneity in elevation and slope and differential temperature and precipitation regimes. Therefore DNR believes it prudent to create models for each study area, to assist agency decision-making.

Table 4. Comparison of Characteristics Between Study Sites. Significant to $P<0.01$

Characteristics 2003	**Coast Plain Mean (SDev)**	**Foothills Mean (SDev)**
Depth of Active Layer (cm)	44.65 (7.5)	19.8 (7.9)
Depth of Active Layer (in)	17.58 (2.95)	7.80 (3.11)
Soil Moisture (%)	83.2 (8.7)	44.2 (21.0)
Soil Temp (C) *	6.3 (1.2)	2.0 (1.6)
Soil Temp (F)	43.34 (2.16)	38.48 (2.88)
PAR Index *	145 (31)	288 (27)

* denotes measurements were taken in 2004 on the No Treatment cells

F. Regression Analysis Methods

Generalized Linear Models, using the SAS ® program, were used to identify relationships among winter variables, summer variables, and treatment vehicle effects. Because winter measurements were taken along a parallel transect and a different number of measurements taken, all winter data is expressed as gate means. These means are then applied to the individual summer transect measurement points for purposes of regression.

Disturbance effects were not observed equally along the transect line. Those measurements at the extreme ends of each transect were more similar to No Treatment cell means than to vehicle treatment cell means. This can logically be explained, as only the central portions of each transect were traversed by vehicles. Taking all points along the transect could bias the results, systematically under-identifying change and disturbance effects. Therefore the model was designed to take into account this pattern along transects, with data categorized as either “inside” or “outside” depending upon the location of the measurement point along the transect. The investigation also found a difference in results between the straight gate and the turn gates of the figure-8. The straight gate received 10 passes of each vehicle, while the two turn gates received 5 passes each. Results indicated greater disturbance effects associated with the straight gate than the turn gates; this may be a function of the greater intensity of treatment related to the number of passes.

G. Baseline Description

DNR conducted baseline surveys for each study area during the 2003 summer field season. The Foothills study area, located 32.19 km (20 mi) north of Happy Valley, contains a mosaic of tussock and moist sedge/shrub tundra. It represents community types that comprise approximately 65% of total natural vegetative cover found typically in the Foothills. The Coastal Plain study area, situated about 4.83 km (3 mi) south of Deadhorse, is a mosaic of wet graminoid and moist sedge/shrub tundra and represents about 64% of total vegetative cover typically found in the Coastal Plain. Wildlife such as musk ox, caribou, wolf, and grizzly bear were infrequently seen in both study areas. Grazing and trampling by ungulates may serve as an unaccounted-for, confounding variable within the study sites but is assumed to have a negligible impact for the purposes of this study.

1. Ecological Change and Calibration to Natural Disturbance Regime

The available scientific literature discussing the processes of cryoturbation, active layer freeze-thaw cycles, and soil moisture and temperature regimes strongly suggests significant inter-annual variation associated with the tundra, in addition to significant differences in these same characteristics across short spatial dimensions. As a result, it is necessary to ensure that study results are calibrated to take into account natural change when defining disturbance as a departure from baseline. The No Treatment cells are used for this purpose.

The summer of 2004 was both warmer and drier than the previous summer at the Coastal Plain and Foothills study sites. It appears that this may have manifested itself in deeper active layer depth and altered soil moisture levels. It is important to note that though mean values for treatment gates within each No Treatment cell changed from 2003 to 2004, the relative ordering of these mean values remained the same across both years. This indicates success in transect placement, ensuring re-measurement of the same points, as well as success in identifying a consistent trend of natural change at the Coastal Plain and Foothills study sites.

2. Coastal Plain Site

a) Pre-treatment Description

In 2003, prior to treatment, vegetation in the Coastal Plain study area consisted of a mosaic formed by wet sedge meadows of *Carex* species and a moist sedge/shrub community type. This low canopy exhibits a nearly uniform physiognomy. A list of total species observed within the study area pursuant to a Releve survey is included as Appendix C of this report. The study area features a terrain dominated by high centered polygons, with frequent hummocks and frost boils. Though present tussocks were rare within this study area.

Active layer depth found in the Coastal Plain study area averaged 44.6 +/- 0.45 cm (17.56 in +/- 0.18 in) within a 95% confidence interval (standard deviation of 7.5 (2.95 in); n=990). Mean soil temperature on No Treatment cells in 2004, at a depth of 15 cm (5.91 in), was 6.3 +/-0.37 degrees C (11.34 +/- 0.67 degrees F) within a 95% confidence interval (standard deviation of 1.2C (2.16F); n=540). Percent volumetric soil moisture content at a depth of 15 cm (5.91 in) averaged 83.2 +/-0.72 percent (standard deviation of 8.7; n=540).

Microtopographical relief is characterized by the presence of high center polygons and hummocks. Geometrically arranged trenches, bordering the polygons, mark the presence of ice wedges. These trenches were typically 10-30 cm (3.94-11.81 in) deep and were frequently partially filled with melt water. Hummocks were irregularly distributed across the study area and ranged in height from 15-40 cm (5.91-15.75 in). Frost boil carapaces created dome like relief, often 30 cm (11.81 in) high and approximately 1 m (3.28 ft) across.

Figure 9: Coastal Study Site Aerial View (Post Treatment, 2004)

Figure 10: Sedge Meadow Community Type (No Treatment Cell)

The dominant characteristic of the Coastal Plain study area is it flatness. Only six of the thirty plots showed a discernable slope. In each of these six plots, the slope measured less than 1%, with a gentle southeast aspect. Elevation change was 1 m (3.28 ft) on the study area, from a low point of 14 m (45.93 ft) to a high point of just 15 m (49.21 ft).

b) 2003/2004, No Treatment Cells

On the Coastal Plain, the average active layer depth on the No Treatment cells changed by 2.4 cm (0.94 in), from a depth of 44.65 cm to 47.05 cm (17.58 in to 18.52 in) (SD 2.5 cm (0.98 in); n=198). This change was not uniform along all measurement points. Instead the change in the depth of active layer at any one point in the No Treatment cells, between years 2003 and 2004, is significantly related to the 2003 active layer depth ($p<0.0001$; r sq= 0.30). In other words, the deeper the active layer in 2003, the less change in active layer depth in 2004. This situation makes intuitive sense. The deeper the active layer, the more energy is needed to penetrate through the soil and melt frozen ground. A comparison of each transect gate in all No Treatment cells demonstrated this consistent pattern. Because cells were assigned randomly within the study site, it is assumed that there were no spatial anomalies across the study site that departed from this pattern.

Soil moisture levels likewise changed between the baseline and post treatment years. On the No Treatment cells, the volumetric soil moisture content declined from a baseline value of 83% to a subsequent value of 76%. The change in soil moisture also was not uniform and instead was significantly related to the moisture content of the previous year ($p<0.0001$; r sq=0.51). Thus the greater the 2003 soil moisture content, the less change was observed in 2004.

Because of equipment malfunction in 2003, no reliable baseline data exists for soil temperature at a standardized depth of 15 cm (5.91 in). Therefore the No Treatment cell temperatures were used as comparison controls and no calibration techniques were employed. PAR index measurements were treated in a similar manner to soil temperature because the scanning equipment was not available in 2003.

3. Foothills Site

a) Pre-Treatment

Vegetation community types within the Foothills study area are dominated by non-acidic sedge and shrub tussock tundra. A list of plant species found within the study area pursuant to a Releve survey is included as Appendix C of this report.

Terrain within the Foothills study area is defined primarily by a north-facing slope without visual evidence of solifluction or other form of frost creep. Hummocks and frost boils are infrequent. The geological bedrock of the hillside is composed of course grained sandstone and poorly consolidated conglomerate, containing clasts consisting of chert, white quartz, and fine grained quartzite (Mull and Adams 1989).

Active layer depth averaged 19.8 +/-0.49 cm (7.80 +/- 0.19 in) within a 95% confidence interval, with a standard deviation of 7.9 cm (3.11 in) (n=990). Mean soil temperature on No Treatment cells in 2004 was 2.0 +/- 0.07 degrees C (35.60F +/- 0.13F) within a 95% confidence interval, with a standard deviation of 0.89C (1.60F) (n=540). The observation that the Foothills study area has cooler soils and a shallower active layer than the

Coastal Plain study area is contrary to what one would expect to find, based upon a review of the available literature. However, this situation can probably be best explained by the fact the Foothills study area is situated upon a slope with a predominant northerly aspect, resulting in colder site conditions. Soil moisture, as measured by percent volumetric water, was 44.2 +/-1.49 percent within a 95% confidence interval, with a standard deviation of 21.0 (n=540).

Microtopography is characterized by the nearly ubiquitous presence of tussocks. In addition, the hillside upon which the study area is located possesses a gentle rolling nature. The gradient of the slope averaged 4% with a northerly aspect ranging 320 to 050 degrees. Elevation change on the site was 42 m (137.80 ft), ranging from an elevation of 320 m (1049.87 ft) at the base of the slope to 362 m (1187.66 ft) at its top (Table 5).

Table 5. Foothills Study Area: Treatment Cell Row by Elevation (m)

Cell Row	A	B	C	D	E	F
Elevation (m)	320	326	334	339	349	362
Elevation (ft)	1049.87	1069.55	1095.80	1112.20	1145.01	1187.66

Figure 11: Foothills Study Site Aerial View (2004)

Figure 12: Tussock Vegetation Community (No Treatment Cell)

b) 2003/2004, No Treatment Cells

Like the Coastal Plain sedge meadows, the tussock tundra of the Foothills study site experienced a natural increase in depth of active layer from 2003 to 2004, indicative of the prevailing warmer and drier conditions during summer 2004. The degree of change eclipsed that found on the Coastal Plain, however. Tussock communities experienced an increased active layer depth of approximately 5.6 cm (2.20 in) (Sdev 4.84 cm (1.91 in); n=198) from a depth of 19.8 cm (7.80 in) in 2003 to 25.4 cm (10.00 in) in 2004. The relationship of change in active layer to the previous year's depth levels was significant. Like the Coastal Plain, the deeper the active layer, the less change in 2004 ($p<0.001$; r sq= 0.19; n=990).

The effect of a warmer summer season on the Foothills site seems to have increased soil moisture. Soil moisture changed by 3.7%, from 44.2% in 2003 to 47.9% in 2004 (Sdev 13.9; n=540). This trend, opposite that observed on the Coastal Plain, may make intuitive sense. The Foothills, with a shallower active layer, would increase the water volume measured at the standardized depth of 15 cm (5.91 in), in part because of the closer proximity of the nearly impermeable permafrost. In this case, the higher the soil moisture in 2003, the greater the increase in soil moisture in 2004 ($p<0.0001$; r sq=0.14; n=540).

IV. RESULTS AND DISCUSSION

A. General Introduction to Results

It is important to acknowledge that there are many approaches toward constructing a regression model and that numerous value judgments are made in selecting predictor variables (covariates), as well as in the generation of interactive variables for use as predictor variables. This model should therefore be viewed in the context of an iterative process, as part of an adaptive management strategy. As new information becomes available and DNR improves its understanding of the tundra, the model will surely be refined and modified.

A number of assumptions are necessary in generating and using a general linear model. These assumptions include (1) normality of errors and homogeneity of error, (2) independence of observations, and (3) linearity of the relationship between independent and dependent variables. In this model, the assumptions of homogeneity and normality were tested and found to be reasonably satisfactory. Independence is assumed, although it is unlikely. Values along a transect are probably correlated with each other in some way.

The models presented here were created by using a process of backward stepwise regression. Models were constructed by initially including a large number of possible predictors and interactions and then progressively removing non-significant predictors. The resulting models are a product of the predictors considered and the process of predictor elimination. There are other models that could be legitimately suggested from the collected data.

DNR investigated the relationship of the following variables with the response variable of change in the active layer depth: (1) ground hardness, (2) snow slab presence and thickness, (3) overall snow depth, (4) treatment type, (5) whether measurement points were in the center of the transect or at its margins, (6) whether the vehicle type was turning or going straight, (7) 2003 depth of active layer, and (8) operator, as well as the interaction of treatment type with all of the above. This produced a set of 36 possible model coefficients. Predictor variables were then reduced upon the basis of significance of contribution to the response variable. Selection was also based upon those variables that were marginally significant but produced larger disturbance predictions, in homage to the precautionary principle.

As a result, a wet graminoid/moist sedge tundra model (r sq=0.272; F value 21.38; n=990) was generated to predict change in active layer depth using ground hardness, snow slab thickness (subjected to a log transformation), measurement points located near the center of the transect (to maximize potential disturbance predictions), treatment type, vehicle direction (to maximize potential disturbance predictions), the interacting effect of vehicle type with ground hardness, the interacting effect of vehicle type with snow slab thickness, and the depth of active layer in the preceding year (2003). A similar model was used to predict change in soil moisture (r sq=0.326; F value 21.34; n=540).

A tussock tundra model to predict change in active layer (r sq=0.375; F value 21.41; n=990) was generated using snow depth, treatment type, elevation, operator, active layer depth the previous year, and the interacting effects of snow depth with vehicle type and treatment type with elevation. Similarly a model for change in soil moisture was created for tussock tundra (r sq=0.279; F value 8.33; n=540).

Following construction of the model, a check for normality was performed by constructing a plot of the residuals with normal percent probability. It is assumed that the plot should track a straight line. This was done and visually determined to be satisfactory. Residuals were also plotted against predicted response values to determine the general scatter. The plots exhibited a random display, suggesting that the variance of the original observations is constant for all values of the response values. Finally studentized residuals were plotted to determine if any point with high values was influencing the least squares fit.

Aerial flights over the study sites revealed visible figure-eight patterns, expressed on treatment cells as green trails. This phenomenon is discussed at length by Chapin et. al. (1988) and Felix and Raynolds (1989a,b) and is assumed to be ephemeral if the physical disturbance is at a low intensity. This study did not evaluate tundra resistance to, nor the persistence of, these green trails. However continued over-flights will monitor them in coming seasons.

B. Winter Description

The Coastal Plain study area ground froze harder than the Foothills study area ground, as measured by the slide hammer. Snow depth on the Coastal Plain study area was also considerably less throughout the winter study period. A summary of Coastal Plain and Foothills study areas' average ground hardness and snow characteristics by treatment date is included in Table 6 (n=45) for each treatment date. The University of Alaska Geophysical Institute maintains soil temperature and moisture arrays near each DNR study site. The soil temperature profile for each treatment date is also included in Table 6 c.

Table 6: Ground and Snow Characteristics

a. Coastal Plain Ground Hardness and Snow Depth by Treatment Date

(dpf=drops per foot of slide hammer; dpf is equivalent to drops per 30.48 cm)

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Ground Hardness (SDev)	11 dpf (3.5)	27 dpf (6.7)	74 dpf (20.2)	89 dpf (23.6)	83 dpf (19.2)	105 dpf (30.2)
Snow Depth (SDev) cm	15.24 (6.41)	12.58 (3.01)	16.00 (5.28)	15.52 (3.87)	16.03 (4.58)	18.65 (6.22)
Snow Depth (Sdev) in	6.00 (2.52)	4.95 (1.19)	6.30 (2.08)	6.11 (1.52)	6.31 (1.80)	7.34 (2.45)
Snow Slab (SDev) cm	0 (0)	0.28 (0.9)	1.6 (2.0)	0 (0)	2.1 (3.1)	1.6 (5.7)
Snow Slab (Sdev) in	0 (0)	0.11 (0.35)	0.63 (0.79)	0 (0)	0.83 (1.22)	0.63 (2.24)

b. Foothills Ground Hardness and Snow Depth by Treatment Date

(dpf=drops per foot of slide hammer; dpf is equivalent to drops per 30.48 cm)

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Ground Hardness (SDev)	3 dpf (2.2)	4 dpf (2.5)	25 dpf (12.5)	23 dpf (13.4)	18 dpf (11.6)	25 dpf (14.8)
Snow Depth (SDev) cm	23.28 (5.58)	27.96 (6.66)	22.21 (5.80)	29.77 (7.10)	28.7 (6.64)	27.88 (8.18)
Snow Depth (Sdev) in	9.17 (2.20)	11.01 (2.62)	8.74 (2.28)	11.72 (2.80)	11.30 (2.61)	10.98 (3.22)
Slab (SDev) cm	0 (0)	0.16 (0.83)	1.10 (2.64)	1.63 (3.05)	2.11 (3.93)	0.22 (1.51)
Slab (Sdev) in	0 (0)	0.06 (0.33)	0.43 (1.04)	0.64 (1.20)	0.83 (1.55)	0.09 (0.61)

c. Soil Temperature by Test Date for 1 Foot Profile (Equivalent to 30.48 cm), in Degrees C at cm Depths and Degrees F at inch Depths.

Coastal Plain/Wet Sedge Study Site

	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
15 cm	-0.42 C	-1.49 C	-6.21 C	-8.01 C	-8.15 C	-14.72 C
23 cm	-0.28 C	-0.88 C	-5.25 C	-7.65 C	-8.01 C	-14.19 C
30 cm	-0.13 C	-0.38 C	-4.34 C	-7.28 C	-7.87 C	-13.66 C
5.91 in	31.24 F	29.32 F	20.82 F	17.58 F	17.33 F	5.50 F
9.06 in	31.50 F	30.42 F	22.55 F	18.23 F	17.58 F	6.46 F
11.81 in	31.77 F	31.32 F	24.19 F	18.90 F	17.83 F	7.41 F

Foothills/Tussock Tundra Study Site

	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
10 cm	-0.52 C	-2.46 C	-7.42 C	-7.62 C	-12.34 C	-10.22 C
18 cm	-0.08 C	-1.31 C	-6.51 C	-6.78 C	-11.50 C	-9.95 C
30 cm	-0.04 C	-0.71 C	-5.49 C	-5.95 C	-10.57 C	-9.86 C
3.94 in	31.06 F	27.57 F	18.64 F	18.28 F	9.79 F	13.60 F
7.09 in	31.86 F	29.64 F	20.28 F	19.80 F	11.30 F	14.09 F
11.81 in	31.93 F	30.72 F	22.11 F	21.29 F	12.97 F	14.25 F

Air temperature at the time of treatments became progressively colder during the winter. Table 7 portrays the ambient air temperature on the day of the treatment for each study site at the time treatments began.

Table 7. Ambient Air Temperature at Time of Treatment

Date	Oct 30	Nov 13	Dec 04	Dec 18	Jan 05	Jan 20
Foothills	-1C (30.20F)	-18C (0.40F)	-27C (-16.60F)	-30C (-22.00F)	-48C (-54.40F)	-38C (-36.40F)
Coastal Plain	-2C (28.40F)	-26C (-14.80F)	-33C (-27.40F)	-17C (1.40F)	-27C (-16.60F)	-30C (-22.00F)

C. Input Variables

1. Ground and Snow Influences

a) Ground Hardness

Freeze-up of the ground and its hardening exhibited a sinosoidal curve trend (Table 6) at both study sites. Little change in ground hardness was recorded during the first two test dates in October and mid-November; then a period of intense change, where the ground hardened quickly, occurred between test date two in November and test date three in early December. The ground hardened only slightly more after this, as measured with the slide hammer during the final three test dates from late December to late January, despite extreme, persistent cold air temperatures. This pattern is consistent with previously published literature and the observation of a zero curtain effect as discussed in Section II.

Mud streaks and ice crystals were visible on the drop hammer probe tip during ground hardness measurements taken during each of the six test dates, though the frequency of such occurrences diminished markedly after test date three. These observations seem congruent with reported literature that suggests significant quantities of liquid water remain in frozen ground, diminishing gradually to about 5% of volumetric water with decreasing temperatures.

Published literature suggests that an increased level of soil moisture content contributes to increased ground hardness. The data and regression analyses appear to substantiate this observation. A significant relationship between soil moisture and ground hardness was observed during treatment date two, coinciding with the period of intense freeze-up ($p=0.02$). No significant relationship between moisture and hardness was found before or after this point. This conforms to what one would expect to find. Soil moisture contribution to ground hardness derives from the structural strength of ice and bonding with the soil matrix. When ground is thawed, such as during test date one, little or no ice is present. Once the ground is thoroughly frozen, as assumed during test dates three through six, ice is already formed and no appreciable contribution by soil moisture is made to hardness. Therefore one would expect to find the relationship between soil moisture and ground hardness strongest during test date two.

A slight positive relationship was also found between ground hardness and snow slab thickness ($p<0.0001$). As snow slab thickness increases, the insulation capacity of the snow decreases (higher density and higher water content increase energy-conducting properties of snow). Thus a small increase in ground hardness is associated with those areas where deep slabs form.

Ground hardness and its interactive effect with treatment type contributed to changes in active layer depth and soil moisture in wet/moist sedge tundra. Consequently ground hardness was included in those models. However ground hardness was not found to contribute significantly to changes in active layer and soil moisture in tussock tundra and therefore was not included in the tussock models.

b) Snow Depth

Typically a bimodal snow deposition pattern dominates the North Slope. Heavy snows occur early in the season and again toward the end of winter, as air masses adopt a more spring like pattern. In the interim, dry air dominates and little snow falls. By the time of the first treatment date on October 30, 15 cm (5.91 in) of snow were already on the ground in the Coastal Plain and 23 cm (9.06 in) in the Foothills. These levels of snow cover did not change appreciably during the series of tests (Table 6). The presence of a large amount of snow cover by the first treatment date, with very little variation in cover over the course of the next five treatments, made it difficult to identify the effects of snow cover on disturbance by regression or other analysis techniques. Therefore the regression models are not directly applicable without a minimum threshold of 15 cm (5.91 in) snow depth in the wet/moist sedge tundra and a minimum threshold of 23 cm (9.06 in) in tussock tundra terrain.

According to the available literature, it is assumed that snow provides a physical buffer to ground compression and mechanical abrasion. At a certain point, snow depth probably reaches a level where the protective effect is completely manifested, and little or no additional influence results from an increase in snow cover.

Snow depth did influence disturbance effects in models for tussock tundra terrain, contributing to significant changes in active layer depth. For example, the more snow present, the less the increase in active layer depth above natural change, depending upon treatment type. As anticipated, the model found that snow had its most profound effect under the tractor and loader treatments and its least effect under the Tucker and Challenger treatments. Snow depth had no significant contribution to changes in soil moisture in tussock tundra terrain and therefore was not included in the model.

In the models presented here, it appears that threshold level for snow depth contribution to change in active layer depth and soil moisture in the wet/moist graminoid communities was achieved, or nearly so, prior to the initiation of treatments. Therefore the effects of snow depth could not be fully modeled.

c) Snow Slab Thickness

Snow slab thickness appeared to have a significant effect in reducing disturbance effects, particularly with heavy vehicle treatment types, such as the tractor and the loader in wet graminoid/moist sedge tundra. Thicker snow slabs in wet sedge vegetation communities reduced the increase in the depth of active layer for each treatment type. The influence of snow slab thickness was most pronounced with the tractor and loader and the least with the Tucker and Challenger. Slab thickness also affected change in soil moisture. The thicker the slab under a particular treatment type, the less change in soil moisture. Snow slab influence was greatest with the tractor and loader treatments and lowest under the Tucker and Challenger. These model findings regarding the role of snow slab thickness are consistent with the U.S. Fish and Wildlife Service study, which suggested a similar relationship. It is assumed that the presence of hard snow slabs offers some form of physical barrier and ameliorates the types of mechanical effects to soil properties that precipitate changes in active layer and soil moisture in the wet/moist graminoid community types.

The role of snow slab thickness was not significant, however, in influencing changes in tussock tundra soil moisture and active layer depths. As a result, the model for these tundra types did not include slab as an input.

2. Vehicle Types

Treatment vehicles may impact the depth of active layer in two ways. First, if the vehicle is light, an early treatment may have the effect of increasing ground hardness and reducing depth of active layer the following summer. This phenomenon is called “pre-packing” and is frequently employed as a technique in preparation for ice road construction. Driving over unfrozen ground with snow cover compacts the snow, reducing its insulation capacity and allowing the ground to freeze harder and deeper more quickly. As a result, summer active layer depths tend to be shallower following “pre-packing” because of the additional energy required to thaw the harder, more deeply frozen ground.

Another effect of vehicle travel is that heavy vehicles may compact the vegetation/peat/soil complex, resulting in a reduction of summer insulation capacity, allowing for more efficient transfer of incoming solar energy to penetrate to the thaw front. Under such circumstances, thaw depth will increase, creating a thicker active layer the following summer. Both possible effects were suggested in the study results.

D. Magnitude of Observed Changes

Disturbance levels, as expressed in terms of depth of active layer and moisture change, are less than the investigators expected (see Appendices F & G). Consequently the changes in these measures predicted by the model are also quite modest. At first these observations seemed contrary to the established literature. However a closer examination of the DNR findings, and a detailed scrutiny of the literature, gives rise to an interpretation that the study’s results and the existing literature are not inconsistent with one another.

The primary literature on seismic exploration impacts to tundra stems from a series of articles originating out of a set of long term studies conducted by the U.S. Fish and Wildlife Service, from 1984-present, on the Coastal Plain of the Arctic National Wildlife Refuge. The federal study identified four levels of disturbance on a scale of 0- None; 1-

low; 2- moderate; and 3- high (Emers et. al. 1995; Felix et. al. 1992; Felix and Raynalds 1989a,b). These investigators defined a level 1, low intensity disturbance as: (1) 0-25% reduction in vegetative ground cover; (2) 0-5% of ground surface with exposed bare mineral soil; and (3) tussocks and hummocks scuffed. The intensities increased accordingly from this level to a level 3, high intensity disturbance defined as: (1) >50% reduction in vegetative cover; (2) >15% of ground with exposed bare mineral soil; and (3) nearly continuous crushing of tussocks and the formation of ruts. Under level 1, low intensity disturbance, the USFWS investigators found no significant difference between control and treatment plot active layer depths in wet graminoid, moist sedge, and tussock tundra types the first year after the seismic activity (Felix et. al. 1992).

It is important to note that in the DNR study, observed disturbance levels in all treatment plots across all treatment types and dates (Coastal Plain and Foothills) did not exceed that which the USFWS study described as a level 1, low intensity damage. Unlike the USFWS study, the DNR investigation found statistically significant changes in depth of active layer and soil moisture associated with treatment type and snow/ground hardness conditions, even though disturbance was limited to the low intensity category. These changes drive the models generated by the DNR study.

As mentioned before, change occurred naturally between 2003 and 2004 in both the active layer depth and soil moisture in wet sedge and tussock tundra types (Table 8). The observed departure from this natural baseline change, attributable to the treatments, was greater in tussock tundra than in wet sedge tundra, in both absolute and relative terms. These findings mirror results reported in the USFWS study. For example, during the first treatment trial, the various vehicle treatment types produced departures from the baseline that were markedly greater in tussock environments than in wet tundra (Table 9 a & b).

Table 8. Natural Baseline Change, 2003 to 2004

Change in Characteristic	Wet Graminoid/Moist Sedge Shrub Tundra	Tussock Tundra
Active Layer Depth (cm)	2.5 cm (0.98 in) deeper	5.6 cm (2.20 in) deeper
Soil Moisture (%)	7% decrease	3.7% increase

(Note: Sedge tundra DAL was 44.6 cm and soil moisture was 83% in 2003; tussock tundra DAL was 19.8 cm and soil moisture was 44% in 2003.)

Table 9a. Change by Treatment, Trial Date One, Tussock/Foothills Tundra.

Characteristic	Tractor	Loader	Challenger	Tucker
Active Layer	7.1 cm (2.80 in) deeper	5.9 cm (2.32 in) deeper	10.0 cm (3.94 in) deeper	4.8 cm (1.90 in) deeper
Soil Moisture	13.7% greater	12.7% greater	14.0% greater	10.7% greater

(Note: 2003 active layer depth was 19.8 cm (7.80 in), 2003 soil moisture was 44%.)

Table 9b. Change by Treatment, Trial Date One, Wet Sedge/Coastal Plain Tundra.

Characteristic	Tractor	Loader	Challenger	Tucker
Active Layer	0.9 cm (0.35 in) deeper	3.5 cm (1.38 in) deeper	0.9 cm (0.35 in) deeper	3.1 cm (1.22 in) deeper
Soil Moisture	6.3% less	11.5% less	8.5% less	8.0% less

(Note: 2003 active layer depth was 44.6 cm (17.56 in), 2003 soil moisture was 83%.)

E. Evaluation of Potential Utility of Other Disturbance Measures

DNR could not create models for change in soil temperature and PAR absorption index because these measurements were not taken in 2003. Equipment was not available to conduct PAR Index measurements, and equipment malfunction invalidated the 2003 soil temperature data. As a result, this study simply discusses the potential utility of these measures in identifying disturbance effects. DNR concludes that further evaluation, study, and monitoring must be conducted before integrating PAR and microtopography into a routine and reliable system for disturbance detection. Soil temperature holds little promise as a useful measure.

DNR did not model changes between microtopography in 2003 and 2004 because there were no measurable changes. Lack of change in microtopography may be the result of a true lack of change, or it may be that the measure is subject to a lag time that exceeds the length of this particular inquiry. Further monitoring should address this question.

1. PAR Absorption Index

This measurement is a ratio based upon the amount of ambient, photosynthetically active radiation striking the ground surface and the amount reflected off the ground (and vegetation). The difference is assumed to be absorbed. PAR Absorption Index is used as a proxy for plant disturbance and replaces the more subjective approaches currently employed by DNR. The Index has no baseline for calibration because the equipment did not become available until 2004. Therefore all treatment cell measurements are compared to the pooled No Treatment measurements that serve as a control.

Several environmental variables significantly influence PAR in the No Treatment cells. Mean gate PAR values are significantly related to both soil moisture ($p<0.0003$) and depth of active layer ($p<0.001$). Thus the more soil moisture and the deeper the active layer, the higher the PAR Index value. Therefore one finds that those treatments whose effects on active layer and soil moisture are most influenced by ground hardness and snow depth probably change PAR values. The relationship of PAR Index to active layer depth and soil moisture may reduce its value as a separate indicator of disturbance in the field.

PAR Index measurements are intended to replace the qualitative and subjective measures previously used to identify disturbance to vegetation on the 0-3 point scale used in earlier studies. This is important because of the high measurement error associated with the qualitative vegetation disturbance approach. Evaluation of the consistency of value assignment to vegetation on the 0-3 scale found error that typically exceeded 15%. Therefore use of this subjective measure may produce misleading results and, because of its numerical scale, may infer a level of precision that is not present. DNR will attempt to refine the potential use of PAR Index for field applications to replace the subjective, qualitative measurements.

2. Soil Temperature

Soil temperature at a 15 cm (5.91 in) depth was highly related to depth of the active layer ($p<0.001$; r sq=0.72). Therefore it is of limited utility, and we recommend it be abandoned as an indicator of disturbance.

3. Microtopography

Change in microtopography carries the potential for utility in controlled experiments; but due to the time, effort, and skill involved, it may be of limited value as a field measure. However it is recommended that the study plots continue to be surveyed for change in order to determine if trends develop later that are not now discernable. DNR did not find any evidence of rutting in any transect in any treatment plot (Appendix G).

4. Variability

DNR investigated the potential effect treatments may have on the variation of active layer depth, soil temperature, soil moisture, and PAR to determine if treatments suppressed or increased variation. No trends in the coefficient of variation were observed among the treatment types, nor treatment types and treatment date. Therefore it is assumed that use of evaluation of variability for a specific measure is not an effective indicator of disturbance.

V. CONCLUSIONS

A. Management Implications

These models do not attempt to infer when a resource manager ought to open the tundra for off-road travel by particular vehicles. Instead the model identifies the change in important abiotic drivers of change in the tundra ecosystem that one may expect as a result of vehicle passage, under varying snow and ground conditions. It is imperative to emphasize that these models only describe what is expected to occur within the study sites. No statistically valid inference can be drawn from the model to describe that which is occurring elsewhere on the tundra. These models merely represent an understanding of processes and relationships that are helpful to understanding interrelationships in the very dynamic tundra environment. Their utility is as an illustrative input, not a precise predictor.

An example of the use of the model for management purposes is included here. Assume that the freeze-up conditions in a future year approximate the conditions that developed over the course of the winter in 2003-2004. If one wishes to predict the change and its departure from natural baseline inter-annual variation that would occur by approving the use of a Challenger, utility of the models readily presents itself.

Assuming conditions were similar to that on October 30, 2003, we input the following variables: Ground Hardness 11; Snow Depth 15 cm (5.91 in); and Snow Slab 0.9 cm (0.35 in); where the previous summer Depth of Active Layer was 40 cm (15.75 in). Now consider the land manager wishes to use a Challenger on a wet sedge plain community type. Running the model, s/he could expect a change in depth of active layer of 3.1 cm (1.22 in) beyond that which would normally occur, absent the vehicle passage.

Now if the manager wished to see what type of change may occur if s/he waited until the conditions changed to those similar to December 4, 2003, the manager would change the inputs. On that date the ground hardness was 74, snow depth was 16 cm (6.30 in), and a snow slab was present with a thickness of 1.6 cm (0.63 in). With these values, we see that the departure from the natural change in depth of active layer would be 0.57 cm (0.22 in). If the manager wished to determine the potential protection that might be realized by waiting, s/he could input the conditions that were found in late December.

Under these conditions (ground hardness of 89, snow depth of 15.5 cm (6.10 in), and a slab thickness of 0 cm (0 in)), we see that the expected departure is 0.56 cm (0.22 in), an insignificant difference. Thus no advantage in environmental protection could be had by delay, waiting for harder ground.

Of course, natural resource management is a splendid blend of art and science, and decisions must never be reduced to a mere quantitative model that removes discretion from field personnel. Therefore the model should be viewed as simply an additional tool, to be taken into consideration when weighing the many values that compete in typical decisions.

B. Recommendations

These models represent a first, important step in bringing quantitative and objective techniques to decision makers, concerning the effects of off-road tundra travel activities. With this information, DNR can better anticipate the degree of disturbance associated with tundra opening decisions.

It is recommended that DNR continue to monitor the modeling study plots on the Coastal Plain and in the Foothills. This information should be utilized to determine if trends, not apparent at this time, manifest themselves on the landscape. Use of the models should adopt an adaptive management strategy, undergoing continual refinement as new information becomes available following rigorous field monitoring. Finally extensive in-field monitoring, as tundra travel activities commence, should accompany any decision utilizing model results to verify prediction accuracy. These monitoring activities should then be used to further adjust and improve the model for subsequent application.

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VII. APPENDICES

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Tundra Travel Research Project:

VALIDATION STUDY
and
MANAGEMENT RECOMMENDATIONS

A Project Prepared for the
Alaska Department of Natural Resources,

Division of Mining, Land and Water

by

Harry R. Bader, Project Consultant

Betula Consulting

EXECUTIVE SUMMARY

In October 2004, the Alaska Department of Natural Resources published a model that used experimental plots to predict changes in important environmental variables caused by winter oil and gas exploration on tundra surface resources. The objectives of this report are to:

5. Validate the study results in real-world conditions;
6. Continue monitoring the experimental plots to determine if degradation or recovery trends change over time;
7. Design a Visual Assessment System to assist staff in making preliminary determinations of disturbance, during summer field inspections of exploration activity; and
8. Make recommendations regarding management standards.

First, observations from this final validation phase of the project indicate that the standard, derived from the model prediction, resulted in preventing significant environmental change as a consequence of overland vehicle travel, pursuant to hydrocarbon exploration under actual working conditions. Indeed based upon the 2005 validation results, it appears the standard may exhibit a conservative bias in favor of environmental protection. This conservative bias in the results is consistent with the

“precautionary principle”, which is an appropriate strategy for decision making in the context of arctic management.

Second, no delayed effects, nor trends toward increasing disturbance intensity, were observed the second year after treatment on the experimental plots. Indeed the trend seems to be toward a return to the natural range of variation among the key indicator variables used in the study. This would suggest rather robust resiliency at the relatively low levels of disturbance recorded as a result of the experiments.

Third, a quick and efficient tool for visual estimations was successfully developed for use by DNR staff. This system employs 250-meter (820.21 ft) segments of trail, to ascertain disturbance not readily detected by the more quantitative and objective measurement approaches.

Finally the report recommends that prior to approval of overland tundra travel by vehicles, the soil temperature within the first 30 cm (11.81 in) of depth be no warmer than –5 degrees Celsius (23F), a minimum of 15 cm (5.91 in) of snow cover be present in wet sedge tundra environments, and a minimum of 23 cm (9.06 in) of snow cover be present in tussock tundra environments.

Under these conditions, tundra disturbance should be minimal. For those disturbance effects that do transpire, the resiliency of the tundra ecosystem, as indicated by the plot monitoring (as well as reported in the scientific literature), is likely to be such that recovery towards pre-disturbance conditions is expected to be relatively rapid.

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I. INTRODUCTION

This report represents the second and final product of a three-year study, initiated by the Alaska Department of Natural Resources in cooperation with the U.S. Department of Energy, Yale University School of Forestry, and the Alaska Oil and Gas Association. The goal of the overall study was to: (1) identify those environmental factors that contribute toward resistance of tundra systems to disturbance caused by hydrocarbon exploration; (2) generate appropriate management standards, which would promote protection of arctic tundra while allowing exploration activity; and (3) develop monitoring protocols that empower the agency to readily determine if management goals are achieved.

The study designed and implemented the first-ever standardized, controlled scientific field experiments to generate empirical data related to tundra disturbance, following winter overland travel by heavy vehicles. The study is prompted by the impact of changing climate trends on exploration activity. These trends substantially shorten the winter exploration window, during which time the ground is sufficiently frozen and covered with snow to permit travel across the tundra by heavy vehicles used in exploration. A detailed description of the study design and findings is found in the first report, released by the state in November 2004, entitled “Tundra Travel Model Study.” This second report details the validation studies following the initial findings and must, therefore, be read and interpreted in conjunction with the first report[1].

The first report successfully identified those factors that contributed to disturbance resistance, as well as those variables that managers could rely upon to ascertain the existence and intensity of disturbance quickly and at low administrative cost in fiscal, temporal, and personnel resources. This second report follows research validating the initial findings and proposes objective, quantitative standards for both implementation and monitoring of hydrocarbon exploration activity.

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[1] Descriptions of study results, tundra features, technical terms, seismic exploration, disturbance theory, and ecological processes important to this study are contained in the first report and will not be repeated here.

Following the first two years of the study, DNR generated a model (described in the Tundra Travel Modeling Report) that the agency used to predict the ideal set of snow and frozen ground conditions, under which no significant disturbance would be observed if exploration activity were to take place. Because the model was generated pursuant to an empirical study under controlled field conditions, DNR recognized the necessity to validate the results. Therefore during the winter of 2004-2005, these predictions were tested under routine activity, as conducted by geotechnical companies in the normal course of actual seismic exploration. Tundra disturbance was then evaluated to determine the success of the prediction during the summer of 2005. DNR also continued to monitor the original study plots, to determine if new or additional disturbance trends were observed and to modify the model if necessary. Finally DNR developed a standardized system of ocular estimation, for rapid field verification of disturbance, and tested this system against known disturbance patterns in the original study plots, treated in 2003-2004. This report addresses the: (1) field validation study, (2) second year monitoring program, and (3) visual field evaluation system.

II. FIELD VALIDATION STUDY

Prior to formal implementation of management standards created from results produced by the modeling study, it is imperative that the prediction be tested in the field, under the conditions of actual exploration practices. Therefore DNR designed a validation study to test whether exploration activity would induce environmental changes different from those in control plots, where no such activity took place.

Figure 1.
VALIDATION STUDY SITE LOCATION

A. Site Selection

In collaboration with Veritas, a Canada based seismic exploration company, DNR selected a winter validation study site. The site is located approximately 17.70 km (11 mi) south and 14.48 km (9 mi) west of the Deadhorse, Alaska airport (Figure 1). The site was selected on the basis of five criteria: (1) scheduled for exploration in the winter of 2004-2005; (2) relatively close proximity to the Dalton highway, permitting DNR personnel to utilize snow machines to access the sites, without undue danger to staff safety in midwinter; (3) sufficient topographic variability to generate vegetation diversity, in addition to the ubiquitous wet sedge tundra so characteristic of the Coastal Plain; (4) proximity to ground temperature monitoring stations established by the University of Alaska; and (5) free of prior disturbance. These criteria were satisfied at the selected site. Maximum distance from the road, to be traveled by snow machine, was 24.14 km (15 mi) in midwinter; the area was scheduled for exploration during the first week of January; the site contained areas of tussocks and moist sedge shrub tundra, as well as the dominant community of wet sedge meadow; and no visual evidence of “green trails” was present in a preliminary over-flight the previous autumn.

The validation study site is characteristic arctic Coastal Plain. Winters are cold and precipitation low (most of which is contributed as snow); and summers are cool and cloudy. Considerable standing water is present in the nearly level terrain, particularly in areas of patterned ground, including the margins of high center polygons and the middle of low center polygons. Frost boils, patterned ground, and hummocks are found within the site and were traversed by the study transects. The study site is frequently grazed by caribou in summer and occasionally by musk ox in winter.

B. Transect Location

Seismic exploration can cover well over 2589.99 sq. km (1000 sq. mi) of territory in very remote locations and require significant logistical support, under conditions regarded as a trade secret to be kept from rival companies. Consequently DNR entered into a confidential agreement with Veritas to receive 1000 “intersection point” GPS coordinates.

An intersection point is that location where both a “receiver line” and a “source line” meet. These points must be accurately determined in advance, to within a few centimeters, to ensure the quality of seismic data collected by companies engaged in exploration.

Seismic exploration involves the use of very large and heavy equipment traveling across the tundra. Vibrators are track vehicles, which contain a pedestal that vibrates at high rpm against the ground, generating an echo that travels through the ground and bounces off various geological formations before returning to the surface. Thus the vibrator vehicles create the “source lines.” Vibrators create a shockwave, traveling through the earth much like a sonar wave through the ocean.

Receiver lines consist of many miles of geophones (microphones) that are laid upon the ground by lighter track vehicles and later recovered. These receiver lines feed into mobile laboratories. The laboratories are situated on large sleds with skids and pulled by Caterpillar tractors.

All source lines must be parallel to one another, as must the receiver lines. The two sets of lines intersect one another at a prescribed angle, on a standard interval, to create a giant grid pattern. In a typical work season, a seismic operation may create more than 3218.69 km (2,000 mi) of combined source and receiver lines, covering many hundreds of square miles. A typical intersection point will receive a single pass by a vibrator and two passes by vehicles laying out, and then picking back up, the receiver lines. Occasionally the points may also be crossed by crews sent to repair damaged vehicles or to trouble shoot problems with the receiver line.

In addition to the source and receiver lines, seismic exploration involves camp moves. Whole cities of staff are moved, housed, fed, and then work in buildings resting upon sleds that are periodically moved as the process proceeds in inchworm fashion across the arctic tundra. Camp move trails typically involve less than 193.12 km (120 mi) of trail.

Because the grid created by the combined source and receiver lines occurs at a landscape level, potentially affecting hundreds of thousands of acres annually, the DNR study focuses upon impacts associated with these lines as the most likely source of significant and widespread ecological disturbance. Camp move trails, due to their limited length, are ignored in the study. However DNR recognizes that the disturbance associated with camp moves is very likely to be far more intense than that of seismic lines, due to the multiple passes by many sleds, pulled by Caterpillar tractors with steel cleats.

In order to ensure that the seismic operators were unaware of the locations of the transects for the validation study, DNR staff selected 12 intersection points from among the 1000 and established both control and treatment transects. Treatment transects were located in an east-west orientation, with the center of each transect located directly over the intersection point. This ensured that each treatment transect would be traversed by both a source and receiver line. Two control transects were established for each intersection point. Each control transect was oriented in a north-south direction, with the center points approximately 30 meters (98.43 ft) from the intersection point. One control transect was oriented at 135 degrees (southeast) from the intersection and the other at 320 degrees (northwest) from the intersection (Figure 2). All transects were left unmarked, so as not to alert seismic crews of their location. Blowing wind and snow obscured all trace of the measurement work by the time crews came in contact with transects, approximately 24 hours later. This layout of control and treatment intersections was intended to prevent control transects from accidentally being affected by treatments. (It should be noted that this design was successfully tested and used in a DNR precursor pilot study, during the winter of 2002, in a similar area.)

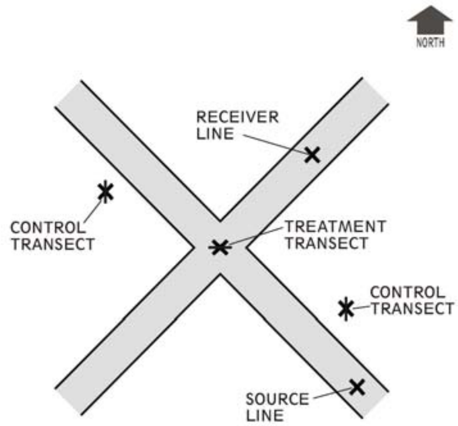

Figure 2.
VALIDATION STUDY
TRANSECT PLACEMENT

C. Measurement Methodology

During the first phase of the study (discussed in the Tundra Travel Modeling Report), DNR evaluated 9 different environmental variables that could be used as indicators of ecological disturbance. The variables found to best serve as key indicators of disturbance were: (1) change in depth of active layer and (2) soil moisture content. These variables seemed to respond most quickly to disturbance stressors; were susceptible to quantitative and objective measurement techniques; and were easy, quick, and inexpensive to measure, thus making them ideal as indicators for management use.

The environmental characteristics found to contribute to disturbance resistance were depth of the overlying snow, hardness of the ground[2], and formation of a snow slab.

[2] DNR later substituted ground temperature along a 30 cm (11.81 in) deep profile for ground hardness in the model. Temperature replaced ground hardness measurements for four reasons: (1) use of temperature instead of ground hardness marginally increased the r-square value of the model; (2) when both temperature and ground hardness were included in the model, ground hardness dropped out as a significant input variable, while soil profile temperature remained significant; (3) temperature had lower variability than hardness measurements; and (4) temperature is an easier characteristic to collect with superior precision. Soil profile temperatures were collected from a University of Alaska research site located near Deadhorse airport.

Also important was whether the ground traveled across was primarily vegetated with wet sedge meadow tundra or tussock tundra.

The day before seismic crews were scheduled to begin work (December 30, 2004) in the sector containing the study intersection points, DNR staff traveled by snow machine; surveyed the transects; and collected snow depth, snow slab thickness, and ground hardness data. Measurements were taken in strict adherence with the winter measurement protocols outlined in the Tundra Travel Modeling Report.

Two months later, after completion of the seismic survey, DNR staff returned to the site by Haagland track vehicle to re-survey and mark transect locations with metal rods pounded into the frozen ground. DNR made a survey-grade quality relocation, with an accuracy of 3 cm (1.18 in), for each transect. The Haagland represented an additional pass over the intersection points, imposing the potential of greater disturbance than that which would be anticipated under routine exploration operations.

In July of 2005, DNR flew by helicopter to the validation transects. Measurements for depth of active layer and soil moisture were taken at all control and treatment transects, in strict adherence with the summer measurement protocols for these characteristics as described in the Tundra Travel Modeling Report.

D. Modeling Prediction

The DNR study anticipated that a snow cover of 15 cm (5.91 in), and a ground soil temperature of -5 degrees C (23F) throughout a 30 cm (11.81) deep soil profile, would ameliorate the effects of cross- country travel by exploration equipment over sedge dominated tundra. DNR anticipated that disturbance changes as a result of vehicular travel would be indistinguishable from the normal range of interannual variation on undisturbed sites. Under the conditions found during the December 30, 2004 measurements, DNR predicted that the summer 2005 depth of active layer would be 34 cm (13.39 in), soil moisture would be 80 percent, and no significant differences would be detected between the treatment and the control transects.

As previously mentioned in footnote 2, DNR substituted ground temperatures along a 30 cm (11.81 in) deep soil profile for ground hardness readings because such readings contributed superior qualities to the model. As a result, all further modeling and monitoring by DNR will use buried soil temperature measuring devices, which can be read by staff in the field to gauge ground temperatures.

In the period just prior to the zero curtain point (see Tundra Travel Modeling Report), when the latent heat of water is released as soil moisture freezes[3], DNR anticipates that soil temperatures may vary markedly from site to site, depending upon local soil moisture content. The more moisture, the longer the period of zero curtain effect.

Thus, in early winter when soil profile temperatures hover between +1 C (33.8F) and –1 C (30.2F), one would expect considerable variability in soil temperature readings along the profile. This variability would continue until temperatures across the landscape had dropped sufficiently below the zero curtain point. At that time, soil temperatures at a landscape level would be most influenced by local topography and the insulation qualities of differential snow cover, rather than soil moisture content. The decrease in soil profile temperature variability over time, as winter progresses, would be consistent with the decrease in soil hardness variability from early to mid winter, as observed by DNR and reported in a prior study[4].

E. Winter Measurements

At the time of exploration equipment travel over the validation site, DNR found an average snow depth of 19 cm (7.48 in) and a ground temperature of -8 C (17.6F) at the soil surface, -7.5 C (18.5F) at a 15 cm (5.91 in) depth, and -7 C (19.4F) at a 30 cm (11.81 in) depth.

[3] Outcalt, S.I., Nelson, F.E., and Hinkel, K. 1990. Zero curtain effect: heat and mass transfer across an isothermal region in frozen soil. Water Res. Research 26(7) 1509-1516.
Hinkel, K.M., Paetzold, F. Nelson, F.E. and Bockheim, J.G. 2001. Patterns of soil temperature and moisture in the active layer and upper permafrost at Barrow, Alaska. Global and Planetary Change 293-309.

[4] Bader, H.R. and Mark Wishnie. 2002. Internal DNR Report on Slide Hammer Use for Measuring Tundra Resistance to Disturbance. (Unpublished.)

F. Validation Study Analysis and Results/Summer Measurements

DNR found no statistically significant differences (p=0.05) between treatment transects (where vehicles passed over them) and control transects (where no vehicles passed) at the validation site (see Figures 3a and 3b.) Treatment transect depth of active layer was found to be 35.5 cm +/- 3.4 cm at a 95% CI (n=132; Sdev=19 cm) [13.98 in +/- 1.34 in at a 95% CI (n=132; Sdev=7.48 in)]. Treatment transect soil moisture was 82.8% +/- 3.5% at a 95% CI (n=72; Sdev=15%). Control transect depth of active layer was 33.9 cm +/- 1 cm at a 95% CI (n=264; Sdev=8.5 cm) [13.35 in +/- 0.39 in at a 95% CI (n=264; Sdev= 3.35 in)]. Control transect soil moisture was 84.4% +/- 2.6% at a 95% CI (n=144; Sdev=40.4%).

DNR employed a standard two-tailed T-test to compare control and treatment means for depth of active layer and soil moisture. Data were normally distributed, with sufficient similarity in variance to permit this parametric test without data transformation.

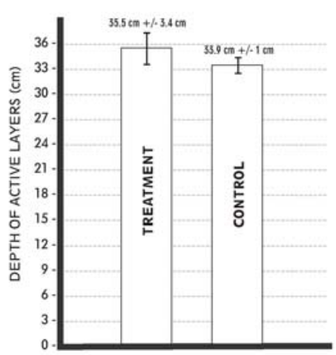

Figure 3a.
VALIDATION STUDY
DEPTH OF ACTIVE LAYER

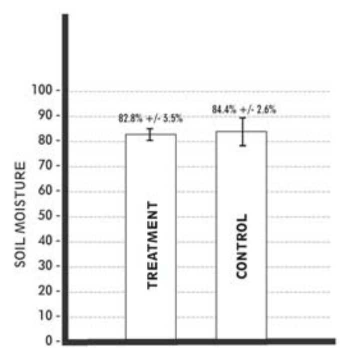

Figure 3b.
VALIDATION STUDY
SOIL MOISTURE AT 15 cm DEPTH

III. POST TREATMENT MONITORING PROGRAM RESULTS

DNR recognizes that ecological disturbances may require a period of time before indicators of change manifest. Therefore DNR has engaged in a long term monitoring program of the original test plots, examining change trends that may indicate unanticipated consequences of the treatments over time. Measurements taken in the summer of 2005 at the experimental plots represent this program thus far. The full suite of characteristics, as identified in the Tundra Travel Modeling Report, were re-measured in 2005.

For the purposes of this study, as explained in the previous report, disturbance is defined as a change in baseline, which exceeds that observed for natural interannual variation for each of the measured characteristics. Thus the technique used by DNR to find disturbance is comparison of the change in No Treatment plots, from 2003 to 2005, to changes observed between 2003 and 2005 in the Treatment plots. For example if change in a No Treatment plot for depth of active layer is 3 cm (1.18 in), it is compared to the change for each treatment type and test period between 2003 and 2005. If a Treatment plot recorded a change of 7 cm (2.76 in), a test is performed to determine if the difference in baseline change between Treatment plot and No Treatment plot is statistically significant or not.

DNR found, in the Tundra Travel Modeling Report, statistically significant changes in soil moisture and depth of active layer in those plots with vehicle treatment type as tractor, when ground profile temperatures were warmer than -5 degrees C (23F) and snow depth was less than 15 cm (5.91 in) in the wet sedge tundra and less than 23 cm (9.06 in) in tussock tundra. The 2005 monitoring measurements found resiliency in these same plots, with the difference in change between Treatment and No Treatment plots converging (see Tables 1 and 2).

Sedge tundra no longer exhibited statistically significant differences in change from baseline between Treatment and No Treatment plots. Statistically significant differences for change in both depth of active layer and soil moisture were present in the tussock tundra tractor plots of the Foothills.

However the actual and relative differences in depth of active layer between Treatment and No Treatment plots located in tussock tundra on the Foothills study site in 2005 declined from that found in 2004 (see Table 2). The difference in change in soil moisture between Treatment and No Treatment, while greater in 2005, trended toward a drier condition. This trend toward drier conditions is less problematic to managers than the reverse, from an ecological disturbance perspective. The scientific literature identifies greater soil moisture as a condition that exacerbates thermal erosion because of water's ability to absorb energy and transport it efficiently through the soil profile. Thus the change from a wetter condition the first year following treatment, to a slightly drier condition in 2005, indicates a trend that seems to alleviate the fear of accelerated disturbance intensity. (See Tundra Travel Modeling Report for details from the published literature and a more complete explanation of tundra disturbance.) Continued monitoring of these plots is warranted, in light of the inconclusive results regarding soil moisture change in the Foothills tussock terrain.

Table 1. Disturbance Characteristics, 2003 to 2005, for Selected Plots

Location	Characteristic	Treatment Type/Date	Year 2003	Year 2005	Change from 2003 to 2005	Difference from No Treatment
Coastal Plain	Depth of Active Layer	No Treatment	44.6 cm (17.56 in)	47.5 cm (18.70 in)	-2.9 cm (-1.14 in)	N/A
Coastal Plain	Depth of Active Layer	Tractor/1	56.3 cm (22.17 in)	55.7 cm (22.93 in)	-2.1 cm (-0.83 in)	0.8 cm (0.31 in)
Coastal Plain	Soil Moisture	No Treatment	83 %	74.6 %	-8.4%	N/A
Coastal Plain	Soil Moisture	Tractor/1	81 %	72.6 %	-8.4%	0 %
Foothills	Depth of Active Layer	No Treatment	17.2 cm (6.77 in)	20.5 cm (8.07 in)	-3.3 cm (-1.30 in)	N/A
Foothills	Depth of Active Layer	Tractor/1	17.4 cm (6.85 in)	25.4 cm (10.00 in)	-8.0 cm (3.15 in)	4.7 cm* (1.85 in)
Foothills	Soil Moisture	No Treatment	50.2 %	34.6%	-15.6%	N/A
Foothills	Soil Moisture	Tractor/1	56.0%	32.2%	-23.8%	8.2%*

NOTE: * denotes a statistically significant departure from natural baseline change.

Table 2. Treatment Plot Departure from Natural Change by Year and Location

Location	Treatment Type & Date	Departure from Natural Change in 2004	Departure from Natural Change in 2005
Coastal Plain- Depth of Active Layer	Tractor (1)	2.5 cm (0.98 in) deeper	0.8 cm (0.31 in) shallower
Coastal Plain- Soil Moisture	Tractor (1)	7% lower	0% difference
Foothills- Depth of Active Layer	Tractor (1)	5.6 cm (2.20 in) deeper	4.7 cm (1.85 in) deeper*
Foothills- Soil Moisture	Tractor (1)	3.7% higher	8.2 % lower*

NOTE: * indicates statistically significant departure from natural baseline change

Based upon these findings, DNR is confident that no new manifestations of disturbance type or trend have developed on the study plots. Therefore DNR does not anticipate new disturbance indicators. However DNR shall continue to take monitoring measurements, in accordance with the established long term program.

IV. VISUAL ASSESSMENT SYSTEM

Objective and quantitative field measurements are essential to confirm disturbance type and intensity for effective management. However these approaches are both labor intensive and expensive, as well as logistically difficult. To first determine if the investment in field measurement is warranted, a system of quick, inexpensive, and easy disturbance evaluation is needed. Accordingly DNR tested a number of quick ocular estimate techniques that could be used to identify and characterize disturbance levels.

DNR field personnel working on the study in 2004 and 2005 noticed that visual changes were present in test plots but were not necessarily manifested within the transects. To determine if ocular estimations could be reliably used as an additional tool to describe disturbance, DNR embarked upon development of procedures to use as a standardized approach for visual disturbance evaluation. This system of visual assessment is not intended to determine changes of ecological consequence; rather the visual assessment is intended to augment the more labor intensive, science based measurements described above. Such an approach may be most useful for quickly evaluating a large area.

The DNR Visual Assessment System is based in part upon the pioneering research of the U.S. Fish and Wildlife Service (USFWS) in the Arctic National Wildlife Refuge[5]. The USFWS system uses a three-tiered approach, characterizing disturbance as high, moderate, and low, based upon damage to surface vegetation and the soil surface. (The USFWS system is described in detail in the Tundra Travel Modeling Report and will not be repeated here.)

As mentioned in the previous report, the maximum disturbance level produced by the DNR field tests during the winter of 2003-2004 did not exceed that which the USFWS

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[5] Emers, M., Jorgenson, J.C. 1995. Response of arctic tundra plant communities to winter vehicle disturbance. Can. J. Bot. 73:905-917;
Felix, N.A., Raynolds, M.K., Jorgenson, J.C. and Dubois, K.E. 1992. Resistance and resilience of tundra plant communities to disturbance by winter seismic vehicles. Arct. and Alp. Res. 24:69-77.

system would characterize as low. However even this low level of disturbance (which occurred in plots traveled by either tractor or Challenger, under conditions where soil temperatures were warmer than -5 degrees C [23F] and snow cover was less than 15 cm [5.91 in]) exceeds that which DNR stewardship finds acceptable. Consequently the DNR Visual Assessment System was applied to plots where statistically significant disturbance, or USFWS-defined low level disturbance, was observed. Under DNR management, the threshold of permissible disturbance is set below this statistically significant, low level disturbance. Such an approach is consistent with the precautionary principle, which is an appropriate management approach for land stewardship in the somewhat fragile arctic environment.

The DNR Visual Assessment System grew out of modifications to techniques studied during the 2005 summer field season. It employs a qualitative and subjective approach of ocular estimation that ranks vegetation and soil disturbance as a percent of total surface disruption, per unit length of seismic trail. The unit of trail length is approximately 250 meters (820.21 ft) long (derived from the average length of each figure-8 in the Treatment plots). Two disturbance characteristics are used: (1) vegetation damage and (2) presence of surface displacement or depression, also called rutting. Vegetation damage is defined as any visible, mechanical alteration of vegetation anatomy, such as broken or abraded branches of shrubs and scuffed or crushed tussocks. Soil surface displacement is defined as any visually discernable depression or displacement of soil, giving rise to a definable track. It must be noted that green trails (as discussed in the Tundra Travel Modeling Report) are not considered disturbance using this technique.

Each linear meter (3.28 ft) of the 250 meter (820.21 ft) length of trail is tallied separately, to determine if either vegetation or soil surface disturbance is present. The total number of meters for each disturbance variable is then summed separately, and the percent of trail with vegetation disturbance and the percent of trail with soil surface disturbance is determined.

A rank of 1, 2, or 3 is assigned to describe each disturbance characteristic (see Table 3), based upon the percent of trail altered. Once the observer has assigned a rank for each disturbance characteristic, the two numbers are multiplied together because it is assumed that these two characteristics interact with one another, giving rise to a change in environment greater than the change each would effect individually. Thus a rating system of 1-9 is created.

Table 3. Assessment Score

Rank Score	Percent Trail Surface with Vegetation Damage	Percent Trail Surface with Soil Displacement
1	0-2	0-2
2	3-4	3-4
3	5 or greater	5 or greater

Each plot on the Foothills treatment study site was then ranked independently by three different DNR staff [6]. The DNR staff responsible for assigning rank values were not informed as to the treatment type or treatment date of each plot, so as to avoid anticipatory bias in the assignment of values.

After values were assigned, the rank scores were compared among the staff to determine consistency. Congruency among the three staff rankings was exceptional. All three staff assigned exactly the same values to 26 of 30 plots, with the remaining plots receiving identical values by two of the three staff. In addition the ranking system was consistent with overall disturbance values found on the plots, as would be expected from the treatment type and treatment date (Table 4).

[6] The Foothills study site was selected because it had the most easily identifiable disturbance patterns, but visual assessment could also be employed on the Coastal Plain.

Table 4. Rapid Assessment Rank Scores by Treatment Type and Date

Treatment Date	Tractor	Challenger	Loader	Tucker	No Vehicle Treatment
Oct 30	9	9	3	1	1
Nov 14	9	6	1	1	1
Dec 3	6	4	1	1	1
Dec 16	4	3	1	1	1
Jan 5	3	3	1	1	1
Jan 20	2	1	1	1	1

The congruency of the rankings among different staff, coupled with the consistency of the ranking system results with plot disturbance measurements, suggests that this technique may prove a useful tool in the field, as a preliminary approach for quick evaluations to determine if intensive field measurements are warranted. If quantitative field measurements are deemed necessary, DNR can implement monitoring protocols similar in methodology to the summer measurements taken for the validation study.

Because no distinction is made between severe or low level disturbance for each characteristic in a particular meter of trail length, a conservative bias resulting in over-estimating disturbance is built into the Visual Assessment System. Again this approach is consistent with the precautionary principle and is appropriate for management of fragile, little-understood environments.

V. CONCLUSIONS AND RECOMMENDATIONS

The 2004-2005 season follow-up study appears to validate the prediction that employing a standard, based upon a minimum snow cover of 15 cm (5.91 in), and a 30 cm (11.81 in) deep soil profile temperature of -5 degrees C (23F) or colder[7], is sufficient to ameliorate ecological disturbance in wet sedge tundra environments. Ecological disturbance is defined for purposes of the validation study as a departure from natural baseline change, determined through two key indicators. The indicators used are: (1) change in depth of active layer and (2) change in soil moisture.

While not specifically tested, the prediction that 23 cm (9.06 in) of snow is sufficient to protect tussock dominated tundra from disturbance seems reasonable, given the observations in the Foothills study plots, tussock disturbance measured in the validation study, and information contained in the scientific literature.

Therefore it is the recommendation of this study that DNR:

(1) implement the 15 cm (5.91 in) snow cover/-5 degree C (23F) or colder 30 cm (11.81 in) deep ground profile temperature standard for sedge tundra;

(2) implement a 23 cm (9.06 in) snow cover/-5 degree C (23F) or colder 30 cm (11.81 in) ground profile temperature standard for tussock tundra;

(3) continue long term monitoring of the Coastal Plain and Foothills study sites to evaluate if new disturbance trends or types become apparent;

(4) monitor field observations to ensure that actual results continue to remain consistent with anticipated results;

(5) adopt the Visual Assessment System for initial field verification of seismic line disturbance; and

(6) discontinue use of the slide hammer in favor of temperature arrays to ascertain appropriate ground conditions for tundra travel (i.e. adopt the objective –5 Celsius (23F) standard and forego the more subjective “ground hardness” estimate associated with use of the slide hammer).

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[7] The temperature should be at least –5 degrees C (23F) throughout the entire 30 cm (11.81 in) depth of the soil profile. DNR uses three temperature sensors, arranged at depths of 10 cm (3.94), 20 cm (7.87 in), and 30 cm (11.81 in), to get the total profile temperature. Each sensor at the three depths for each profile must read –5 C (23F) or colder to meet this condition.

Company Names and Logos -- Except as indicated above, company names, logos, or similar material should not be incorporated into reports.

Copyrighted Material -- Copyrighted material should not be submitted as part of a report unless written authorization to use such material is received from the copyright owner and is submitted to DOE with the report.

Measurement Units -- All reports to be delivered under this instrument shall use the SI Metric System of Units as the primary units of measure. When reporting units in all reports, primary SI units shall be followed by their U.S. Customary Equivalents in parentheses ( ).

The Recipient shall insert the text of this clause, including this paragraph, in all subcontracts under this award.

Note: SI is an abbreviation for "Le Systeme International d'Unites."

APPENDIX A: TUNDRA OPENING AND CLOSING DATES FOR TUNDRA TRAVEL

OPEN	CLOSE
13-Nov-69	21-May-70
20-Oct-70	27-May-71
1-Nov-71	20-May-72
1-Nov-72	4-Jun-73
15-Nov-73	20-May-74
18-Nov-74	30-May-75
1-Nov-75	28-May-76
Unknown-1976	29-May-77
25-Nov-77	3-Jun-78
4-Nov-78	8-May-79
Unknown-1979	20-May-80
7-Nov-80	9-May-81
11-Nov-81	22-May-82
4-Nov-82	29-Apr-83
15-Nov-83	18-May-84
5-Jan-85	20-May-85
4-Dec-85	4-Jun-86
7-Nov-86	20-May-87
13-Dec-87	3-May-88
16-Nov-88	29-May-89
11-Jan-90	14-May-90
19-Nov-90	19-May-91
27-Nov-91	12-May-92
21-Nov-92	17-May-93
6-Dec-93	20-May-94
8-Dec-94	29-Apr-95
4-Dec-95	10-May-96
6-Jan-97	9-May-97
7-Jan-98	21-Apr-98

OPEN	CLOSE
14-Jan-99	12-May-99
20-Dec-99	11-May-00
10-Jan-01	14-May-01
25-Jan-02	8-May-02
20-Jan-03 - West Coastal	9-May-03 - Upper Foothills
20-Jan-03 - Lower Foothills	9-May-03 - Lower Foothills
27-Jan-03 - General Opening	19-May-03 - General Closure
23-Dec-03 - Eastern Coastal	5-May-04- Upper Foothills
9-Jan-04 - Western Coastal	13-May-04- General Closure
28-Jan-04 - L & U Foothills	

APPENDIX B

TREATMENT CELL BY DATE AND TREATMENT TYPE- TUSSOCK/FOOTHILLS

PLOT DESIGNATOR	TREATMENT DATE	TREATMENT TYPE
A1	3 December 4, 2003	TUCKER
A2	1 October 30, 2003	TRACTOR
A3	2 November 14, 2003	LOADER
A4	3 December 4, 2003	NO TREATMENT
A5	5 January 5, 2004	NO TREATMENT
B1	2 November 14, 2003	TUCKER
B2	3 December 4, 2003	CHALLENGER
B3	3 December 4, 2003	LOADER
B4	4 December 16, 2003	NO TREATMENT
B5	4 December 16, 2003	TRACTOR
C1	2 November 14, 2003	NO TREATMENT
C2	3 December 4, 2003	TRACTOR
C3	1 October 30, 2003	NO TREATMENT
C4	6 January 20, 2004	TRACTOR
C5	2 November 14, 2003	TRACTOR
D1	6 January 20, 2004	TUCKER
D2	5 January 5, 2004	TRACTOR
D3	1 October 30, 2003	LOADER
D4	5 January 5, 2004	CHALLENGER
D5	1 October 30, 2003	TUCKER
E1	2 November 14, 2003	CHALLENGER
E2	1 October 30, 2003	CHALLENGER
E3	4 December 16, 2003	CHALLENGER
E4	5 January 5, 2004	LOADER
E5	4 December 16, 2003	LOADER
F1	5 January 5, 2004	TUCKER
F2	6 January 20, 2004	LOADER
F3	6 January 20, 2004	CHALLENGER
F4	4 December 16, 2003	TUCKER
F5	6 January 20, 2004	NO TREATMENT

TREATMENT CELL BY DATE AND TYPE WET SEDGE/COASTAL PLAIN

G1	1 October 30, 2003	TRACTOR
G2	1 October 30, 2003	LOADER
G3	4 December 16, 2003	LOADER
G4	3 December 4, 2003	TUCKER
G5	5 January 5, 2004	TRACTOR
H1	4 December 16, 2003	NO TREATMENT
H2	6 January 20, 2004	NO TREATMENT
H3	3 December 4, 2003	NO TREATMENT
H4	5 January 5, 2004	TUCKER
H5	2 November 14, 2003	LOADER
I1	5 January 5, 2004	CHALLENGER
I2	1 October 30, 2003	TUCKER
I3	3 December 4, 2003	TRACTOR
I4	4 December 16, 2003	TUCKER
I5	1 October 30, 2003	CHALLENGER
J1	6 January 20, 2004	LOADER
J2	2 November 14, 2003	NO TREATMENT
J3	1 October 30, 2003	NO TREATMENT
J4	6 January 20, 2004	TRACTOR
J5	4 December 16, 2003	TRACTOR
K1	5 January 5, 2004	LOADER
K2	6 January 20, 2004	CHALLENGER
K3	3 December 4, 2003	CHALLENGER
L1	4 December 16, 2003	CHALLENGER
L2	3 December 4, 2003	LOADER
L3	2 November 14, 2003	CHALLENGER
M1	2 November 14, 2003	TUCKER
N1	2 November 14, 2003	TRACTOR
O1	5 January 5, 2004	NO TREATMENT
O2	6 January 20, 2004	TUCKER

APPENDIX C: Plants Found by Releve Assessment within Study Areas

TUSSOCK TUNDRA-FOOTHILLS STUDY SITE

Vascular Species
Arctagrostis latifolia
Betula glandulosa
Betula nana
Cassiope tetragona
Carex aquatilis
Carex biglowii
Dryas integrifolia
Empetrum nigrum
Epilobium latifolium
Eriophorum angustifolium
Eriophorum vaginatum
Ledum paustre
Minuartia arctica
Oxytropus maydelliana
Parrya nudicaulis
Polygonum bistorta
Polygonum viviparum
Potentilla uniflora
Rubus chamaemorus
Salix phlebophylla
Salix reticulate
Salix rotundifolia
Saxifraga hirculus
Saxifraga foliosa
Saxifraga oppositifolia
Silena acualis
Vaccinium vitis-idaea

Bryophytes
Dicranum spp.
Distichium capilaceum
Hypnum spp.
Sphagnum spp.
Tomenthypnum nitens

Lichens
Alectoria nigricans
Cetraria islandica
Cetraria aculeata
Dactylina arcitca
Ochrolechia frigida
Thamnolia vermicularis

WET/MOIST SEDGE TUNDRA- COASTAL PLAIN

Vascular Species
Carex acquatilis
Carex scirpoidea
Equisetum variegatum
Eriophorum angustifolium
Eriophorum vaginatum
Juncus biglumis
Pedicularis sudetica
Salix arctica

Bryophytes
Aulacomnium turgidum
Aulacomnium palustre
Bryum spp.
Campylium stellatum
Dicranum spp.
Distichium capillaceum
Ditrichum flixicaule
Drepanocladus spp.
Hylocomium splendens
Scorpidium scorpoides
Spaghnum spp.

Lichen
None found in wet sedge plots

APPENDIX D:

History of the Alaska Department of Natural Resources, Tundra Travel Management 1969 -2003

Alaska Department of Natural Resources,
Division of Mining Land & Water *
Northern Regional Office

Prepared by

Patricia Bradwell
Alison Macalady
Sherri Wall

October 2004

(It is acknowledged that the Division has undergone several name changes over the years and is referred to generically throughout this report as DMLW)

About the Authors

Patricia Bradwell is currently a second-year law student at the University of Oregon School of Law and a fellow at the Wayne Morse Center for Law and Politics.

Alison Macalady is pursuing a Master's Degree in Environmental Science at Yale University, School of Forestry and Environmental Studies.

Sherri Wall is an Interdisciplinary Economic Ph.D. student at the University of Alaska Fairbanks in the Resilience and Adaptation Program funded by the National Science Foundation

Executive Summary

Since the late 1960's, the Alaska Department of Natural Resources – Division of Mining, Land and Water (DMLW), Northern Region Office has managed off-road travel related to oil and gas development on the state lands of the arctic North Slope. Since this time, off-road travel has been limited largely to winter, with decisions made yearly by DMLW staff as to when conditions warrant a general work-season opening. Opening decisions have been based on determinations about the presence of adequate ground frost/hardness and snow cover to limit disturbance to the tundra.

Under DMLW's management, the length of the winter season has declined from an average of 200 days in the 1970s to less than 120 days over the past five years. This shortening work window has become the center of a debate about management protocols at the DMLW, access to the tundra for oil and gas development, and the effects of climate change on the arctic environment. To provide a background for future DNR decisions about managing access to the tundra, this report documents the history of DMLW oversight of off-road tundra travel and analyzes the evolution of DMLW management decisions. The main findings of this report are outlined below:

- The methods employed by DMLW in making the decision to open and close the tundra have evolved substantially between the 1970s and 2004. While variants of a "12-and-6" standard (12 inches of hard ground/frost and 6 inches of snow) for determining when to open the tundra to off-road travel have influenced DMLW tundra management since the early 1970's, the methods used to measure ground frost/hardness and snow depth have changed. Specifically, DMLW has changed the tools, locations, and protocols for determining the 12-and-6 standard.

- Although many have cited the shrinking tundra work season as evidence of climate change, it's important to recognize that the collapse of the tundra travel season is likely a result of a number of factors, including both climate change and management change. While both the shortening winter work season and climate and tundra active layer data collected by researchers in the Alaskan arctic exhibit a downward trend, the variety of methods used over the years by DMLW to measure the hardness of the tundra makes it difficult to conclude exactly what portion of the shrinking season is due to climate change, and what portion is due to changes in DMLW measuring techniques.

- The evolution of DMLW decision-making is not well documented, and appears largely directed by professional judgment. The application of repeatable experiments and systematic observation of results has been weak. However, documentation, systematic protocols for data collection, scientifically driven monitoring approaches, and the utilization of outside scientific expertise have improved considerably in recent years.

- The protection-level provided to tundra vegetation by the DMLW is thought to be conservative, but evidence is largely anecdotal. There is little baseline information and spotty monitoring data on state lands to verify this conclusion. The most comprehensive studies to evaluate the impacts of oil and gas related travel across the tundra were done on federal lands in the 1980's, and indicate significant impacts to vegetation but generally high rates of recovery and resiliency. Spatial and ecological variability substantially influence the degree of initial impact and recovery, with tussock and shrub-dominated vegetation more prone to significant disturbance.

Introduction

For nearly 35 years, seismic exploration and the drilling of test wells on the tundra has been largely limited to winter, when the tundra's surface is deemed sufficiently hard and snow cover adequate to provide a level of protection to tundra vegetation and the thermal stability of the underlying permafrost. But during the last three decades, the length of this season has dwindled from an average of about 200 days in the 1970s to about 120 days over the last 5 years (see Figure 1). While it is unclear how much of this dramatic trend is attributable to climate change and how much to changes in management protocols over the timeframe, the shrinking season highlights future challenges of managing oil and gas development in a warming arctic environment.

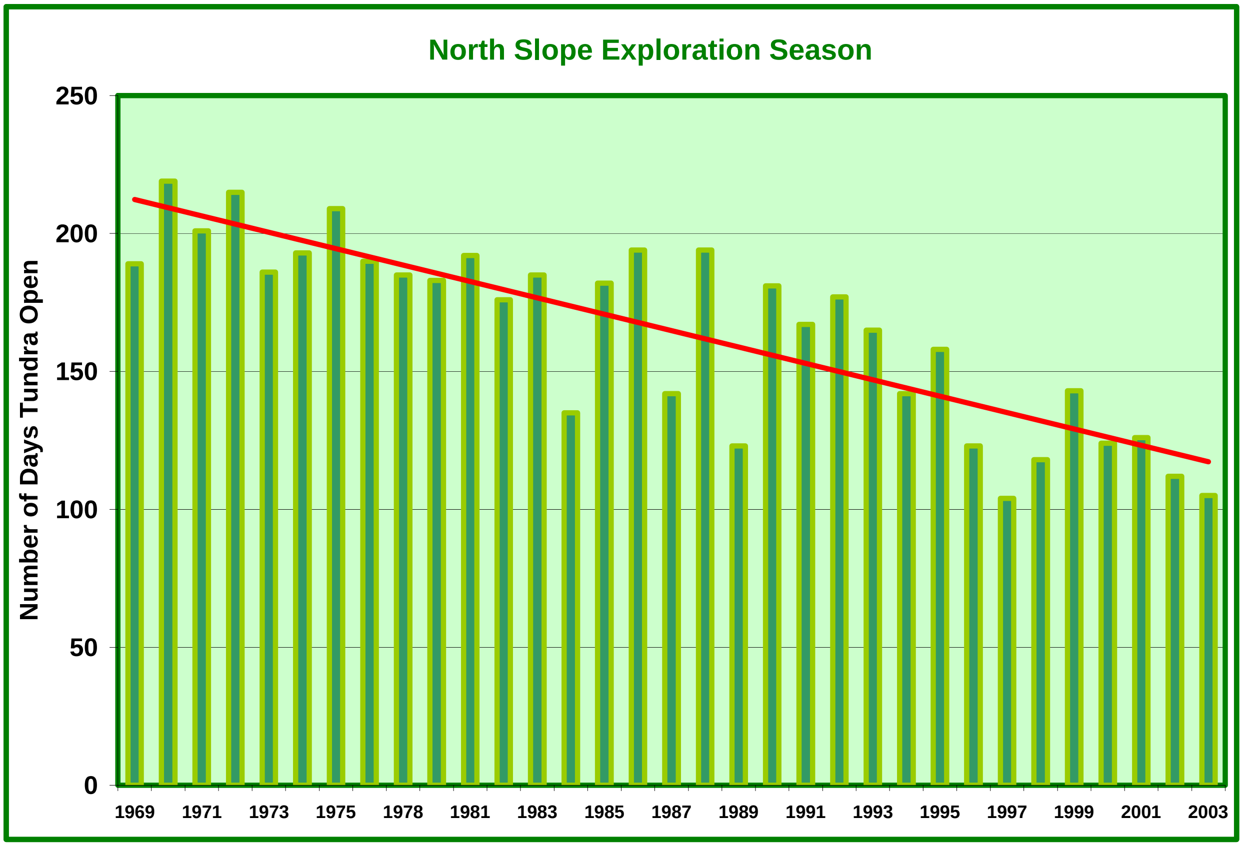

Figure 1- Length of the winter tundra travel season, as determined by the DNR-Division of Lands, Northern Regional Office

As the primary agency that manages the surface estate of Alaska's public lands, the Alaska Department of Natural Resources - Division Mining, Land and Water, Northern Region Office (DMLW) is responsible for managing many of the impacts associated with oil and gas exploration outside lease tracts on the North Slope. One part of this management is deciding when to open the tundra to off-road travel.[1]

[1] DNR Commissioner to DNR Division Directors, memorandum, 27 November 2000, *Department Order North Slope Management*, (Anchorage, 2000).

In an effort to improve future management of the tundra, this report aims to document the history of the Department of Natural Resources' management of off-road tundra travel since the late 1960s, and to discuss some of the related scientific, economic, land management and institutional issues the recent trends have brought into focus.

This report is divided into two broad sections:

1) History of tundra travel management.

2) An analysis of tundra travel policy.

Research Objectives and Methods

One of primary challenges in compiling a history of DMLW's management of the tundra is the lack of a written record of the agency's decision-making process. While DMLW has been grappling with environmental issues related to oil exploration and development since its formation in DNR, the high degree of attention given to the impact of off-road tundra travel and the length of the oil exploration season is a relatively recent phenomenon.[2] For much of the agency's history, decisions regarding when to open the tundra to off-road travel have been left to the discretion of DMLW land managers who often left little record of the rationale behind their decisions. Another potential reason for the lack of documentation of the methods used to determine the opening of tundra travel season has to do with changing perceptions of the tundra itself. Over the years, perception of the tundra within the Department of Natural Resources has changed from that of a vast, barren wasteland to that of a complex, and potentially fragile ecosystem.

Perhaps the best explanation for the lack of documentation, however, is that prior to the 1990's, the length of the tundra travel season on the North Slope was simply not a matter of controversy. There are two likely reasons for this. 1) The season was sufficiently long to allow oil companies to implement their exploration and development programs, many of which were proximal to permanent infrastructure.[3] In recent years, in contrast, exploration activities have extended farther east, away from the early development near Prudhoe Bay, giving oil companies less time to cover greater distances;[4] 2) Climate change and variability has become an issue of great concern in Alaska and across the country. These two factors have increased pressure from the oil industry to extend the oil exploration season and increased public concern over the environmental impact of tundra travel.

To address the challenge of documenting the largely anecdotal history of DMLW's tundra management, we have conducted a series of interviews with past DMLW land managers, members of DMLW's North Slope operations team, oil industry engineers, and decision-makers from a variety of state and federal agencies who have been involved with issues surrounding transportation on the tundra. When available, internal memos, formal and informal study

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[2] Id.
[3] Northern Regional Land Manager to DNR Deputy Director, memorandum, 7 April 2003, *Winter off-road travel season and other factors that affect oil exploration*, (Fairbanks, 2000).
[4] Id.

reports, field notes, policy papers and letters provide the written documentation for the history and the analysis of past DMLW decision-making. Sources are cited as internal footnotes, and in the case of material from the scientific literature, footnotes refer to references in the *Sources and References* section at the end of the report.

<u>The evolution of DMLW's management of off-road tundra travel</u>

Summary

The "12-and-6" standard – 12 inches of hard ground or ground frost and 6 inches of snow – currently employed in making the decision to open the tundra is a source of controversy on the North Slope. Variants of the 12-and-6 standard have influenced DNR tundra management in some form or another since the early 1970's. However, the methods used to measure the 12-and-6 standard have varied considerably over the decades, and contrary to popular conception, ground frost/hardness was not directly measured by the DMLW until 1985. Until this point, air temperature on the Coastal Plain and snow depths were the main determinant for opening the tundra. Prior to the mid-1990's, ground frost was measured as a threshold depth at which a steel rod broke through frozen soil and into melted permafrost.

Since at least 1991, DMLW has interpreted the phrase "adequate ground frost and snow cover" - the language contained in the Alaska Coastal Management Program's General Concurrence-19, internal DMLW guidelines and land use permits - to mean more strictly an average of 12 inches of hard ground or frost (depending on the time-period) and about 6 inches of snow at testing sites (today, this means 30 sampling sites along a geographically diverse transect). Starting in 1993, field measurements of ground frost and ground hardness were made on an inch-by-inch basis, although they were not recorded consistently until 1998. In 1995, a new testing rod – a slide hammer penetrometer, was created and began to be employed by field staff to measure both frost depth and ground hardness over a 12 inch profile (hardness in the units of "hits per inch"). Since 1998, methods of using the slide hammer penetrometer have become more standardized, data recording more systematic, and rationale behind decision-making more transparent.

Today, DMLW announces separate tundra openings in 4 different management units, based on an assessment of the hardness of the ground to 12 inches (in "drops per inch" of a standard weight from a standard height), snow cover, and snow type. DMLW has exercised the right to open certain areas early (such as road corridors in which the snow has been "pre-packed" by industry to quicken freeze-up of the tundra below), to allow certain light-weight vehicles early access to the tundra, and to close other areas of the tundra as needed to protect tundra vegetation. DMLW staff also monitors the impacts of the season's work through field checks in the winter and spring, and requires rehabilitation of areas where damage was not prevented.

Introduction

The DMLW is today responsible for issuing land use permits, which are required for most off-road travel on the North Slope. For all oil and gas-related work (with the exception of work with light-weight, DMLW-approved vehicles), off-road travel is limited to the winter, and in each land use permit, the DMLW exercises the right to determine the opening and closing of this winter work season in order to limit damage to the tundra surface.

Figure 3 - Right, 1959 D-8 Caterpillar; left, tracks left by a summer cat-train near Prudhoe Bay.

The following sections document the evolution of DNR and DMLW oversight and decision-making regarding off-road tundra travel and the length of the travel season. Because the season has shortened asymmetrically, with more days lost on the front end of the season than in spring (an average of 85 days later in winter and 15 days earlier in spring since the 1970's), this document is slanted somewhat toward the history of DMLW tundra opening protocols.

As will become clear in the sections that follow, the methodology used to open and close the tundra to winter travel has evolved considerably since the 1970s. Because it is the source of some of the controversy regarding tundra-opening decisions, the history section begins with a description of the origin of the 12-and-6 standard.

Origin of the 12-and-6 standard

The 12-6 standard was first developed by Dr. Max Brewer, an arctic geologist, engineer and permafrost expert, who was a leading scientific figure in Alaska throughout the l960s and 1970s.[5] Brewer is probably best known for his work with the Naval Arctic Research Laboratory (NARL) in Barrow, where he served as director from 1956 to 1971. During the two decades that Brewer served as director, the agency's focus expanded from mostly biological studies to include the physical sciences, oceanography, atmospheric studies and social sciences.[6]

In addition to his contributions to arctic ecology, Brewer was instrumental in developing engineering techniques used in the Navy's early oil exploration on the North Slope, and later in the construction of the trans-Alaska Pipeline. Brewer developed a standard of "12 inches of frozen ground and 6 inches of snow" while advising the U.S. Geological Survey (USGS) on the construction of roads, airstrips, and drilling pads on permafrost. The guidelines were based upon his professional judgment about the amount of solid ground and snow cover necessary to support the weight of moving vehicles on the tundra and to protect the surface vegetation from damage. During Brewer's work for USGS and NARL, he observed that 12 inches of frozen ground was sufficient to provide a "cement-like" surface, capable of supporting the weight of winter

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[5] Kenai Peninsula Online, *The Voice of the Times supports research on global warming*, April 29, 2002, http://peninsulaclarion.com/stories/050602.shtml
[6] Karen Brewster's interview with Max Brewer, Byrd Polar Research Center Archival Program (2001).

exploration vehicles in the meadows of the Coastal Plain. He also determined, through professional experience, that 6 inches of snow provided adequate protection for tussocks on drier ridges above the Plain, where early snowfall is often blown away by the wind. Brewer explained that, "as an engineer, you always want to design for the worst-case scenario. That's what I did, and it has worked for nearly forty years."[7]

In 1975, Brewer incorporated the 12 inches of frozen ground and 6 inches of snow standard into the environmental impact statement ("EIS") he wrote for the Navy's exploration of Naval Petroleum Reserve No. 4 (now NPRA).[8] Like the guidelines that DMLW uses today, the report does not specify a preferred method for measuring the depth of frozen ground.[9] When asked about how to verify when the standard is met, Brewer stated that he envisioned a variety of possible techniques. "You could dig a hole in the ground and take a temperature reading. You could also measure the ice layer on nearby lakes and streams."[10] However, Brewer suggested that in his opinion, the method of measurement was irrelevant because, "you could almost always hang your hat on November 1st."[11]

These comments are consistent with the language of Brewer's 1975 EIS. Unlike the current DMLW policy requiring 12 inches of hard ground and 6 inches of snow, Brewer's original EIS stipulations provided an explicit estimate of when the off-road travel season was likely to begin.[12] This suggests that Brewer's 12-6 standard was less of a scientific standard as it was a precautionary measure intended to prevent vehicle access to the tundra before mid-October.

It is interesting to note that while Brewer's 1975 EIS estimates that the conditions necessary for off-road tundra travel should be present sometime between October 15 and November 1, there have only been three years since 1969 in which DNR has opened the tundra to off-road travel before November 1.[13] Although the variety of techniques DMLW has used to measure tundra frost and hardness since 1985 makes the correlation between hardness and opening date difficult to unravel, these direct measurements of the tundra illustrate the difficulty in pinpointing a specific date after which the ground conditions will always be adequate to prevent tundra damage.

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[7] Max Brewer, personal communication.

[8] *Stipulations Concerning Winter Seismic and Related Geophysical Operations Within Naval Petroleum Reserve No. 4*, 5 September 1975 (Anchorage, 1975).

[9] DMLW's guidelines for winter cross-country travel state that all vehicle travel is allowed when there is 12 inches of hard ground. The distinction between "frozen" and "hard" ground has become important in recent years. In many instances, DMLW has found that while the ground temperature at 12 inches may be at or below zero, the tundra is still not hard enough to open to prevent damage.

[10] See Supra, note 34

[11] Id.

[12] In the section of the 1975 EIS entitled, Stipulations Concerning Winter Seismic and Related Geophysical Operations within Naval Petroleum Reserve No. 4 states "Seismic survey operations are to begin after the seasonal frost in the tundra and underlying mineral soils has reached a depth of 12 inches; the average snow cover a depth of 6 inches. Normally these conditions will not prevail until about 15 October, occasionally not until 1 November."

[13] DMLW records, North Slope Opening and Closing Dates For Tundra Travel

DMLW tundra management, 1963-1980

While the DNR has been responsible for managing tundra travel since 1963, DMLW oversight evolved gradually between 1963 and 1980. This transition is not neatly documented, and was pieced together to the greatest extent possible through interviews, internal memos and letters, and some field notes.

Impacts of early off-road travel increases general State oversight

Although the problems associated with off-road travel in Alaska did not receive extensive media attention during the late '60s, the impact of vehicles on environmentally sensitive tundra was well documented.[14] During the mid-'40s and '50s, large bulldozers provided much of the horsepower necessary to haul equipment used in the Navy's exploration of the North Slope.[15] Bulldozer-pulled sleds known as "cat-trains" were used during the summer months to carve away the surface vegetation, allowing the sled loaded with equipment to slide directly on top of a slick layer of mud.[16] The impact of this type of vehicle activity was dramatic and many of these bulldozed trails are still visible today.[17] They often appear as linear paths of shallow ponds, or as Dr. Brewer put it, "a trail of swamp that will last as long as Hadrians' Wall."[18] Cat-trains continued to be employed during the '60s and '70s - before the completion of the Dalton Highway that now connects Fairbanks with Prudhoe Bay. A 1969 report published by the BLM presents a photographic tour of the early impacts of oil exploration vehicles on the tundra and describes these disturbances in relation to the vegetation and topography of the region.[19]

Despite the evidence of harm to the tundra which was available at the time, interviews with former DMLW employees and DNR records indicate that during the '60s and early '70s, the DMLW did not play an active role in preventing environmental damage to the tundra. Throughout the period of construction for the Trans-Alaska Pipeline and the development of the Prudhoe Bay oil field, DNR's Division of Minerals and Energy Management (DMEM became the Division of Oil and Gas in 1984) had oversight authority over all activities related to oil and gas leases, including the transportation of equipment to and from oil and gas lease tracts.[20]

In contrast to the current management scheme, the Division of Forests, Land, and Water Management (DFLWM, now the Division of Mining, Land, and Water) advised DMEM regarding surface land uses related to oil and gas development, but did not issue off-road travel permits for vehicle access.[21] Throughout the 1970s, DMEM managed vehicle access to the tundra through the stipulations it included on oil and gas leases, but had no direct mechanism for ensuring that these stipulations were met.

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[14] Reed, J.C., 1958
[15] Fredrick, C., 1991.
[16] Max Brewer, personal communication.
[17] McKendrick, J. D. et. al., 2000.
[18] See Supra, note 43.
[19] Hok, J., 1969.
[20] DNR Leasing Manager to DNR Leasee, letter, 17 October, 1979, (Anchorage 1979)
[21] Former DMEM Director, Pedro Denton, personal communication.

In the early 70s, when DMEM issued a lease for the construction of a drilling pad, it would include a stipulation that prohibited "blading" (traveling across the tundra in a bulldozer with the blade down to scrape off uneven surfaces), or disturbance of the tundra vegetative cover. However, DNR never established a policy to explain this language – for example, did it also prohibit damage to the tundra that occurred while hauling equipment to and from the drilling pad tract?[22] Confusion over this policy is illustrated in a letter written by an Alaska Department of Fish &Game (ADF&G) employee to DMLW. It states, "On a recent trip to the Slope, I noticed that X is doing a considerable amount of travel on thawed tundra with a bulldozer. . . I don't know if this falls within his lease stipulations or not but thought you should know."[23]

In addition to confusion regarding the precise area covered by lease stipulations, DNR's policy regarding the length of the off-road travel season was open to broad interpretation. Until 1969, there is no written documentation about the start of the tundra travel season, and interviews with DMLW employees and oil industry engineers indicate that during the 60s and early 70s, DNR generally allowed all off-road travel as soon as the tundra was hard enough for vehicles to drive on it without getting stuck.

DMLW's increasing role in travel management

According to George Hollett, who served as Director of North Slope operations from 1963 to 1973, the DMLW management of the tundra increased during the early 1970s, after the impact of off-road vehicles began to generate criticism from both ADF&G and the media. Mr. Hollett recalled one incident in which an off-duty employee working for an oil development project used a bulldozer to carve the company's initials into a 360 square foot stretch of tundra.[24] The incident generated a great deal of negative publicity and helped to convince the DNR commissioner that the agency needed to be more involved in managing tundra travel from an ecological standpoint.

In 1970, DMEM Chief Pedro Denton asked DMLW staff and members of ADF&G to begin monitoring snow and weather conditions for the purpose of determining the opening and closing dates of the tundra travel season.[25] Although DMEM continued to issue miscellaneous land use permits for off-road tundra travel directly from the DNR office in Anchorage, decisions regarding opening and closing of the off-road travel season were now based on observations and recommendations of DMLW and ADF&G staff working on the North Slope.[26]

DMLW resources for fieldwork were severely limited during this period.[27] For half of the period between 1963 and 1989, DMLW had only one staff member responsible for permitting and field operations for 12 million acres of state land, land that contained hundreds of oil wells, pads and pipelines. Under these circumstances, DMLW land managers also relied heavily upon

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[22] Id.
[23] Letter from Bob Wienhold of ADF&G to George Hollett of the Alaska Division of lands dated September 10, 1971.
[24] *A Handbook for Management of Oil and Gas Activities on Lands in Alaska*, U.S. Fish and Wildlife Service, August 1983, FWS/OBS-80/23.
[25] DMEM Director Pedro Denton to DMLW employee George Hollett, letter, 20 April 1970, (Anchorage, 1970).
[26] There are no records that clearly indicate when DMLW began to issue miscellaneous land use permits directly from the Fairbanks office.
[27] Former DFLWM employee George Hollett personal communication.

information from oil industry engineers and Department of Environmental Conservation (DEC) agents stationed near Deadhorse to make tundra-opening decisions.[28] And while DMLW was able to conduct some summer monitoring operations by borrowing aircraft owned by BLM or the oil industry, budgetary constraints and a lack of personnel support often limited the division's ability to enforce the terms of the permits it issued until after the damage had already occurred.

Role of ADF&G in transitioning authority from DMEM to DMLW
Members of the ADF&G were instrumental in convincing DNR to base its decision of when to open the tundra on the observations and judgment of DMLW field staff.[29] In the late '60s, DMLW and ADF&G staff informally tested the protections provided by Brewer's 12-and-6 standard by observing the effects of driving vehicles over areas with different snow and "frost depth".[30] They measured the depth of compression left by the vehicle tracks and retuned to the site the following summer to see whether the places where the vehicles had driven looked different from the surrounding area.[31] The group found that 12" of frozen ground and 6" of snow resulted in "flattening" of the tundra vegetation but didn't "tear up the surface." Mr. Hollett acknowledged that methods used in these tests were not particularly scientific. The group did not attempt to make repeatable tests or to conduct a detailed survey of changes to the vegetation, nor did they conduct tests in different vegetation types. It is unclear how they measured frost depth.[32]

The effect of these trials, however, began to influence tundra opening and closing beginning in the early 1970s. DMLW staff soon began to fly to the sites where off-road travel was to occur, and make measurements to determine that there was adequate snow depth to protect the tundra.[33] However, ground frost was still not measured directly in the field.

During this time period, monitoring of off-road travel occurred in the summer following activities. Companies that conducted off-road activities would provide DMLW with a precise map of the territory where they had driven and would arrange to have a DMLW field officer fly over the route to verify that no damage had occurred. DMLW records from this period indicate that when problems were identified, companies would generally fulfill the terms of their lease agreements by paying to restore damaged areas. However, limited resources available for monitoring during this period make it difficult to assess the extent of damage to the tundra or how it was remedied.

Methods for determining tundra travel opening and closing dates, 1969-1980

Opening
DMLW records between 1969 and 1980, and interviews with former staff members responsible for field operations, indicate that the DMLW used a variety of measurement techniques to determine the opening date of the tundra travel season during its early management. While it appears that snow depth was measured ad hoc in areas where activity was planned, ground frost

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[28] Id.
[29] Former ADF&G Director Al Ott personal communication.
[30] See Supra, note 57.
[31] Id.
[32] Id.
[33] Id.

depth or ground hardness was not measured directly. In other words, while DMLW staff may have known of and even loosely followed a 6-and-12 rule of thumb during the early '70's, they did not attempt to systematically measure for ground frost and snow depth parameters. Instead they relied heavily upon weather station information regarding cumulative snowfall and air temperature to estimate when the standard was likely met. For example, when 12 inches of snow had fallen in Deadhorse, DMLW assumed that the tundra was frozen up to 12 inches.[34]

DMLW staff also sometimes attempted to approximate the depth of frost on the tundra by taking measurements of the depth of ice on the Colville River.[35] Using a sledgehammer, a DMLW staff person would pound a graduated metal rod into the ice and record the point at which it broke through into the water below. Once it had been determined that the ice layer on the river was thick enough to support the weight of vehicles loaded with equipment, DMLW assumed that the tundra was hard enough to open for off-road travel.

All of the early field reports from this period consist of tabulations of snow depth and the daily maximum and minimum air temperatures from Barrow and Barter Island. According to Bill Copeland, who worked for DNR during the mid to late '70s, this temperature data was primarily used to predict the beginning of the opening season.[36] If a company's exploration or drilling crew was particularly concerned about having enough time to complete their operations, DMLW would provide them with an estimate of when the off-road season was likely to begin. Records from this period indicate that tundra travel generally occurred when the daily high temperatures dropped below zero. However, in 1971 and 1972 opening occurred despite high temperatures of 20 and 28°F respectively.[37]

Closing

DMLW's tundra closure procedure during this period is documented in a memo by former DMEM chief Pedro Denton. The memo indicates that decisions regarding the closing date were based upon the judgment of DMLW staff.[38] Beginning in early April, a field officer would make several trips to the North Slope to monitor ice and snow break-up. When it appeared that the melting snow cover would soon be inadequate to protect surface vegetation from damage, DNR gave seismic and development crews 72 hours in which to demobilize and return to the Dalton Highway. While in recent years oil companies have instructed their crews to demobilize over a month before the official end of the tundra travel season, several memos from ADF&G during this period show seismic crews continuing to work up until the middle of May.[39]

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[34] Id.
[35] Id.
[36] Natural Resource Specialist to Northern Regional Land Manager, memorandum, *Tundra Opening History*, 10 June 2004, (Fairbanks, 2004).
[37] DMLW North Slope field records.
[38] See Supra, note 55
[39] In a letter dated May 15, 1970 from Robert Pegau of ADF&G to Bruce Hinsman of DNR, Pegau wrote, "Spring has already arrived from the Amatusuk Hills southward. . .There is so little snow in the area that the tracked vehicles, when they are on land are running on the vegetation rather than snow. I would suggest closing off the operation as soon as possible."

Year	Opening Date	Snow Depth in Inches
1969	November 13	4
1970	October 20	2
1971	November 1	4
1972	November 1	7
1973	November 15	7
1974	November 18	5
1975	November 1	5
1976	No opening date available	
1977	November 25	3
1978	November 4	3
1979	No opening date available	

Table 1 - Snow depth data from Barrow, 1969-1979, as reported by NOAA. The data indicate that DNR often opened the tundra before the snow depth reached 6 inches at Barrow.

Methods for determining tundra travel opening and closing dates, 1980 -1992

The 1980's were the most active years of seismic exploration and oil production in Alaska's history.[40] [41] At the height of oil production, resource management specialist Greg Zimmerman was DMLW's primary field presence on the North Slope.[42] In addition to making decisions regarding the opening and closing dates for the tundra travel season, Mr. Zimmerman monitored leasing operations on the North Slope and kept track of the enormous volume of paperwork associated with land use permits, lease operations, and gravel sales. Although the implementation of the Alaska Coastal Management Program on the North Slope in 1979 brought some additional funding for field operations, DMLW's budget was still limited.[43] DMLW staff provided their own protective clothing for winter fieldwork and there were no funds available for radio communication devices or other safety equipment.[44]

Both DMLW field records and interviews with former staff suggest that during the '80s, the 12 inches of frost or hard ground and 6 inches of snow standard was understood as a rule-of-thumb

[40] See Supra, note 12

[41] Figure 3 is from, Myers, Mike, *Alaska's Oil & Gas Future – New Frontiers, Expanding Opportunities*, prepared at the request of the DNR (Anchorage, 2004).

[42] Former DMLW Natural Resource Specialist, Greg Zimmerman, personal communication.

[43] Former DEC employee, Brad Fristoe personal communication.

[44] See Supra, Note 71

more than a strict guideline. As in the previous decade, there are no concise records explaining the methods DMLW used to determine the general opening date for the tundra travel season. Mr. Zimmerman recalled that he would begin calling oil companies with crews stationed on the North Slope in early October to find out how much ice had formed on the Colville River. When he received reports that the ice layer was sufficiently thick, he would drive up the Dalton Highway and "kick the snow around."

Based upon his impressions of the snow cover, temperature data from the U.S. Weather Service, and reports of the thickness of ice on the Colville River, he would use professional judgment to determine when the tundra was ready to permit off-road travel. Field records from this period are similar to those kept during the '70's. However, beginning in 1982, DMLW expanded its catalogue of air temperature data from Barter Island and Barrow to include information from Umiat and Deadhorse.[45]

In 1985, DMLW made its first attempt to directly measure the thickness of the frozen tundra layer.[46] A graduated steel spike with a steel eye welded to the top was pounded with a sledgehammer into the ground, and the point at which the spike met little resistance or "broke through" was observed but not recorded.

This practice apparently continued through 1990, and although it has been generally assumed that DMLW actually measured and waited until there were 12 inches of frozen/hard ground before opening the tundra, there is virtually no mention of this standard in documents prior to 1991.[47] Throughout the '80s, it appears that the amount of snowfall was the major limiting factor in tundra opening. Memos documenting the January openings, which occurred in 1985 and 1990 each, attribute the delay to late snowfall.[48]

DMLW tundra management, 1993 – 2003

A review of the trip files from 1993 to 2004 indicates that the decision making process for opening the tundra has evolved considerably over the past ten years. The reports from the 1993 season provide indication that Brewer's 6:12 standard, with frost depth (measured as a function of resistance felt using a sledgehammer to drive a rod into the tundra) was used in making the determination to open the tundra. Measurements were taken for a literal 12 inches of frost, without documentation of specific "hardness" determinations.

Later, in the 1990's, with the adoption of a slide hammer, DNR started recording how many "hits" and then "drops" of a slide hammer it took to penetrate an inch (HPI, DPI) of frozen tundra. Frost depth measurements were still reported; however, they were not "literal"

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[45] Beginning in 1986 files documenting the opening and closing season includes a report entitled, *Alaska Snow Survey* published by the U.S. Department of Agriculture which contains snow depth and density data from the previous year; however it's unclear how this data was incorporated into the decision-making process for tundra opening.

[46] Id.

[47] The only reference made to the standard in the '80's field reports appears in a handwritten note on a file from 1981 which states, "Needed to open: over 6 inches of snow, one week below zero, and 8 plus inches of frozen ground."

[48] See Supra, note 66

measurements of depth. Instead, they were a manager's assessment of "hard frost" which was a function of DPI and probe tip conditions.

The adoption of the slide hammer in 1995-1996, and specifically the change to measuring "ground hardness" instead of a literal "frost depth" left managers with the task of assessing how many hits or drops of the slide hammer correlated with adequate frost hardness within the soil profile to permit winter tundra travel. Between 1993 and 2003, it appears that 15-20 HPI was considered sufficiently hard. In 2003, using a new, slimmer probe, the DMLW determined that 10 DPI is sufficient for tundra opening (takes less DPI to penetrate tundra than the older probe).[49]

Beginning with the 1999 – 2000 season, tip conditions were recorded in the reports with documentation of observations of the number of inches of crystals, frost, dirt, and mud on the tip as it was removed from the tundra. This would affect the determination of calculated frost depth. For example, if 12 inches of frost were present and 3 inches of ice or mud appeared on the tip, frost depth would be recorded as 9 inches. Subsequent seasons reveal how mud/dirt/ice on the probe increasingly factored into the actual decision making process.

Frost Depth
Reported: 0 to 10" – 15 to 16 dpi 10 to 12" – 8 dpi ***Total: 12*** *Deduct for:* 2" of ice crystals on tip
Frost Depth Recorded: 10"

Finally, in 2003, the column for "frost depth" was no longer included in the reports, and only DPI down to 12 inches was recorded. However, the 2003 season covered by this report indicates that managers still factor tip conditions into their opening decision, interpreting their presence as a soft layer.

[49] Internal DMLW report, H. Bader & M. Wishnie, 2003.

Season	Date of Trip	Average HPI or DPI through Frozen Active Layer
1997 – 1998	**January 5 – 8, 1998**	21.97 HPI
1998 – 1999	**December 14 -17, 1998**	13.61 HPI
	December 28-31, 1998	17.009 HPI
	January 4-7, 1999 (opened January 14, 1999)	19.72 HPI
2000 – 2001	**December 26-29, 2000**	10.98 HPI
2001 – 2002	**January 25, 2002**	6.03 DPI
2002 – 2003	**January 27, 2003**	9.4 DPI
2003 – 2004	**December 15, 2003**	Approximately 7 DPI[50]

Table 7 – Average HPI or DPI for field reports 1997-2004.

In 2002, DNR made attempts to ascertain the impact of snow density on vehicle impacts. Accordingly, during the season information on average snow depth and the density of snow in grams per cubic inch at each test site were collected. As a result of the samples taken, snow was classified as slab, hoar frost, or surface snow. A further improvement in data collection occurred when 30 permanent sites were selected that are located along the road system for systematic sampling. Prior to this, staff sampled the same general areas, but not the same locations. By sampling at the same locations, changes in ground hardness at specific sites started to be evaluated over the course of the winter.

By the year 2003, DMLW engaged in a rapid series of attempts to further standardize their methods. The staff at DMLW and industry representative identified a problem with data collection due to operator variability in using the slide hammer. For example, a large and fit person could potentially drive the probe tip into the ground with fewer blows per inch than a smaller person. To eliminate this sampling variability, DMLW implemented the following three procedures:

1. The probes were standardized as follows so that they were all the exact same size and weight.

Total weight	20 lbs
Slide weight	15 lbs
Drop distance	24 in
Total length	45 in
Shaft diameter	9/16 in
Handle length	14 in
Tip diameter	3/8 in
Tip length	13 in

[50] Decision Spreadsheet, December 15, 2003

2. Use of the slide hammer was standardized by mandating that the weight be dropped from a known distance. Gravity is thus the force that drives the tip into the ground.

3. The tip size was reduced from 9/16 inch to 3/8 inch to facilitate penetration.

DMLW also made a decision to divide the North Slope into different management units. Until 2002, all State land on the North Slope was treated as one unit. With the recognition that coastal areas may freeze up faster than the foothills, four geographic areas were established called Tundra Opening Areas (TOA's). This decision was a consensus decision amongst industry representatives, scientists and agency representatives, and distinctions between the Eastern Coastal TOA, Western Coastal TOA, Lower Foothills TOA and Upper Foothills TOA were based on factors such as elevation and vegetation cover. The southern boundary for the two coastal areas was taken from the Alaska Coastal Management Plan.[51]

A memo dated December 19, 2003, describes the factors used by DMLW managers to "determine if conditions are adequate to open the tundra." As recorded in the memo, the following five factors are listed as weighing into the decision:

1. Is the tundra consistently hard throughout the vertical profile?

2. Is there a soft layer? If so, how soft is it?

3. Is there ice or mud on the probe tip? We have found in the past that this is a good indication of a thawed layer. We see this often in the early winter, but we never see it later when we find the ground to be hard enough to open the tundra. (Anecdotally, it seems that on the 9/16" tip it is easier to see these things, but we still do get them on the 3/8" tip.)

4. Based on the above, I estimate the depth of hard frozen ground.

5. Bader & Wishnie (2003) compared the 9/16" tip with the 3/8" tip. This document states that adequate hardness for opening is achieved with an average of 10 drops per inch. (Note that on the decision spread sheet, I estimated a rough mean DPI for each site.

[51] Leon Lynch memo June 2004.

Analysis of Tundra travel Policy

Introduction

Much of the current concern surrounding management of tundra travel by the DMLW has centered on methods for determining when the tundra can be safely opened for off-road travel by oil and gas company vehicles. It is clear from the *History* section of this report that DMLW's decision-making related to tundra travel has evolved over time. The next section of this report analyzes the reasons for past decisions.

Protocols and techniques used to determine tundra readiness

The 12-and-6 standard

Dr. Brewer's original standard for protecting the tundra from significant impacts (12 inches of frost and 6 inches of snow cover) appears to be a rule of thumb based on years of experience managing infrastructure in the arctic environment. As an engineering-based standard, it was formulated as a conservative estimation, with margins of error built in informally by Dr. Brewer. While it may make intuitive sense, the standard's scientific underpinnings are unclear, and the standard was not based on extensive or direct testing to understand the specific relationship between two environmental variables (snow and ground frost) and tundra disturbance levels from off-road travel.

Based on an interview with Dr. Brewer, however, it is clear that the standard is based on years of valuable experience gained from scientific research on permafrost dynamics, arctic engineering and tundra ecology. As such, the standard is likely reliable guideline of one threshold condition under which tundra disturbance will be low. Indeed, based on it's varied implementation over the past 30 years, this 'rule-of-thumb' has proven effective in protecting tundra from the level of impact observed in the early days of oil and gas development.[52] It has also kept impacts in more recent years to anecdotally low levels on State lands. In the Arctic Refuge, the standard as applied in the mid 1980's resulted in generally low, but sometimes-significant impacts, with greater impact observed in higher, drier sites dominated by tussock vegetation[53].

Despite it's subjective origins, the standard is attractive as a management guideline because of its simple, rule-of-thumb approach. The standard would become more scientifically credible if it were tied to specific impacts and disturbance levels across different types of tundra vegetation.

DMLW's tundra opening methodology and the application of the 12-and-6 standard

As is clear from the *History* section of this report, the DMLW's has used the 12-and-6 standard as a guideline but not a hard and fast rule for opening the tundra. The application of this guideline has evolved significantly over the past three decades. This evolution has been hampered by the lack of scientific information and by a methodical and consistent approach to data collection. Instead, it seems to have been guided somewhat by incremental efforts DMLW field staff to understand tundra dynamics and standardize methods of for making decisions. The evolution is punctuated by changes in staffing resource levels, and changes in the tools used to measure ground frost and ground hardness. The informal nature of these decisions to modify

[52] Id.
[53] Felix & Reynolds 1989a, 1989b, Jorgenson 2003, Emers & Jorgenson 1997, Reynolds & Felix 1989

decision-making may not have been scrutinized or particularly important because when season lengths were much longer, opening the tundra was not considered controversial. It may also have been due to a lack of staff and budget.

Because of its mostly informal nature, DMLW decision-making before the 1990s was characterized by a reliance on proxy weather information, and a lack of actual testing of conditions in the field. When conditions were tested, data were not always recorded, and were not collected in a manner that could easily be repeated or validated. For example, varying locations were used for testing and methods for measuring ground frost and snow depth varied from year to year and person-to-person.

Anecdotally, it appears that testing was focused in areas where development activities were to occur. This informal constraining of the extent of the management area is a potentially good way to limit variability in measurements, but it makes comparing opening dates from year to year difficult. Furthermore, prior to 2002, it is not clear that attempts were made to ensure the data collected was representative of conditions in either informal 'management units', or of conditions overall.

Additional early limitations in DMLW protocol include lack of a clear decision-making framework for opening the tundra (not always clear how the collected data factored into decision-making).

In the mid-1990s, records switch from documenting the depth of ground frost to recording ground hardness over a depth profile in "hits per inch" or "drops per inch." Here, a slide hammer probe measures ground hardness. "Hardness" is both a more sensitive and less precise measure of ground conditions than "frost depth." Ground hardness allows an incremental measurement of conditions over a depth profile, whereas ground frost is recorded as a single threshold depth. However, while frost depth is theoretically an actual physical parameter, 'ground hardness' is a qualitative description with units that depend on the instrument used to measure it (units in the case of DMLW have been "blows per inch," "hits per inch," or "drops per inch").

After 1985, when DMLW field staff started to actually measure ground conditions, a steel rod was used to crudely estimate hardness over a profile (although this isn't recorded), and based on intuition, the depth at which hardness (resistance) lessened significantly was recorded as the threshold frost depth.

Measuring ground hardness through a probe test is not necessarily an untested approach to understanding the properties of a freezing surface. According to a Cold Regions Research Engineering Laboratory (CRREL) report on Snow Roads and Runways, the probe hardness test is one of three typical measurements used in cold region engineering: surface load, sample strength, and probe. A surface load test, such as a plate indentation test, applies a vertical load to the snow surface and has the highest degree of reality in simulating load application. In a sample strength test, a core sample is removed from the snow and subjected to a strength test, and is less accurate in its correlation to load bearing strength. A probe measuring technique, such as the DMLW has used, is the easiest method, but does not simulate load application. The 1990 report CRREL on Snow Roads and Runways states the following about probe testing:

"These tests are the most convenient and least time consuming; in addition they provide a vertical hardness profile of a snow layer or a snow pavement. The hardness values, however, have no real physical meaning; they are simply indices of the 'relative hardness' of snow and have to be correlated empirically with more meaningful or familiar strength properties or actual bearing capacity."[54]

Tom Krzewinski, a geotechnical engineer with Golder Associates[55] in Anchorage, Alaska, stated that these methods for testing snow road and runway strength are also "all used frequently" for measuring frost depth of the active layer.[56]

Thus the DMLW's probe test has always been limited by the fact that "hardness" has not been systematically correlated with more meaningful environmental variables such as impacts to vegetation, ground temperature over the profile, final-freeze up, or load-bearing strength.

Consultation with experts in permafrost dynamics and engineering earlier on in management history could have improved staff understanding of the meaning of measurements and perhaps tightened measurement protocols used by field staff. Consultation could have also illuminated other factors that are potentially important in describing permafrost conditions or in predicting disturbance levels.

For example, according to Dr. Hinzman, an arctic scientist at UAF, the top inches of frozen active layer receive the most pressure from equipment, and the force is spread out below. This would suggest that the hardness of the upper inches is critical in determining the load-bearing strength of the tundra.[57] As noted in the *History* section, hardness measurements were often not recorded for the first few inches, and no regression has been attempted to relate the relative importance of hardness at different depths over the standard 12-inch profile.

Another instance in which consultation could provide important insight is in the case of measuring mud streaking and ice crystals on probe tips starting in the 1990s. While this observation has been used by DMLW staff as indication of soft layers in the permafrost, it is not clear that this assumption is consistent with current knowledge of permafrost characteristics. Even though tundra can be frozen solid, liquid water is always present in some quantity, and can lead to streaking. Testing would be needed to determine whether this DMLW assumption is valid.

Within the "ground hardness" regime, the use of scientific information and methods in DMLW management has improved dramatically in the last few years. Recent efforts have lead to increased standardization and repeatability of tundra readiness measurements, and new staff studies are investigating the sensitivity of current methods to testing location and number of testing replications at each location. Furthermore, a clear decision-making framework has been

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[54] Abeles, G, 1990.
[55] Golder Associates is an international group of consulting companies that specializes in ground engineering and environmental science.
[56] Personal communication, September 3, 2004.
[57] Personal Interview August 5, 2004.

established so that the rationale behind yearly decisions (including supporting data) is clearly documented in agency files.

Recent consultation with scientists and stakeholders has also led to the adoption of four tundra-opening areas. The divisions are based on current understanding of tundra ecosystem types and elevation gradients, and allow managers more flexibility in determining when to open each area to oil and gas activities. Informal and formal studies by DMLW and industry (e.g. an Ice Road Demonstration Project & the tundra modeling effort) have increased understanding of tundra systems on the part of DMLW staff, and have for the first time systematically documented disturbance levels related to certain activities and certain initial conditions. The most successful internal studies take care to set out hypotheses or research objectives, to develop good ways of testing the hypotheses, and then use data collected in the experiment to confirm or reject the hypotheses in a statistically informed manner.

Tundra Closing

While considerable effort has gone into increasing the use of science in tundra opening procedures, tundra-closing procedures have remained relatively constant for the past three decades. Closing the tundra is primarily a pragmatic decision, as vehicles need a few days notice to return the existing infrastructure from remote areas. The closing decision is based on observations of snow cover and short and long term weather forecasts. Once the insulating snow layer is gone, warming air temperatures begin to melt the permafrost active layer. Permafrost freezes each winter from both the surface in and the edge of the active layer out, and the same is true in spring. This means that after snow is gone, the surface of the permafrost is the first part to thaw.

Tundra closing decisions have been less controversial than tundra openings, for two reasons:

1) While winter temperature and snow conditions have changed significantly in the arctic, the onset of spring has not changed as drastically.[58] This is reflected in the asymmetry of days lost on either end of the DMLW travel season over the past few decades. While 85 days on average have been lost in winter, only 15 days have been lost on average in spring ;
2) It is of great importance to industry that equipment be moved out of remote areas before they are liable to become stranded across rivers with inadequate ice depth to support crossings, or stuck in melting permafrost. Once snow begins to melt, this happens quite quickly. This dynamic may induce a more precautionary approach on the part of industry and state managers.

Some scrutiny of tundra closing methodology might be in order, however. To avoid controversy over tundra closing in the future, it becomes important to standardize approaches and document decision-making, as in the case of tundra opening. Some testing of the assumptions implicit in the decision-making protocol may be in order, as well.

[58] Smith et. al. 2003.

Vehicle Testing

It has been DMLW's policy to allow certain vehicles access to the tundra at different times of the year depending on how they perform in informal tests on the tundra surface. Over the past few decades, these tests have resulted in a list of vehicles allowed on the tundra both during the summer and when snow depth is above 6" but ground hardness has not reached the threshold for opening the tundra to general traffic. [59]

Thresholds for allowing or prohibiting a vehicle are not entirely clear, and methods used to measure these threshold disturbance levels are not clearly documented. Based on interviews with staff, the general standard is that the vehicle will not tear the vegetative mat.[60]

Standardized testing, record keeping, and data collection procedures could improve the transparency of this practice.

Monitoring disturbance and impacts

There is a noted lack of scientific study on the impacts of winter off-road travel on the North Slope tundra.[61] This scientific gap extends from peer-reviewed scientific journal articles to technical reports and informal field monitoring studies.

Years of informal monitoring of trails and rehabilitation sites have enhanced institutional understanding of the range of impacts and their specific causes. This knowledge and the transparency of the system to the public could be greatly improved by standardizing methods and measurement parameters. This could be as simple as standardizing the number of disturbed sites visited and the questions asked by monitors every year. Further steps might include establishing monitoring plots in areas where high disturbance is anticipated, or establishing a more formal program of monitoring by air or even potentially from satellite. Cumulative impacts have not been and are still not monitored.[62] Although maps of work areas are collected, they are not compiled.

Based on interviews of past and current staff, similar informal testing has informed DMLW's approach to rehabilitating the tundra in areas where it is damaged by off-road traffic. The results of these informal investigations are largely contained in case-files, and have not been compiled into a single resource or document. Again, the implementation of standard scientific practices with regard to data collection and documentation could improve future rehabilitation efforts.

[59] DMLW memorandum from H. Bader and G. Schultz to N. Welch, April 17, 2003.
[60] DMLW staff interviews.
[61] See Appendix B.
[62] NAS 2003.

Measuring for 12-and-6: DMLW tundra management timeline

Early 1970's – DMLW, with help from DH&G, begins to play more of an active role in deciding tundra opening and closing date, taking over from Division of Minerals and Energy Management (now Division of Oil & Gas).

Early 1970's-1980 – Mean tundra season length is 200 days. DMLW relies mostly on remote weather data from Barter Island and Barrow (on the Arctic Ocean), snow depth information, river ice depth, and intelligence from people in the field to judge whether the tundra is ready to open. "Frost depth" not measured in the field. "Ground hardness" not used as a determination for opening tundra. DNR staff sometimes flies to intended work areas to measure snow depths. The 12-and-6 standard occasionally mentioned, but if used at all is only used as a guideline for determining adequate conditions are met.

Early 1980's – According to interviews with former staff, DMLW continues to rely primarily on air temperature from remote weather station data and river ice depth as proxies for frost depth. When remote station data and intelligence from people in the field indicates average snow depths are close to 6 inches, DMLW staff drives or flies to field and gauges average snow depth. 12-and-6 standard may be used for guidance, but is not a fast and hard threshold for opening.

1982 – DMLW expands weather station data to include information from stations at Umiat and Deadhorse.

1985 – DMLW makes first attempt to measure frost depth directly. Uses sledgehammer to drive a steel rod into the tundra. DMLW assumes frost depth corresponds to the depth at which resistance to rod decreases. 12-and-6 standard followed, although still as a guideline. The depth information is not recorded, field reports are spotty, and testing locations are inconsistent and sparsely distributed mostly on the coastal plain.

1985 – 1994 – Sledgehammer and steel rod technique continues, augmented by weather station data and sporadic testing of snow depth. Staff history indicates that tundra is opened if field staff determines that frost depth is to 12 inches and no significant soft layers are encountered when pounding the probe down into the tundra.

1991 – Mention of 12-and-6 guideline becomes more common in field reports and files.

1993 – Turnover in DMLW North Slope field staff. Rod now marked in one-inch increments and number of blows needed to pound in each inch is observed but not always recorded. Thus "hardness" as well as frost depth is crudely measured. Snow depth, ground frost and crude hardness in "blows per inch" measured at various locations, but blows per inch not consistently recorded. Unclear exactly how decision is made to open tundra, but 12-and-6 is still apparently a guideline as it applies to average snow depth and average frost depth as measured by the steel probe and sledgehammer technique.

1995 -1996 – New staff designs and employs new, safer probe - the slide hammer penetrometer. Penetrometers used by staff are generally similar but not standardized in hammer weight or height, or probe diameter, although the diameter is generally about 9/16". User assists hammer in driving probe into ground. Increasing number of sites sampled and additional measurements made, including "snow depth at probe site."

1996-1997 – Ground "hardness" now measured and recorded as well as frost depth. Hardness expressed in Hits per Inch (HPI) of the slide hammer. While ground frost can be present over 12 inches, a certain HPI is necessary to be considered adequately "hard frost." HPI not always recorded for first few inches of tundra.

1998 – Field observations begin to be systematically recorded in more standardized field reports, and sampling intensity is increased but not entirely standardized. Geographic area covered by sampling also increases. Observations of dirt, ice crystals and mud begin to be noticed and factored into ground hardness and frost depth assessment.

2002 –Working group formed; 4 different management units (Tundra Opening Areas or TOAs) are created for phased tundra opening. Pilot study conducted that indicates that the current method for determining tundra readiness may be conservative. Tundra modeling project begins.

2002 –2003 – New, slimmer 3/8 " probe is employed, with standardized height, weight and diameter.
Ground hardness is now measured in terms of unassisted "drops per inch" (DPI) of the slide hammer from a specified height. 'Adequately hard' determined to be 10 DPI on average over the entire 12-inch profile with new probe. Standardized testing methodology implemented, with visits to 30 permanent sample stations distributed along both an E-W and a N-S transect, scheduled every two weeks starting in November. Decision-making matrix created. Reports issued explaining each opening decision, methodology for decision, and supporting data. DMLW manager over-rides decisions influenced by observations of mud, ice and dirt on probe tip until these observations can be linked to increases in tundra impacts.

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APPENDIX E: WINTER CHARACTERISTICS

The following histograms portray the ground hardness and snow characteristics by study site and treatment date. This appendix groups the histograms by study site, characteristic, and treatment date in the following order:

WET SEDGE/COASTAL PLAIN

1. Ground Hardness
    a. Distribution of all ground hardness measurements summed for all treatment dates.
    b. Ground hardness measurements by treatment date in sequential order 1-6.

2. Snow Depth
    a. Distribution of all snow depth measurements summed for all treatment dates.
    b. Snow depth measurements by treatment date in sequential order dates 1-6.

3. Snow Slab Thickness
    a. Distribution of all snow slab thickness measurements summed for all treatment dates.
    b. Snow slab thickness by treatment date in sequential order dates 1-6.
    Note that missing treatment date sheets denote an absence of any slab found within treatment cells for that date.

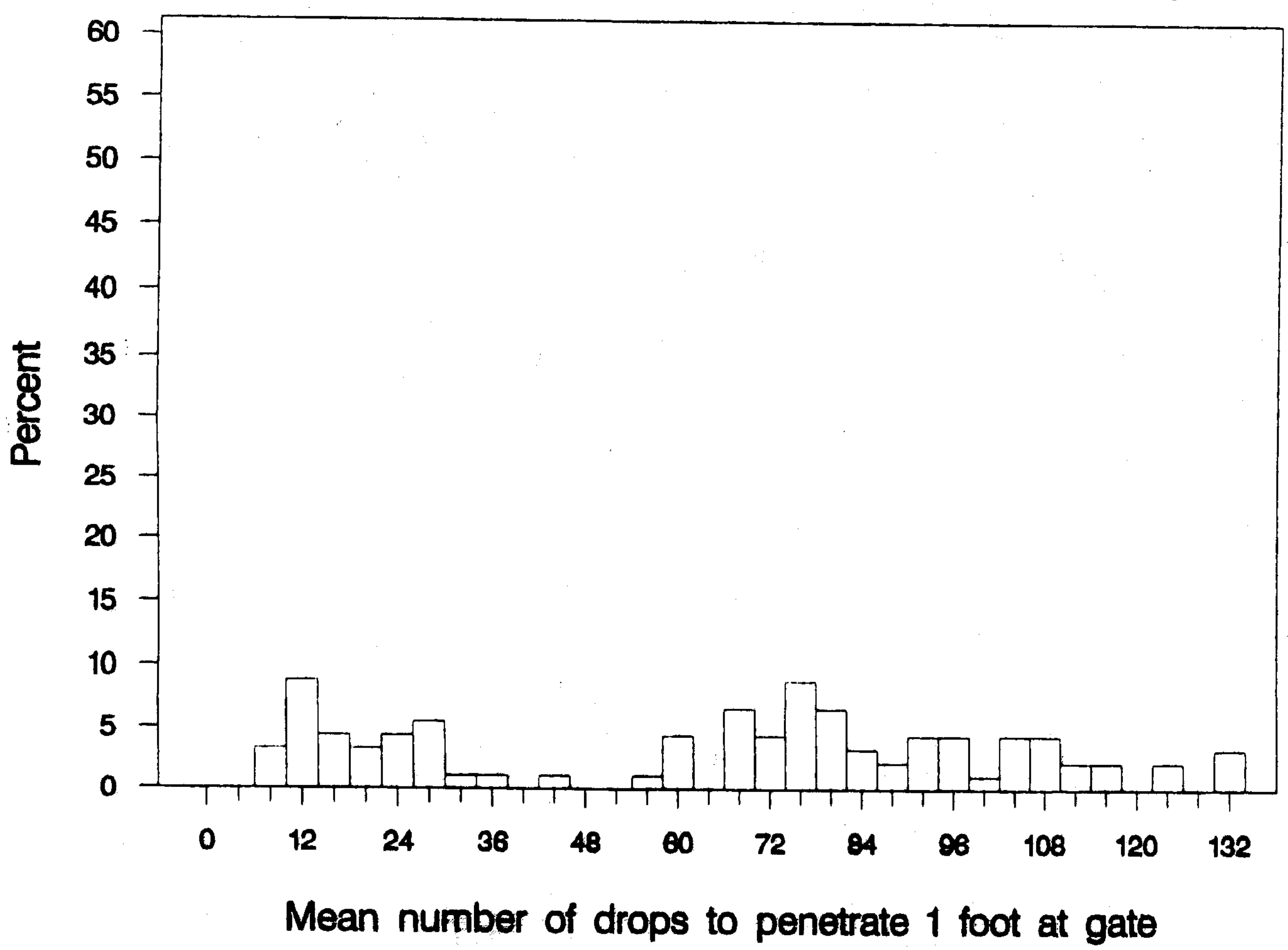
TUSSOCK TUNDRA/FOOTHILLS

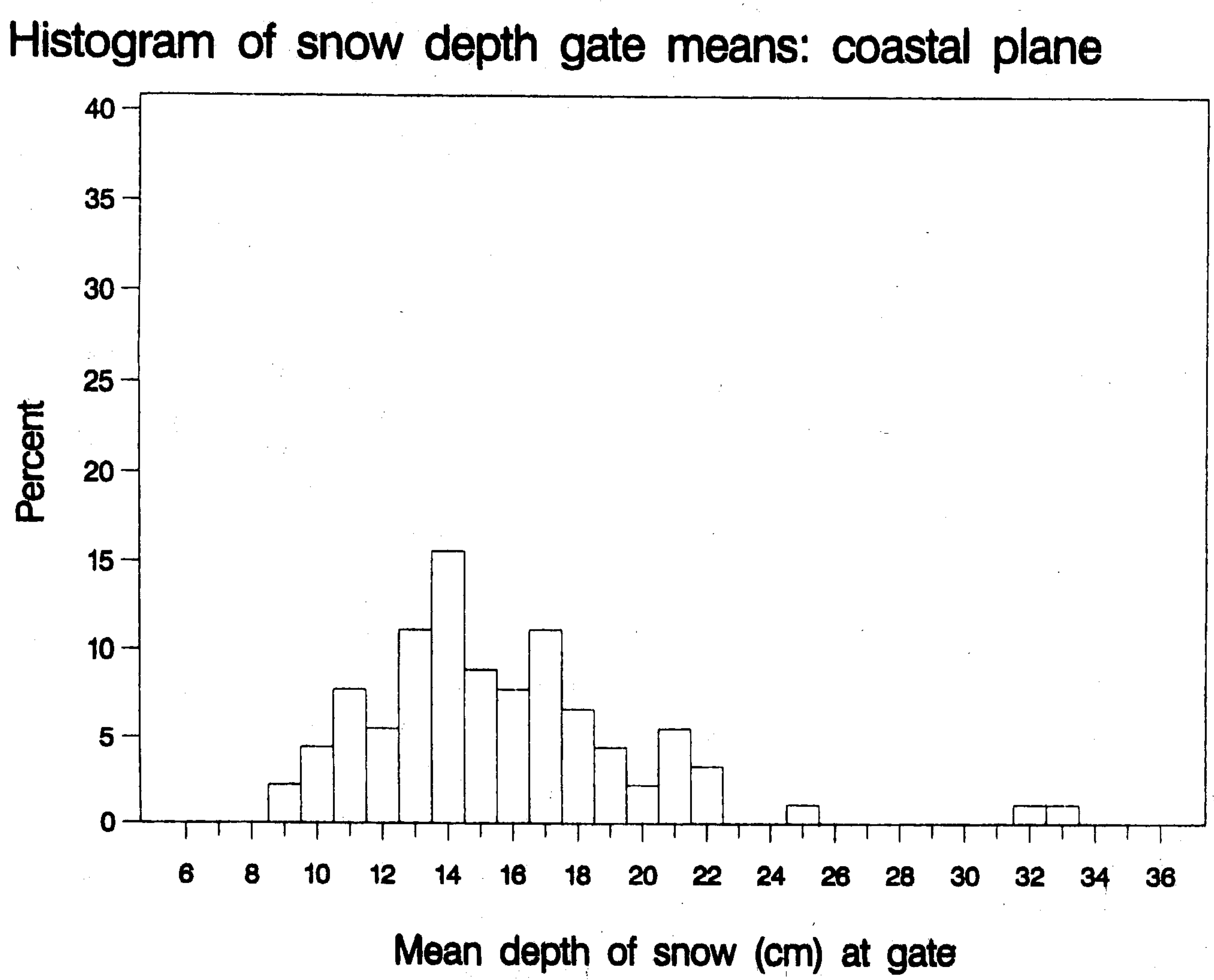
1. Ground Hardness
    a. Distribution of all ground hardness measurements summed for all treatment dates.
    b. Ground hardness measurements by treatment date in sequential order 1-6.

2. Snow Depth
    a. Distribution of all snow depth measurements summed for all treatment dates.
    b. Snow depth measurements by treatment date in sequential order dates 1-6.

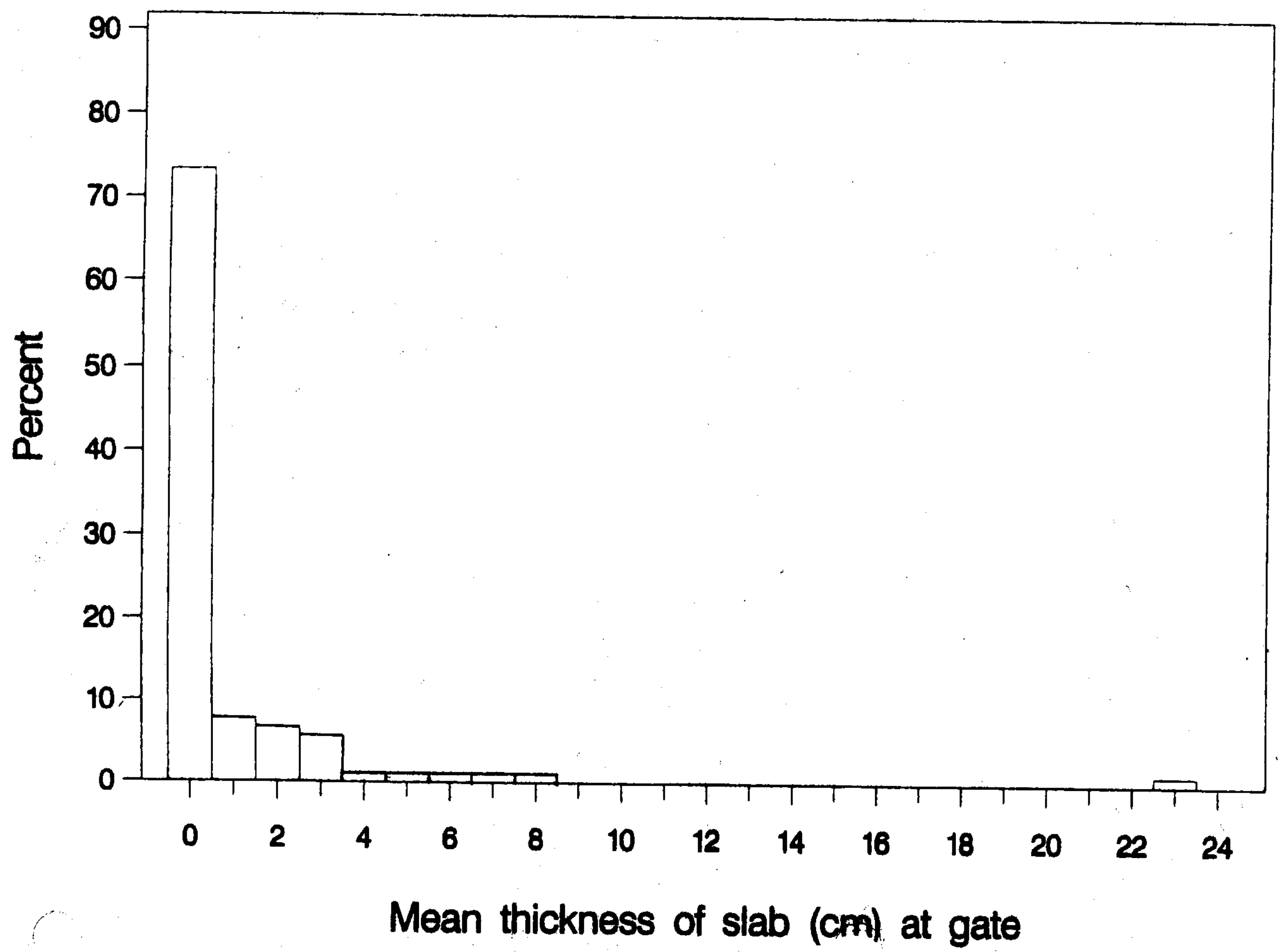
3. Snow Slab Thickness
    a. Distribution of all snow slab thickness measurements summed for all treatment dates.
    b. Snow slab thickness by treatment date in sequential order dates 1-6.
    Note that missing treatment dates result when no snow slab was found within treatment cells.

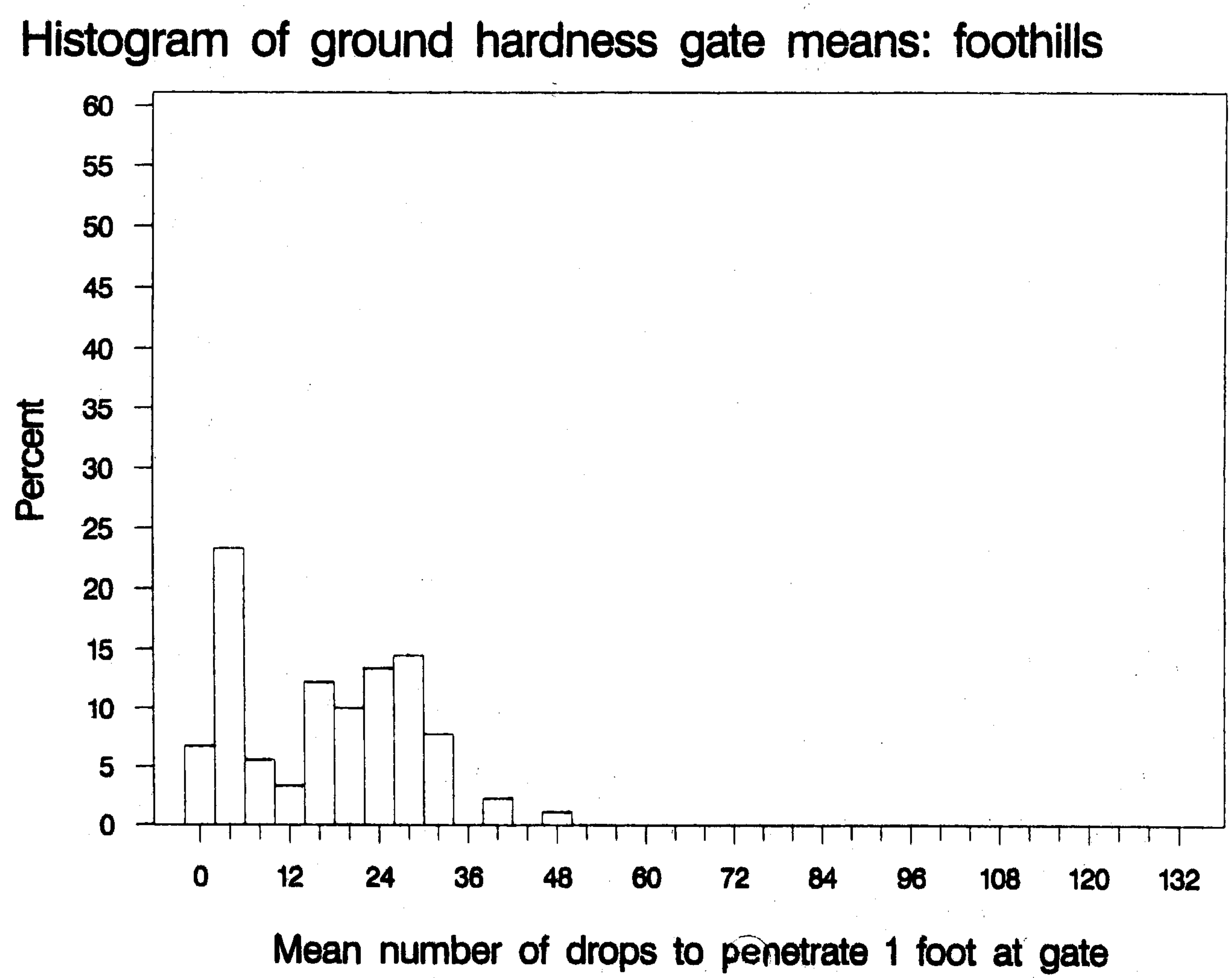
Histogram of ground hardness gate means: coastal plane



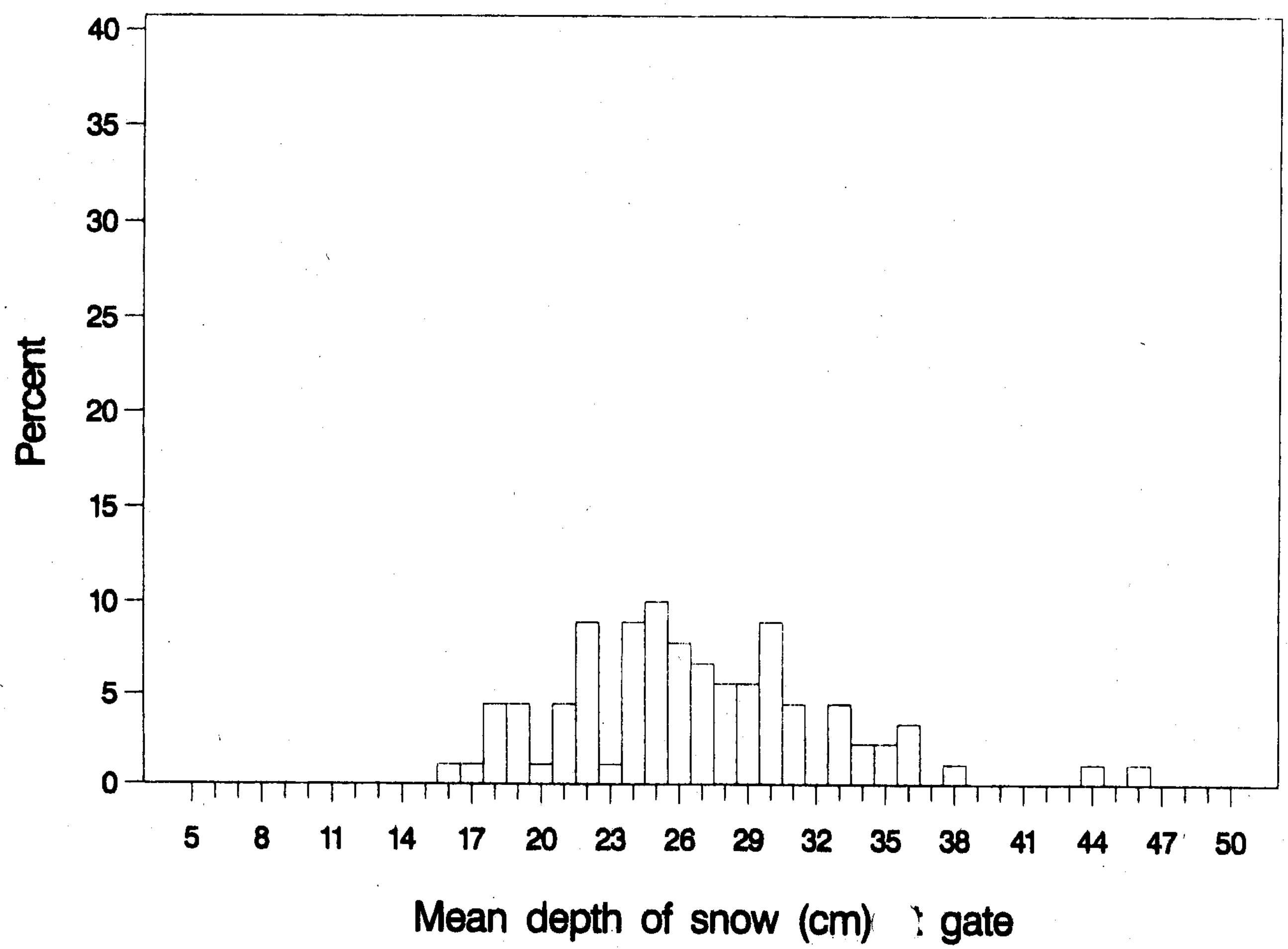

Histogram of snow depth gate means: coastal plane
Percent
0
5
10
15
20
25
30
35
40
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Mean depth of snow (cm) at gate

Histogram of slab thickness gate means: coastal plane

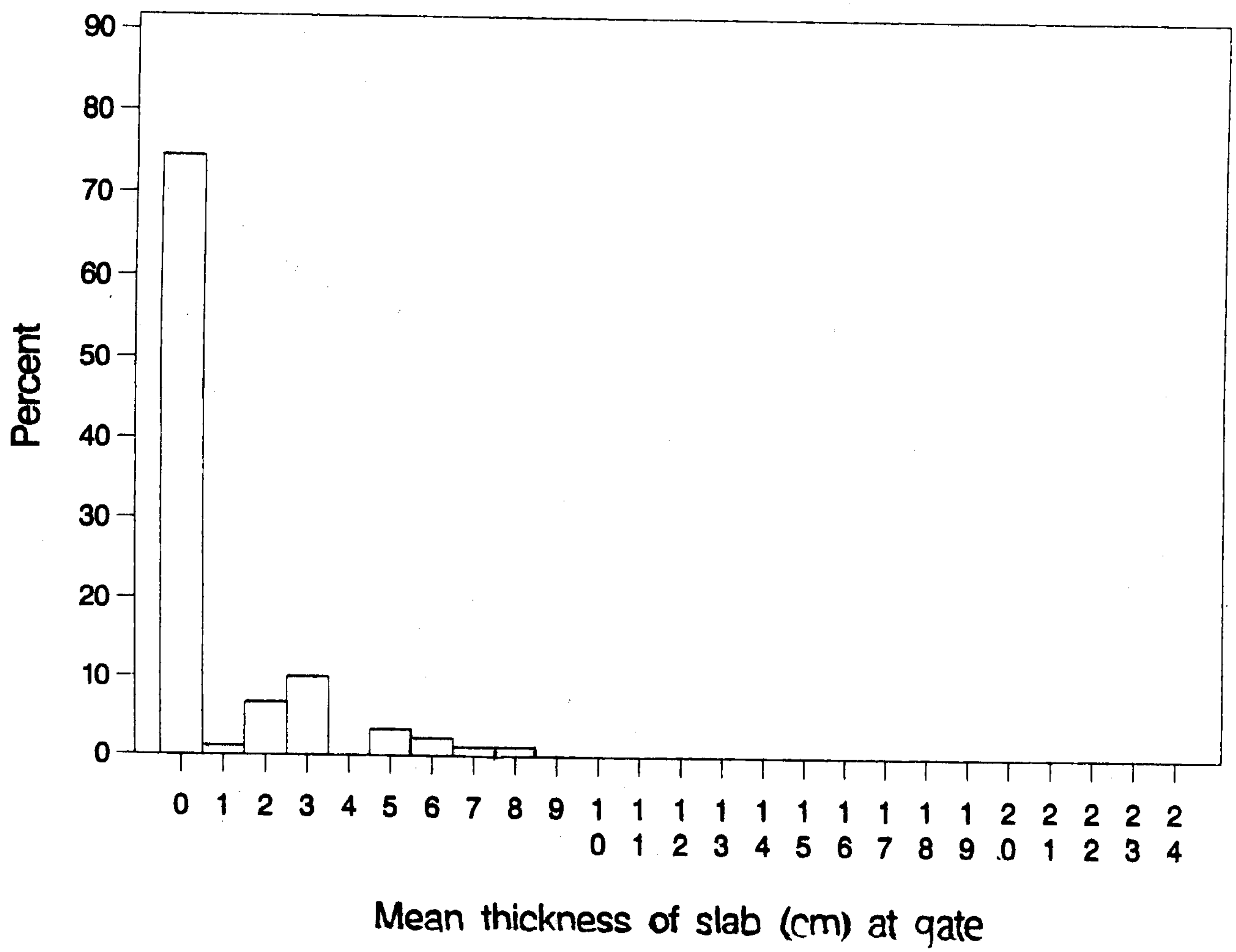



Histogram of ground hardness gate means: foothills
Percent
60
55
50
45
40
35
30
25
20
15
10
5
0
0
12
24
36
48
60
72
84
96
108
120
132
Mean number of drops to penetrate 1 foot at gate

Histogram of snow depth gate means: foothills



Histogram of slab thickness gate means: foothills

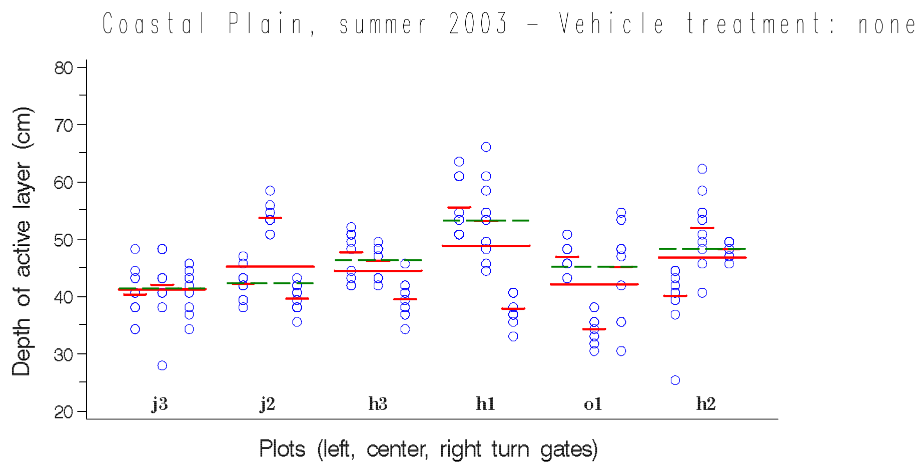


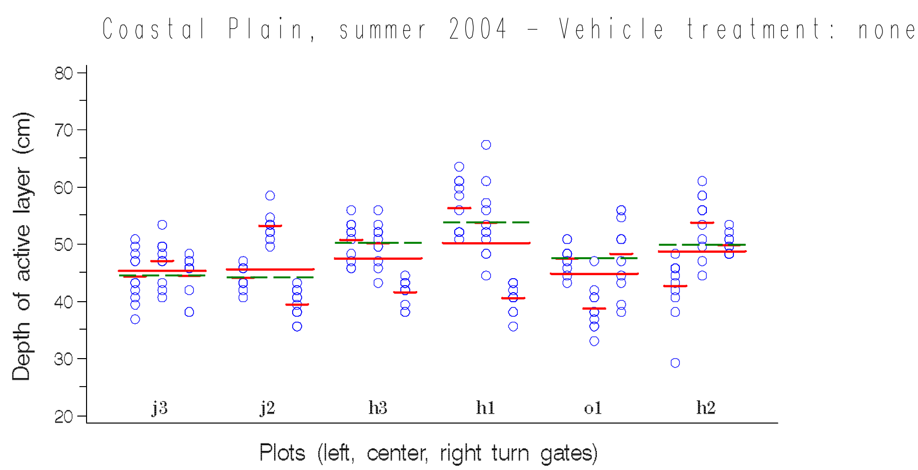
APPENDIX F:
Change Characteristics

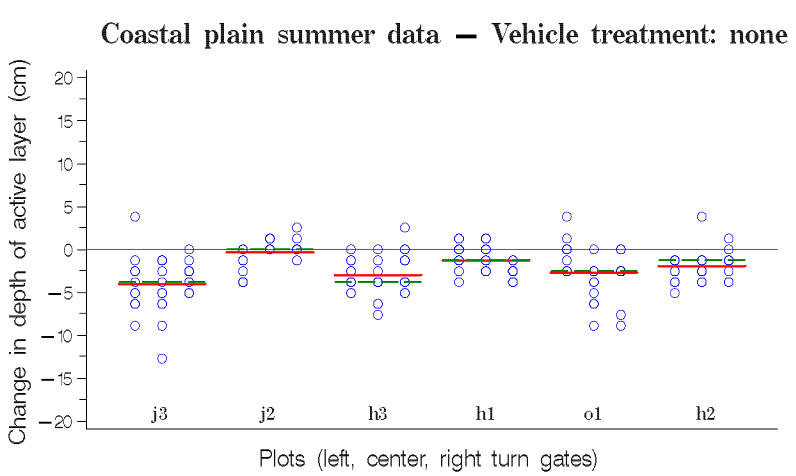
The following graphs portray the data for each transect in each treatment cell collected in the years 2003 and 2004 as well as the absolute and relative change between the two years.

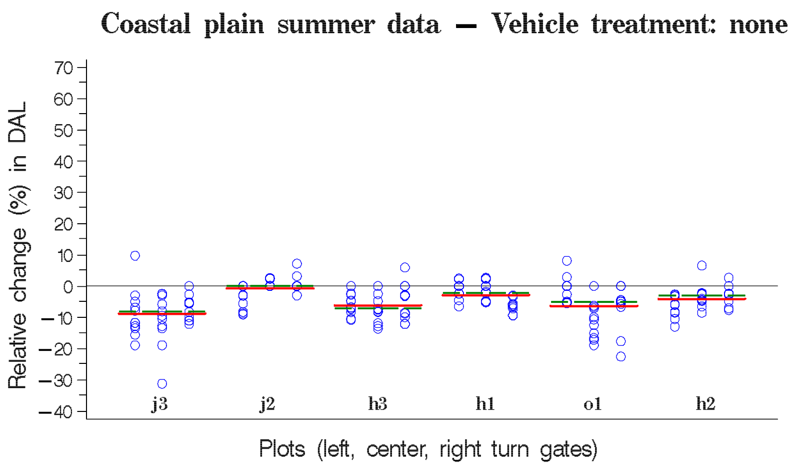
Each treatment cell for a particular treatment type is portrayed with the three transects located within the cell. Each transect appears as vertical line of circles. Arranged from left to right, the vertical lines represent transects portraying data for the left turn, center, and right turn gates. The circles denote an actual measurement for a particular variable on the transect. Transect means are represented as short horizontal lines for each transect. The gate mean is represented by a long horizontal red line and the gate median is represented by a dashed green line. A single circle may represent multiple measurement points of equal value.

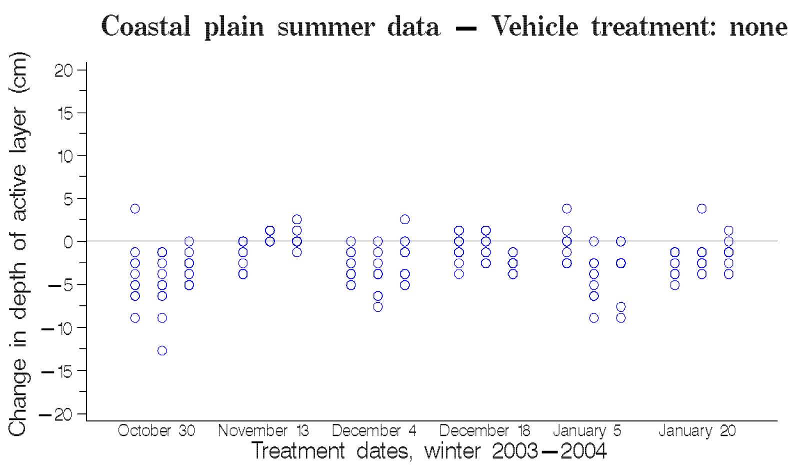
These graphs are arranged by treatment type.

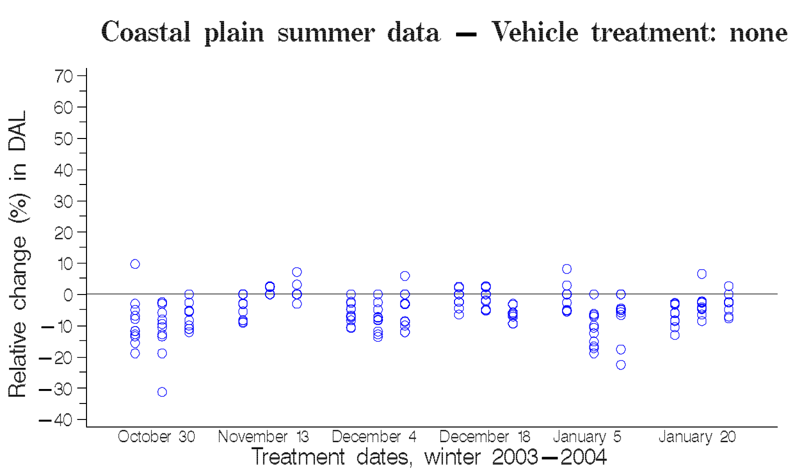

Coastal Plain, summer 2003 - Vehicle treatment: none
Depth of active layer (cm)
80
70
60
50
40
30
20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)


Coastal Plain, summer 2004 - Vehicle treatment: none
Depth of active layer (cm)
80
70
60
50
40
30
20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)

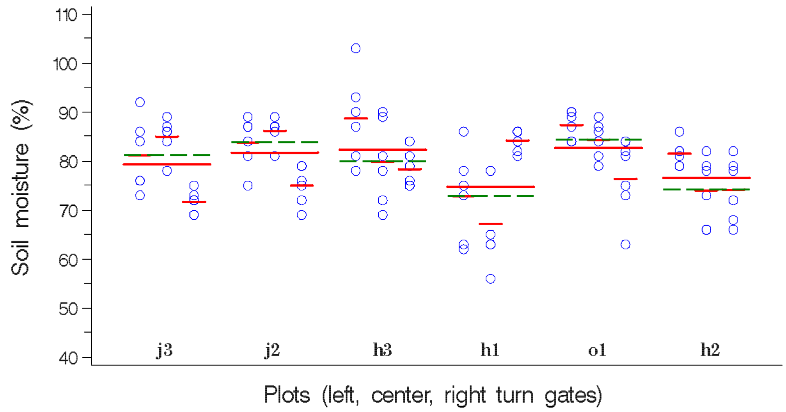

Coastal plain summer data — Vehicle treatment: none
Change in depth of active layer (cm)
20
15
10
5
0
-5
-10
-15
-20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)


Coastal plain summer data — Vehicle treatment: none
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)

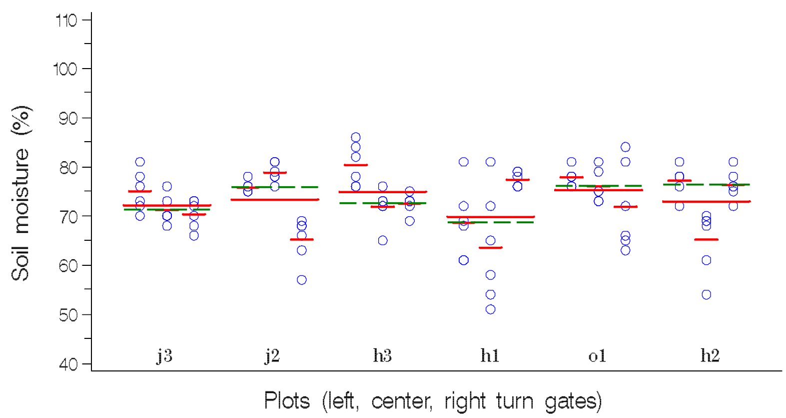

Coastal plain summer data — Vehicle treatment: none
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: none
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

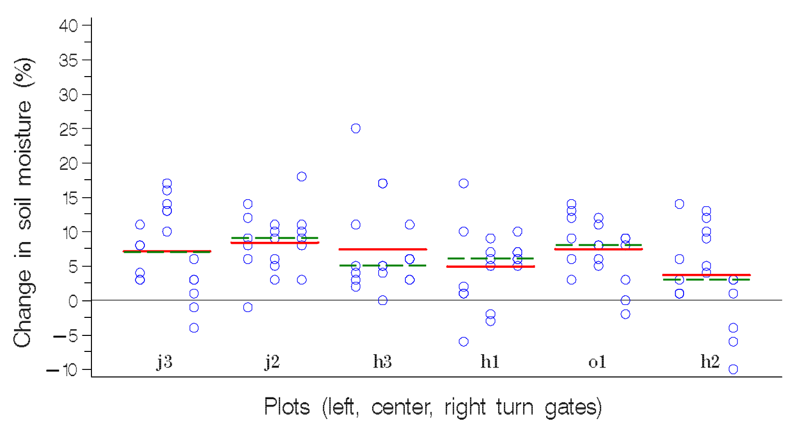
Coastal Plain, summer 2003 - Vehicle treatment: none

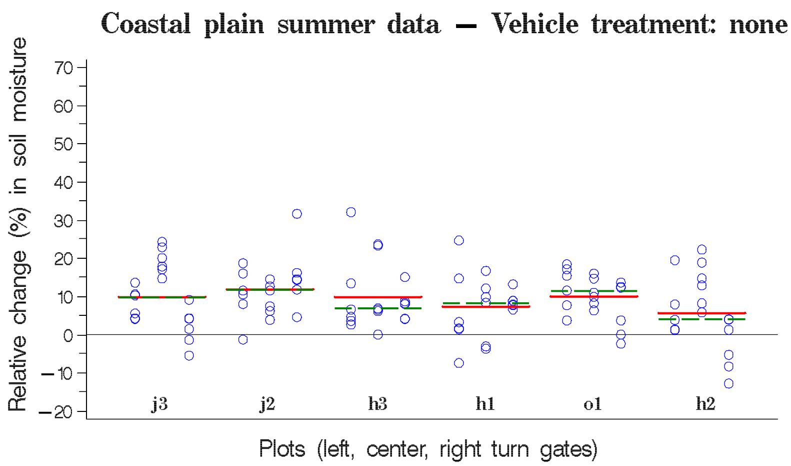


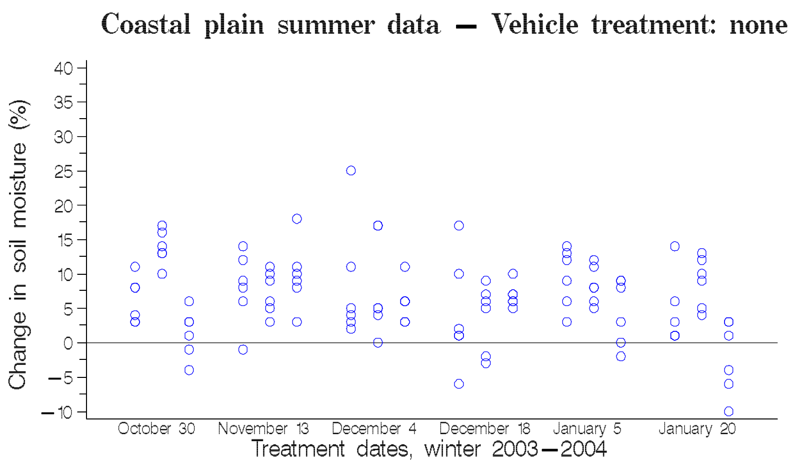
Coastal Plain, summer 2004 - Vehicle treatment: none

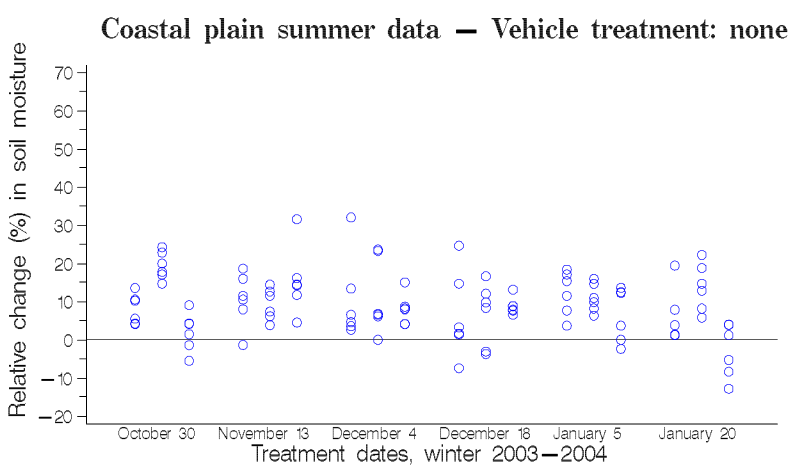


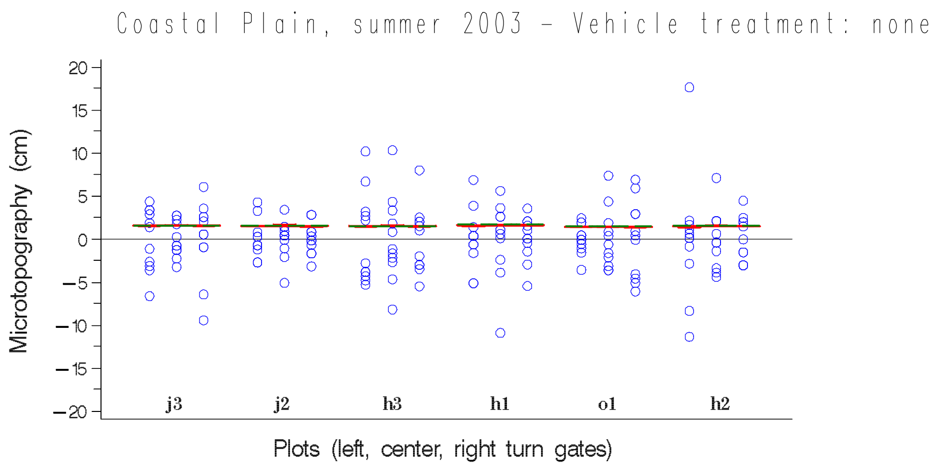
Coastal plain summer data — Vehicle treatment: none

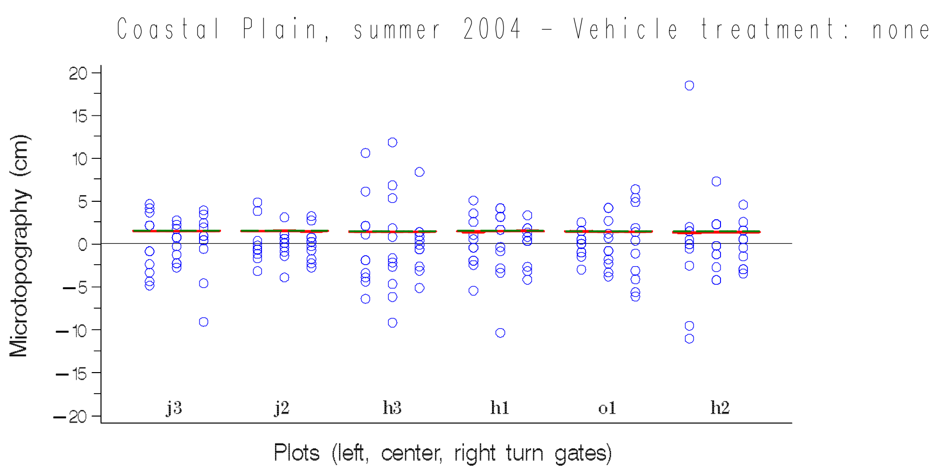


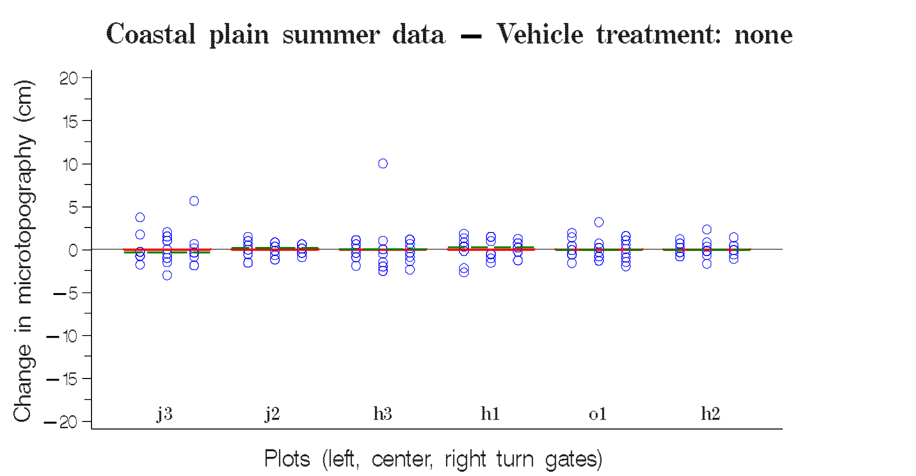

Coastal plain summer data — Vehicle treatment: none
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)

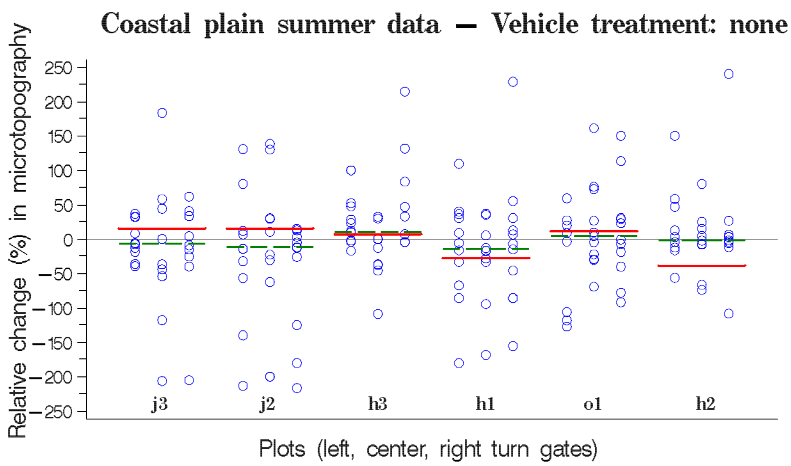

Coastal plain summer data — Vehicle treatment: none
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

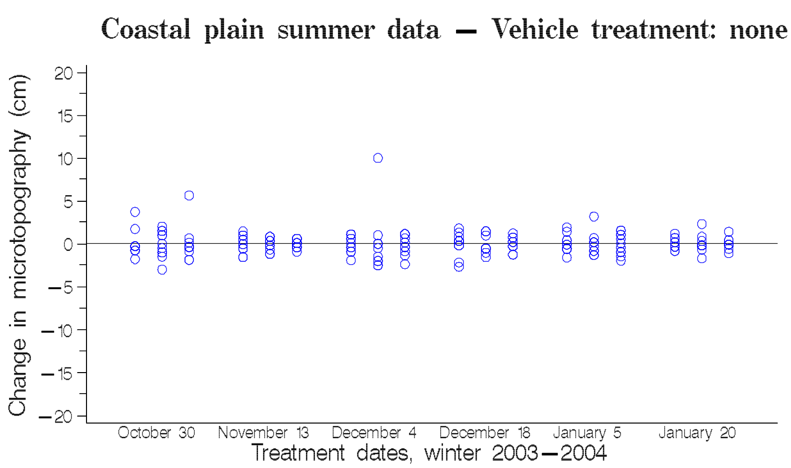

Coastal plain summer data — Vehicle treatment: none
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

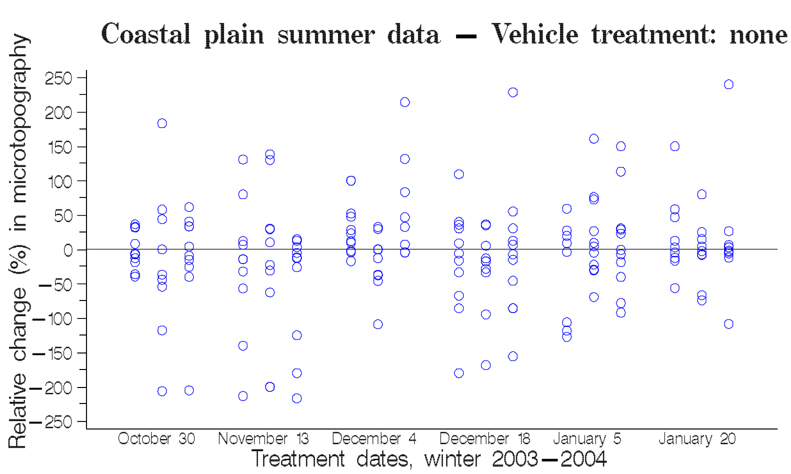

Coastal Plain, summer 2003 - Vehicle treatment: none
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)


Coastal Plain, summer 2004 - Vehicle treatment: none
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)

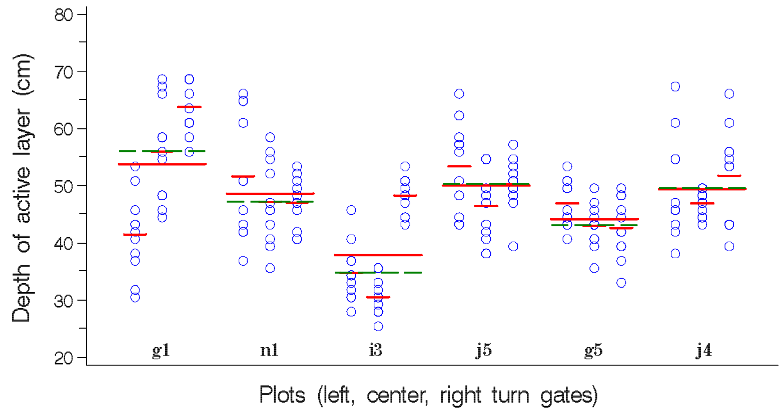

Coastal plain summer data — Vehicle treatment: none
Change in microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)


Coastal plain summer data — Vehicle treatment: none
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
j3
j2
h3
h1
o1
h2
Plots (left, center, right turn gates)

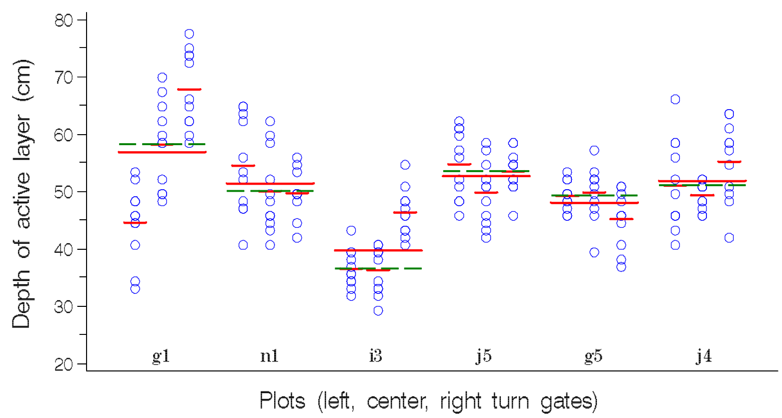

Coastal plain summer data — Vehicle treatment: none
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: none
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

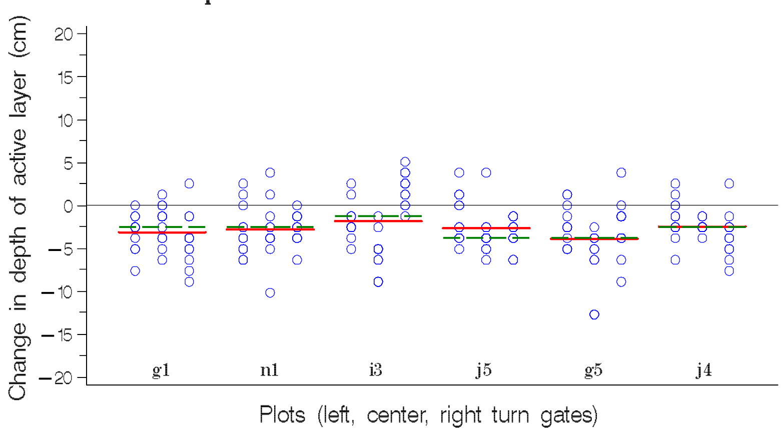
Coastal Plain, summer 2003 – Vehicle treatment: tractor



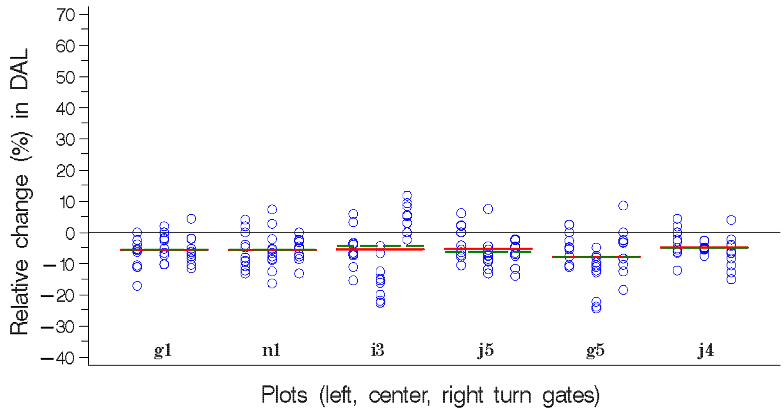
Coastal Plain, summer 2004 – Vehicle treatment: tractor



Coastal plain summer data — Vehicle treatment: tractor

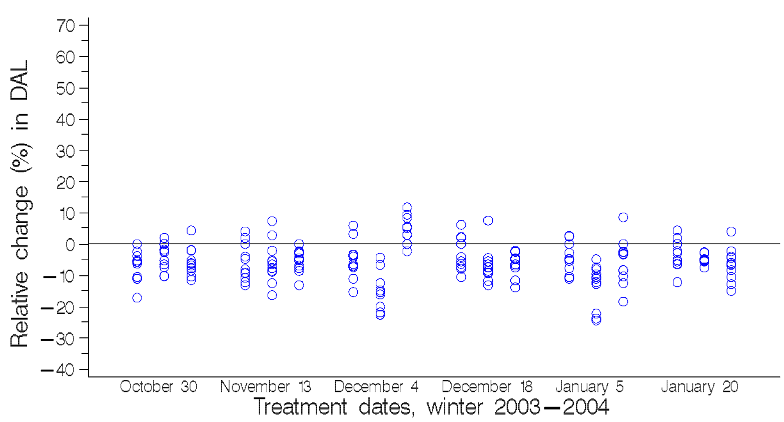


Coastal plain summer data — Vehicle treatment: tractor

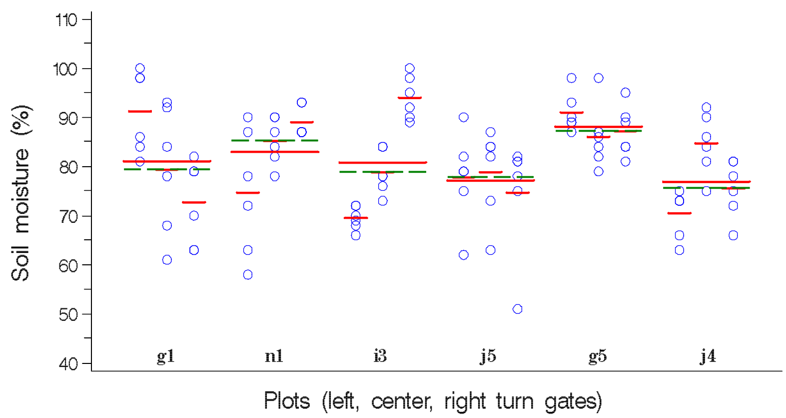


Coastal plain summer data — Vehicle treatment: tractor

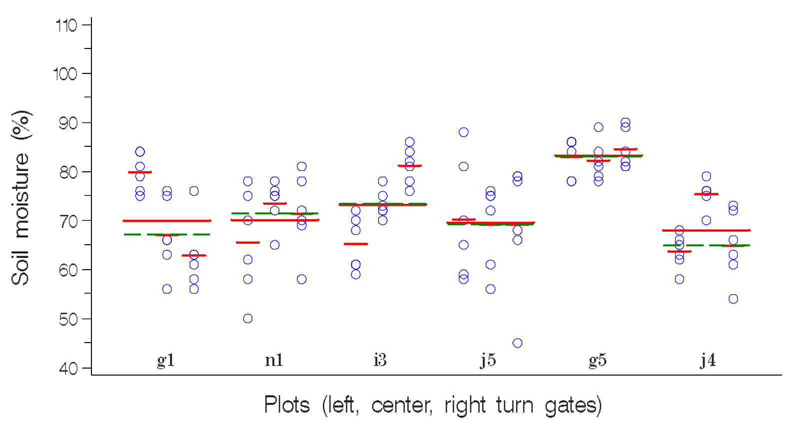
Coastal plain summer data — Vehicle treatment: tractor



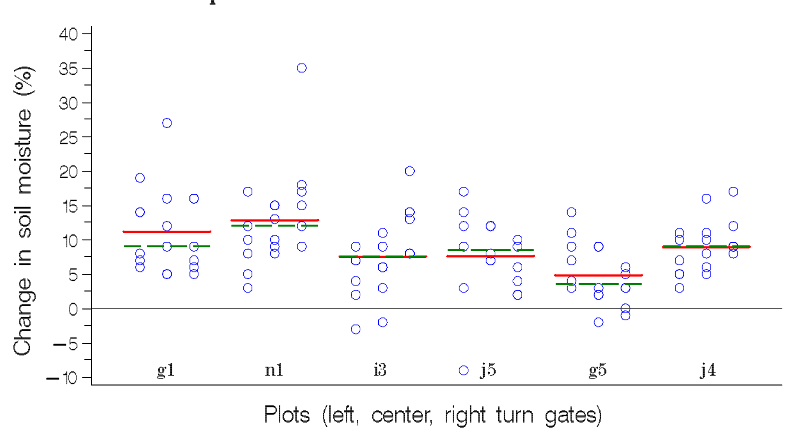
Coastal Plain, summer 2003 – Vehicle treatment: tractor



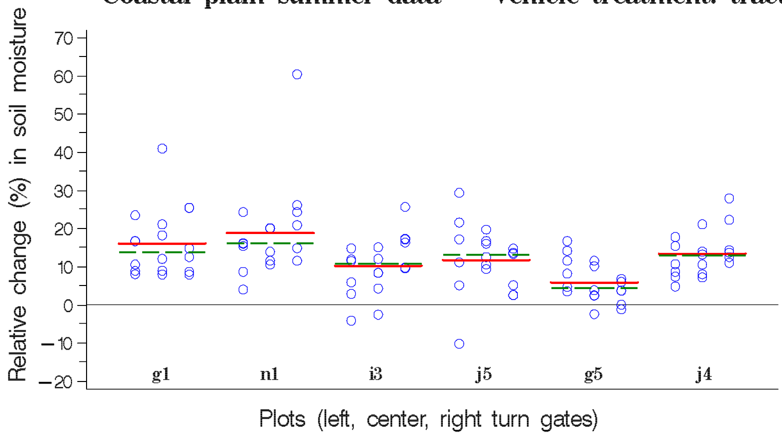
Coastal Plain, summer 2004 – Vehicle treatment: tractor



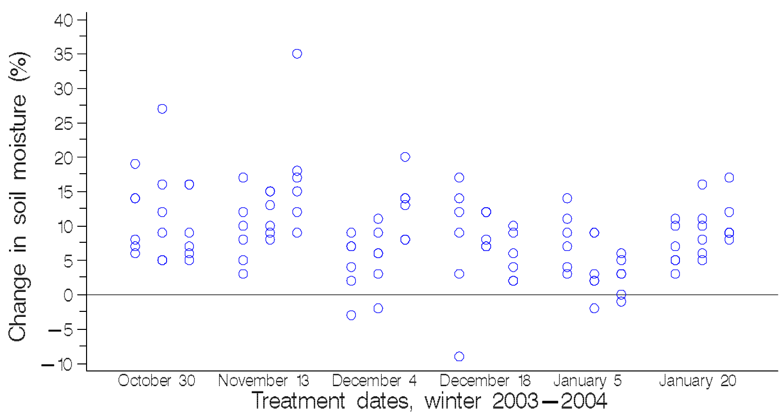
Coastal plain summer data — Vehicle treatment: tractor



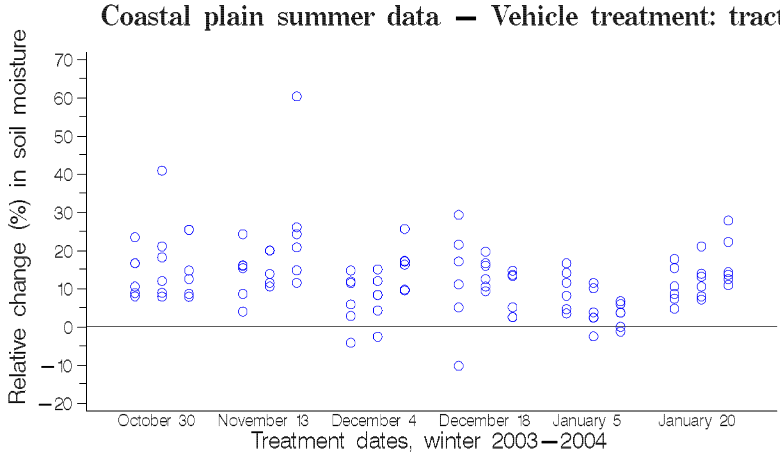
Coastal plain summer data — Vehicle treatment: tractor

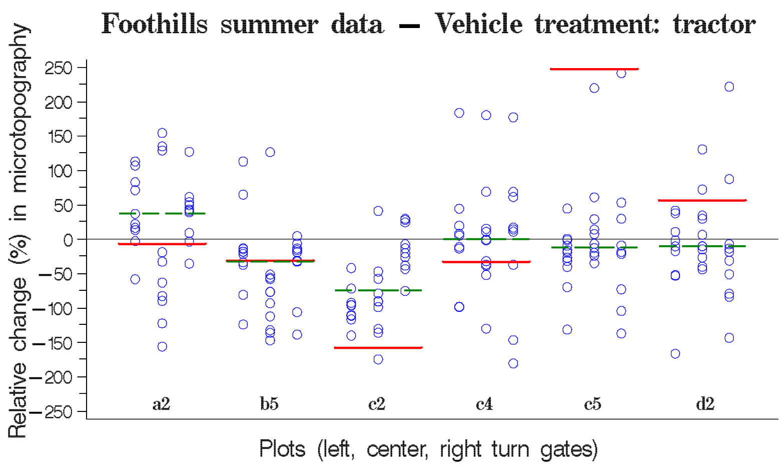


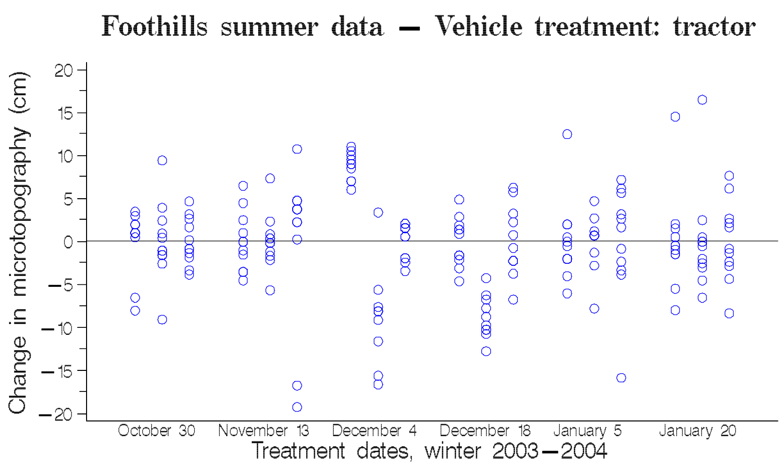
Coastal plain summer data — Vehicle treatment: tractor

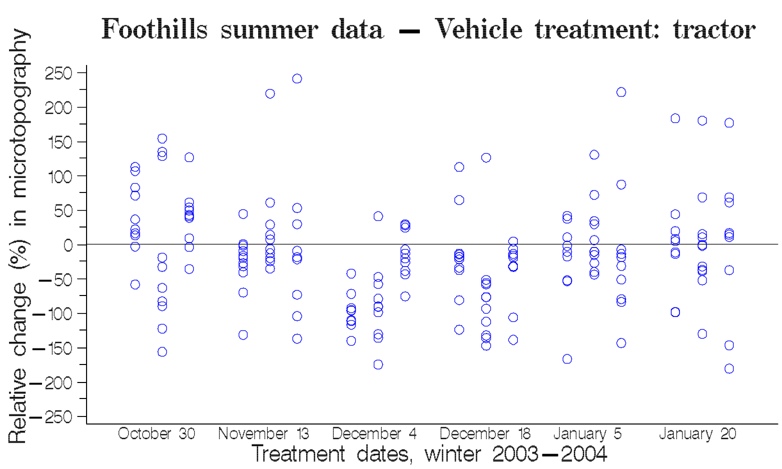


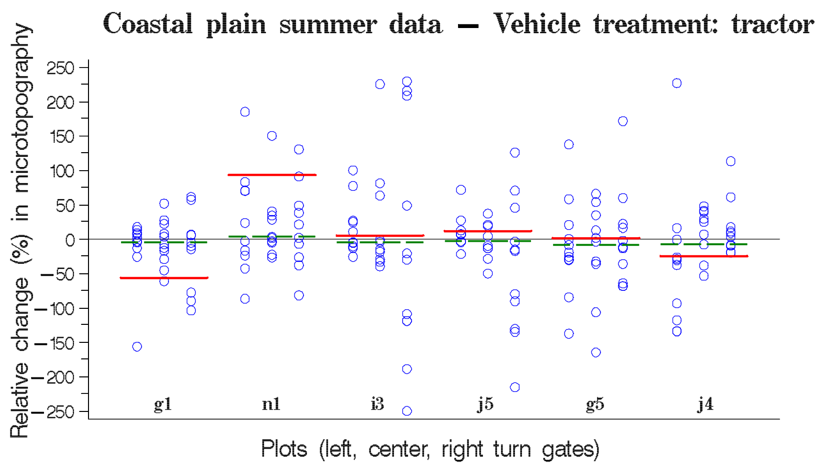
Coastal plain summer data — Vehicle treatment: tractor

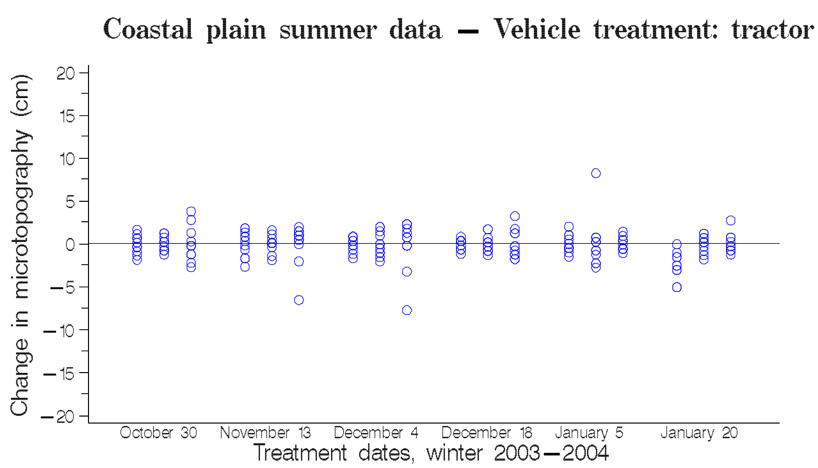


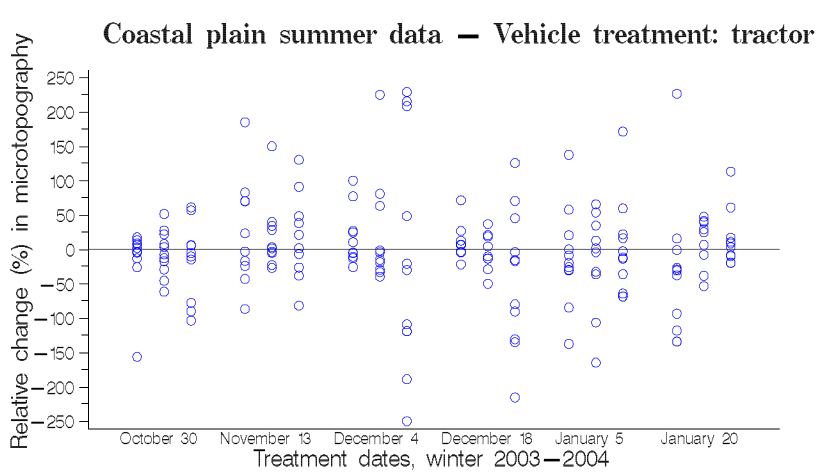

Foothills summer data — Vehicle treatment: tractor
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

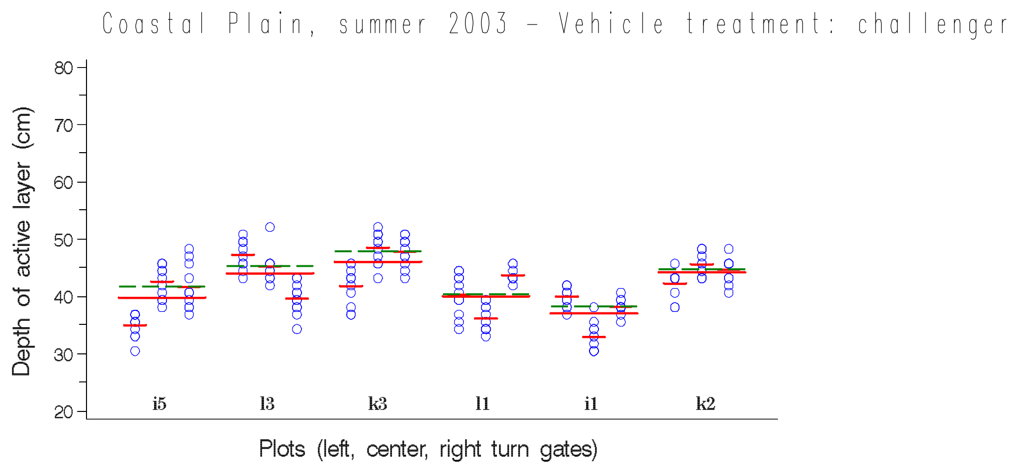

Foothills summer data — Vehicle treatment: tractor
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

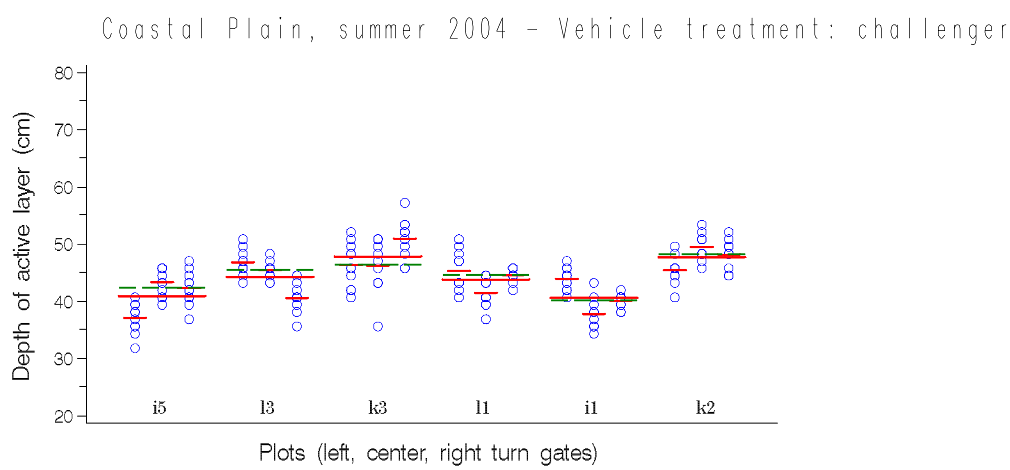

Foothills summer data — Vehicle treatment: tractor
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

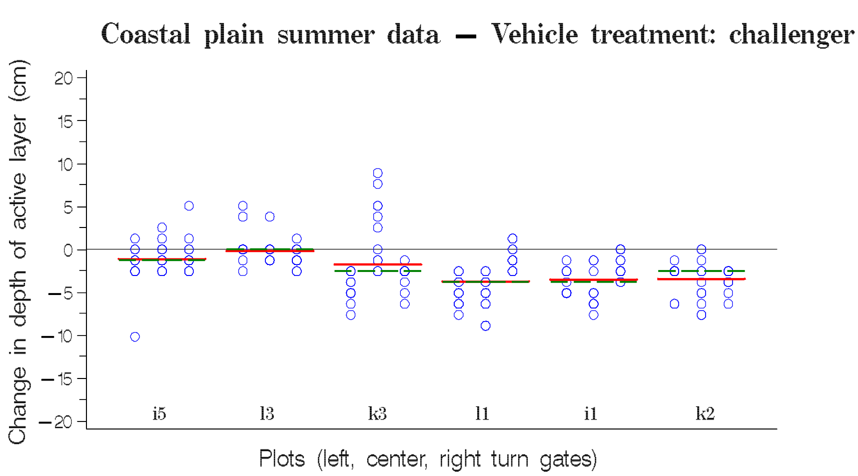

Coastal plain summer data — Vehicle treatment: tractor
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
g1
n1
i3
j5
g5
j4
Plots (left, center, right turn gates)

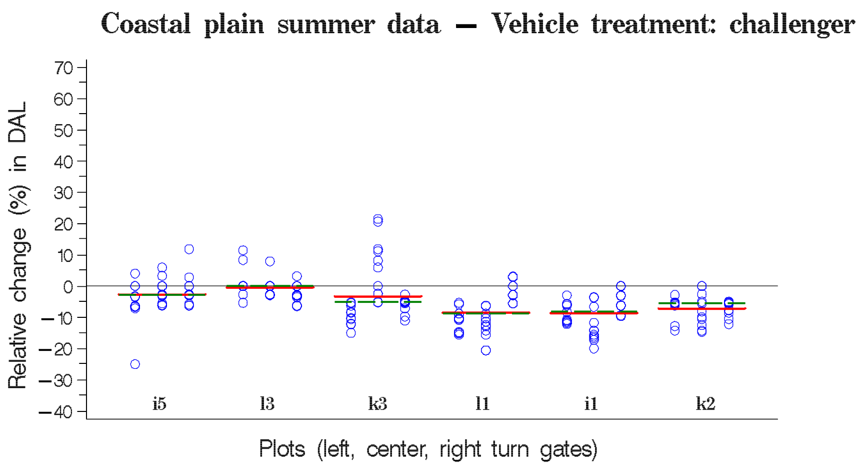

Coastal plain summer data — Vehicle treatment: tractor
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

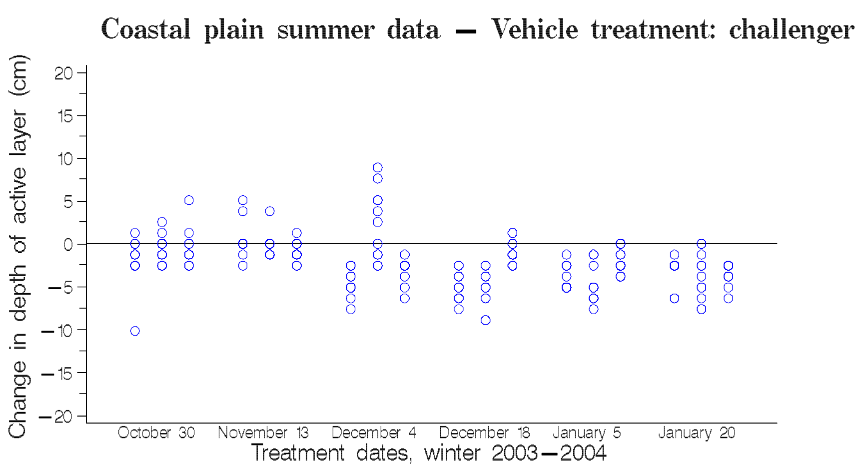

Coastal plain summer data — Vehicle treatment: tractor
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

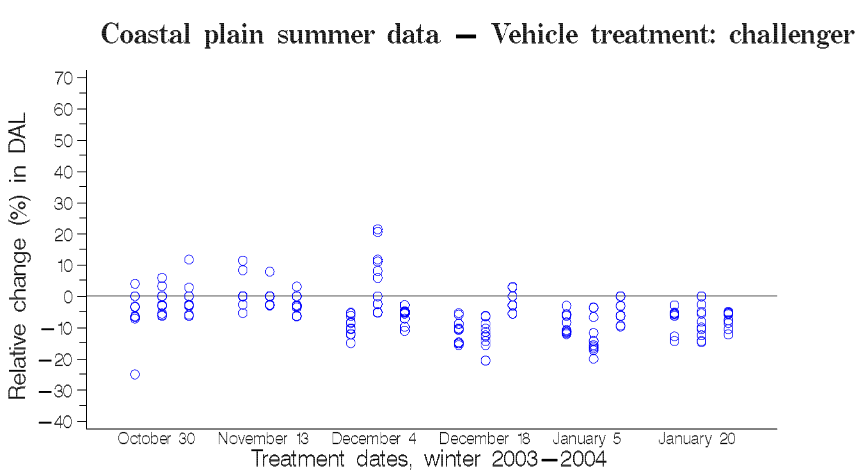

Coastal Plain, summer 2003 - Vehicle treatment: challenger
Depth of active layer (cm)
80
70
60
50
40
30
20
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

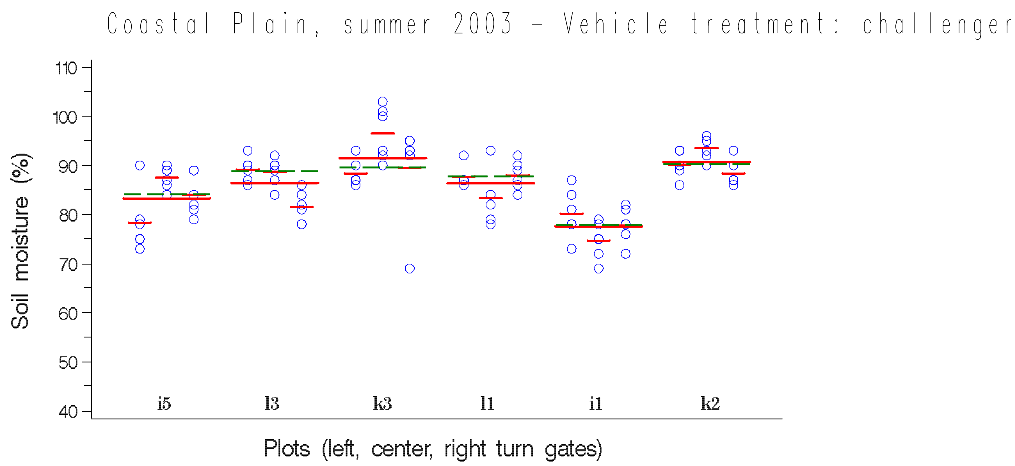

Coastal Plain, summer 2004 - Vehicle treatment: challenger
Depth of active layer (cm)
80
70
60
50
40
30
20
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

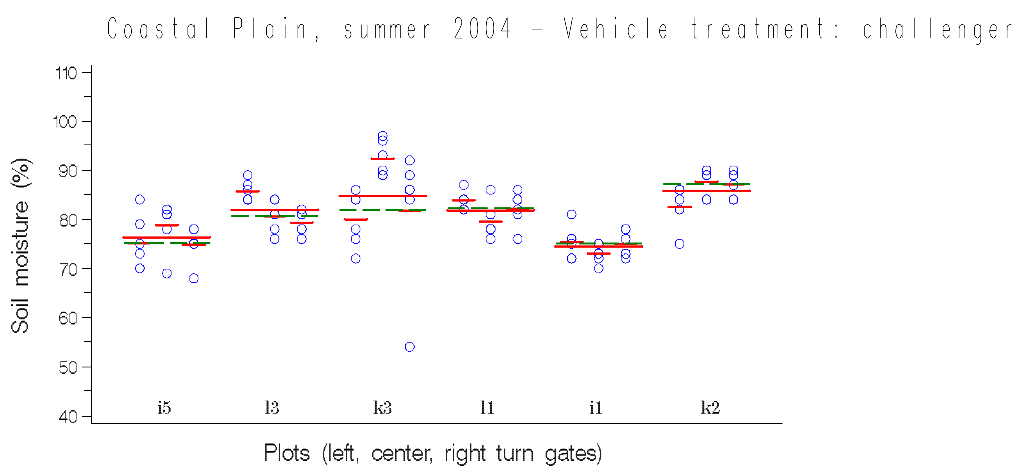

Coastal plain summer data — Vehicle treatment: challenger
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

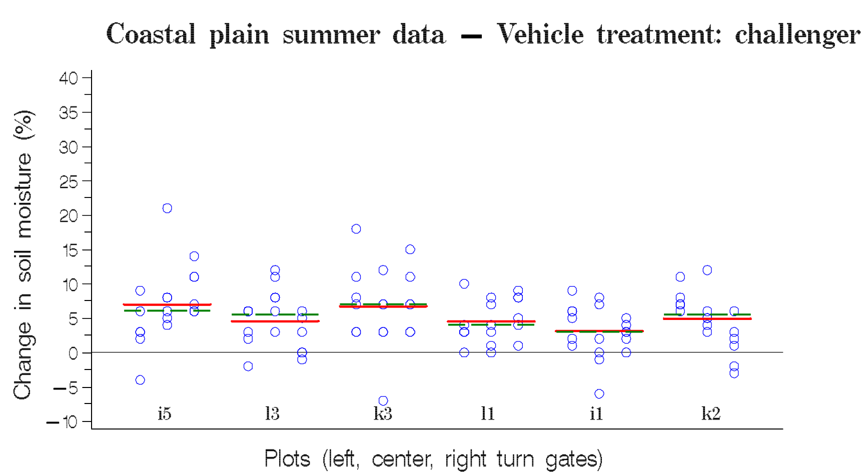

Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

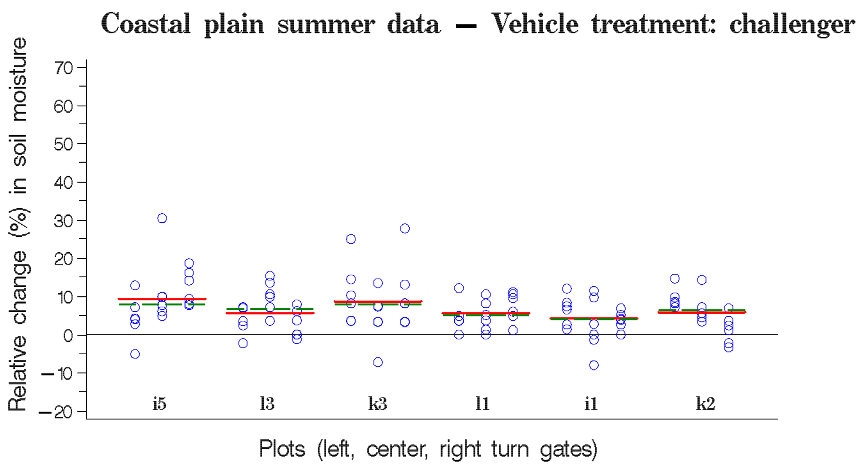

Coastal plain summer data — Vehicle treatment: challenger
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

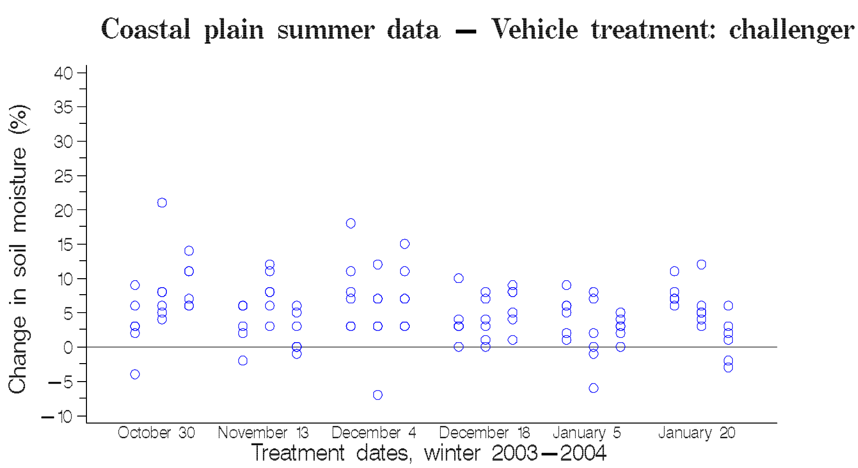

Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

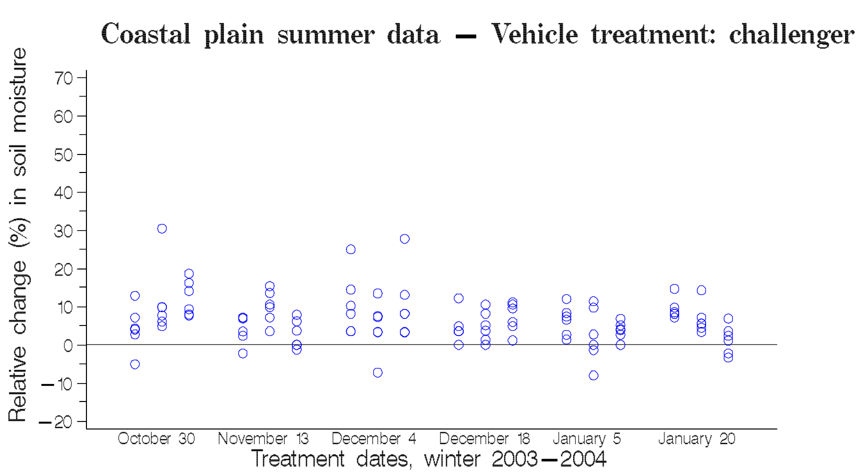

Coastal Plain, summer 2003 - Vehicle treatment: challenger
Soil moisture (%)
110
100
90
80
70
60
50
40
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)


Coastal Plain, summer 2004 - Vehicle treatment: challenger
Soil moisture (%)
110
100
90
80
70
60
50
40
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

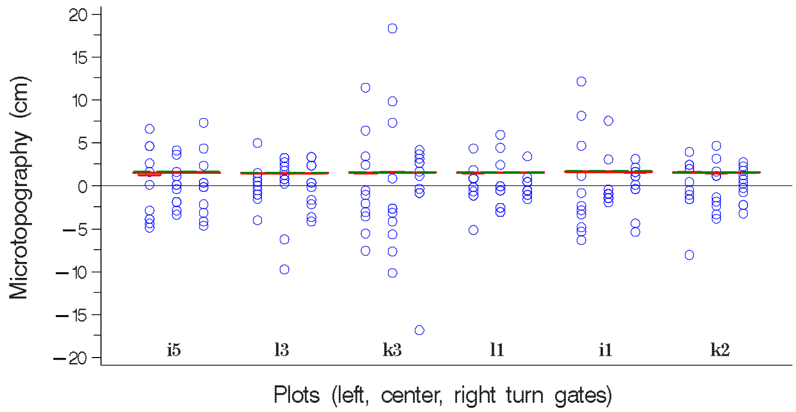

Coastal plain summer data — Vehicle treatment: challenger
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)


Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

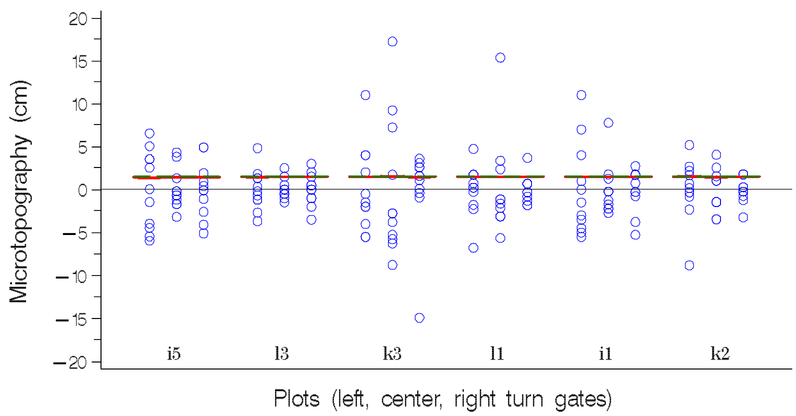

Coastal plain summer data — Vehicle treatment: challenger
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

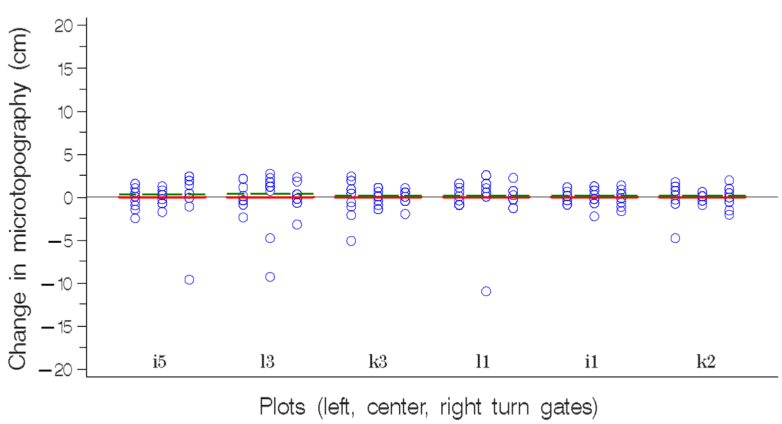
Coastal Plain, summer 2003 - Vehicle treatment: challenger

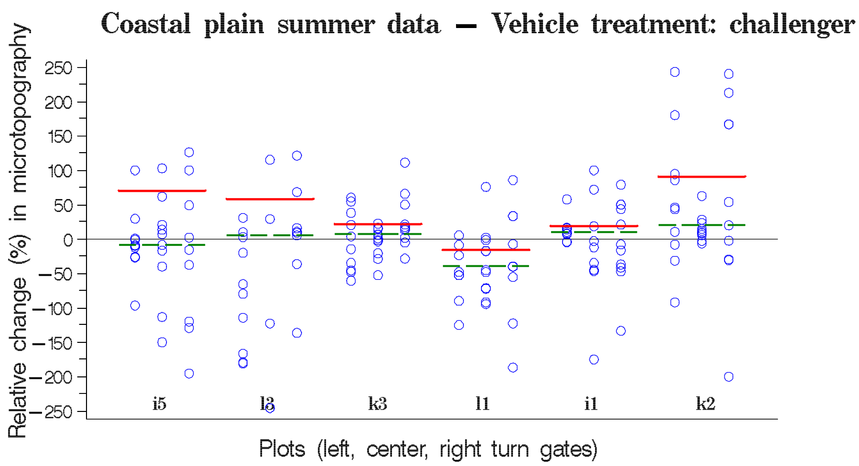


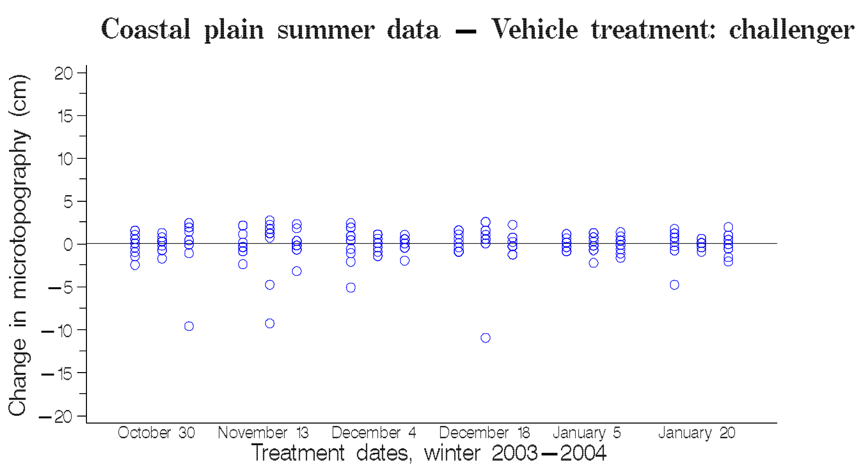
Coastal Plain, summer 2004 - Vehicle treatment: challenger

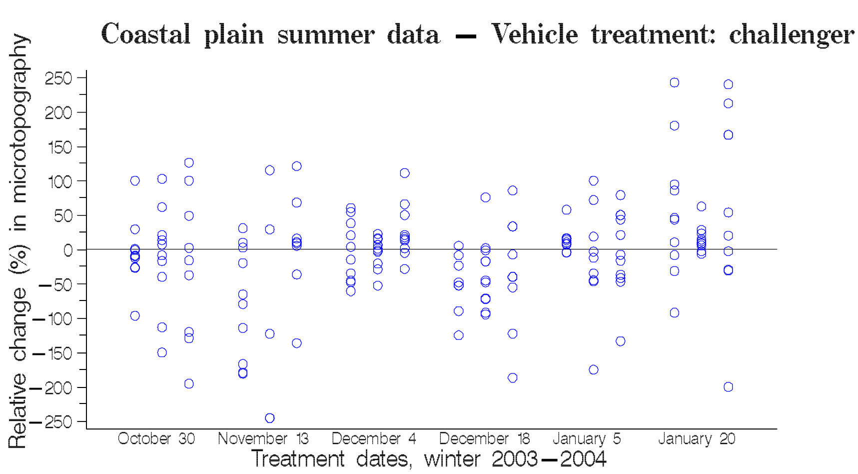


Coastal plain summer data — Vehicle treatment: challenger

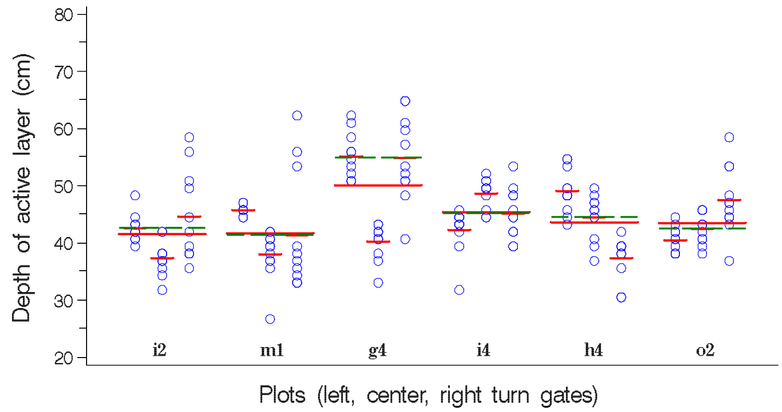



Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
i5
l3
k3
l1
i1
k2
Plots (left, center, right turn gates)

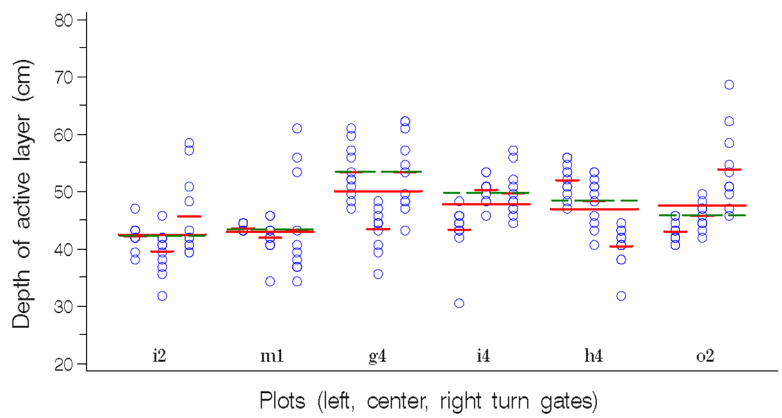

Coastal plain summer data — Vehicle treatment: challenger
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: challenger
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

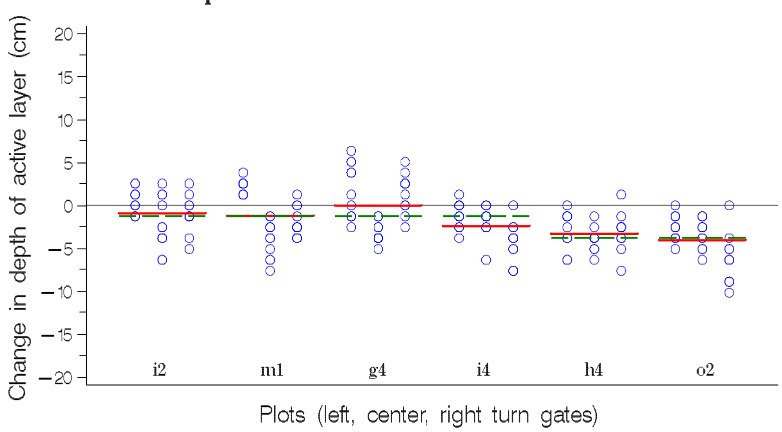
Coastal Plain, summer 2003 - Vehicle treatment: tucker

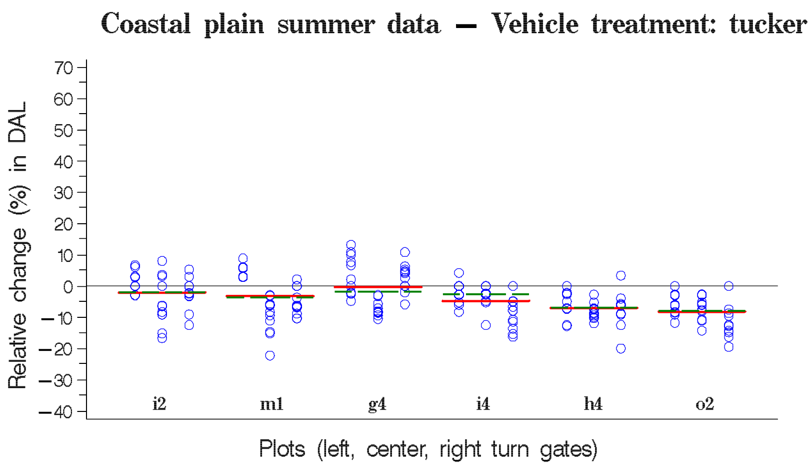


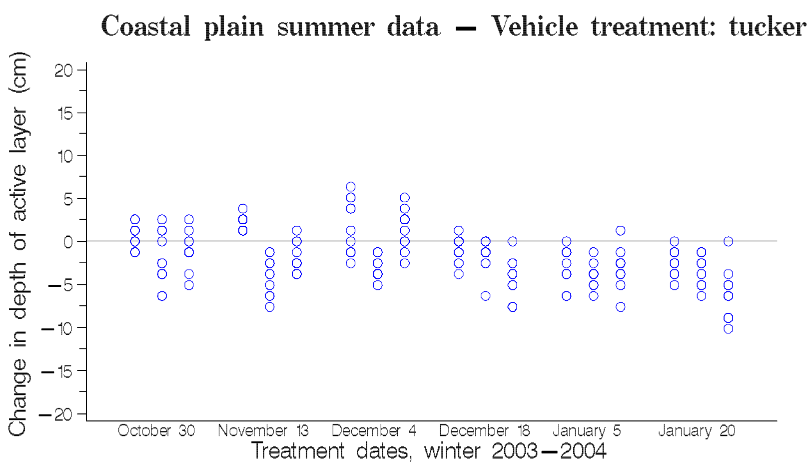
Coastal Plain, summer 2004 - Vehicle treatment: tucker

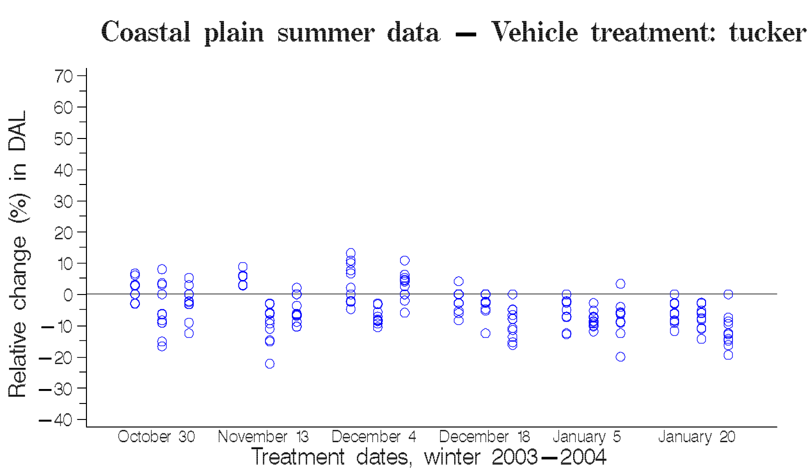


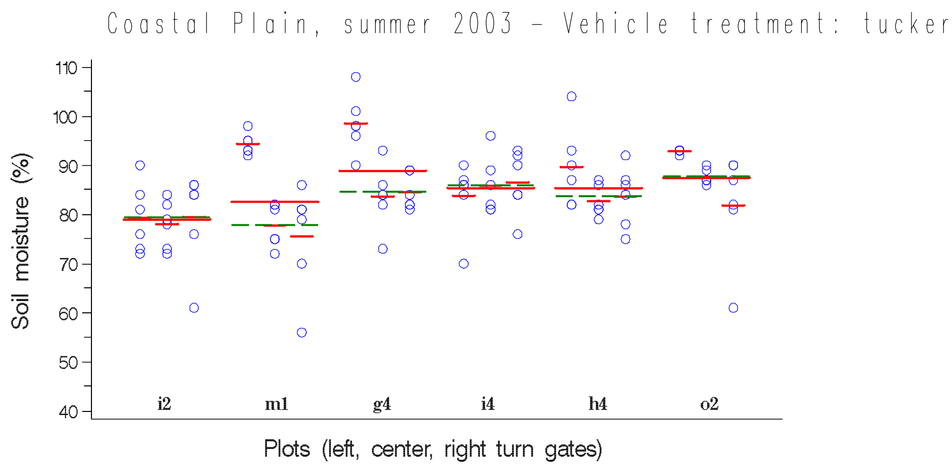
Coastal plain summer data — Vehicle treatment: tucker

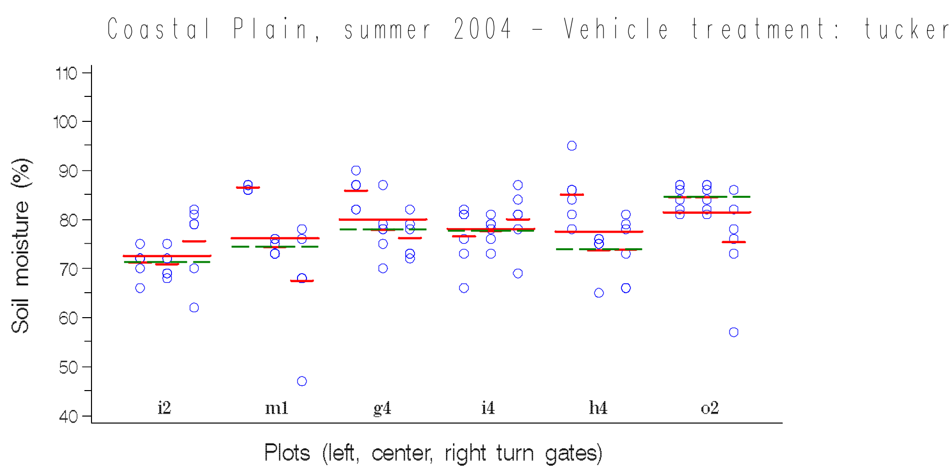


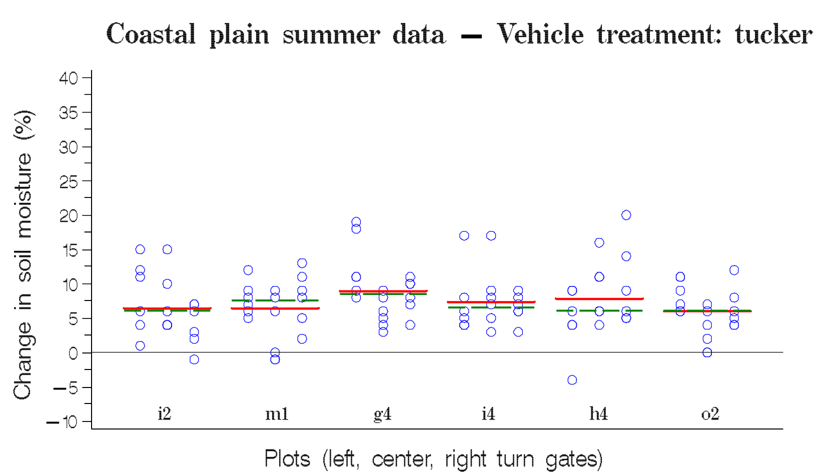

Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)

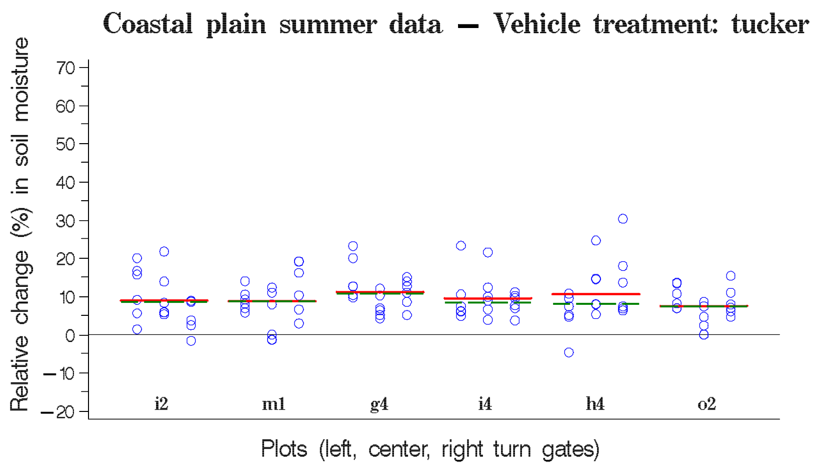

Coastal plain summer data — Vehicle treatment: tucker
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in DAL
70
60
50
40
30
20
10
0
−10
−20
−30
−40
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

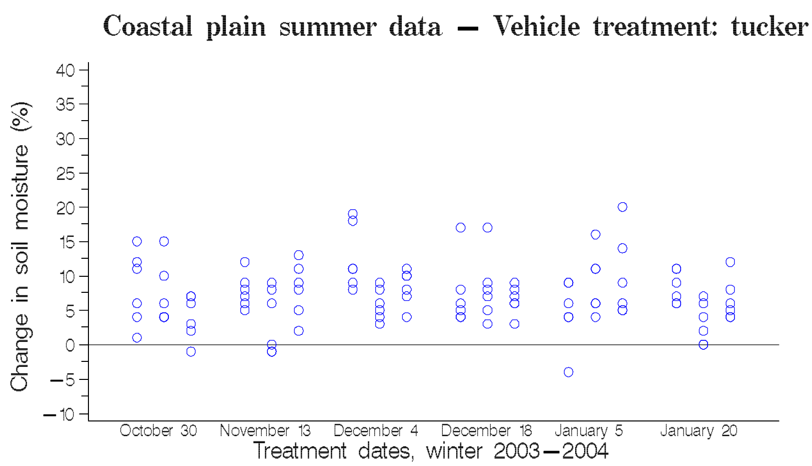

Coastal Plain, summer 2003 - Vehicle treatment: tucker
Soil moisture (%)
110
100
90
80
70
60
50
40
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)


Coastal Plain, summer 2004 - Vehicle treatment: tucker
Soil moisture (%)
110
100
90
80
70
60
50
40
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)

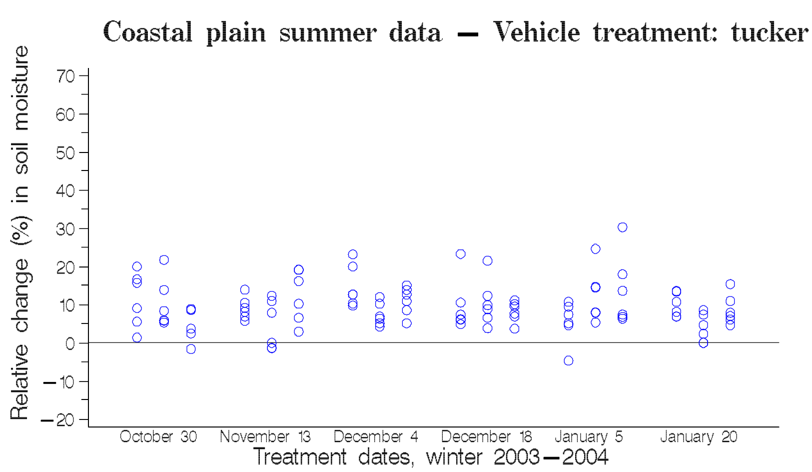

Coastal plain summer data — Vehicle treatment: tucker
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)



Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)

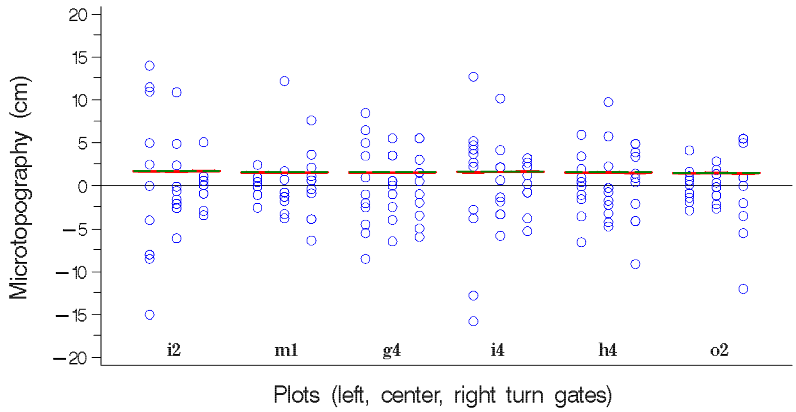


Coastal plain summer data — Vehicle treatment: tucker
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

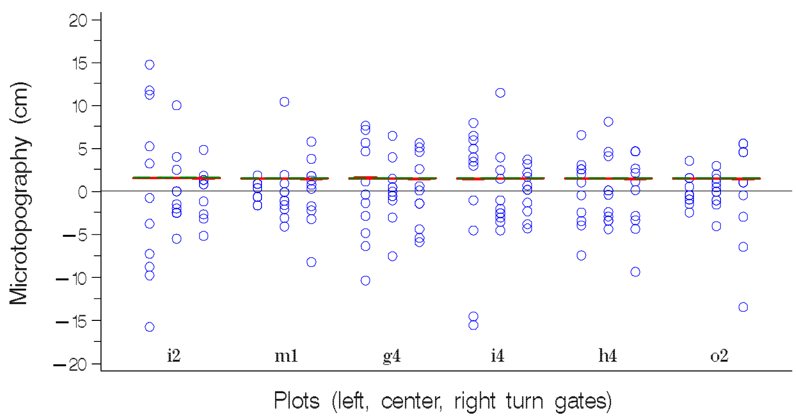


Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

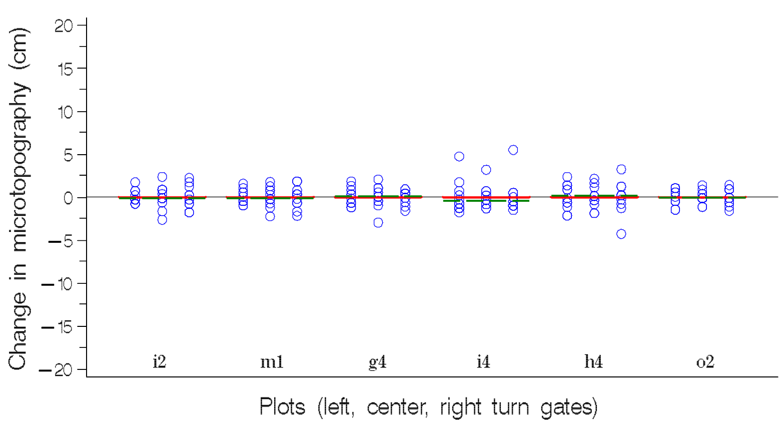
Coastal Plain, summer 2003 - Vehicle treatment: tucker

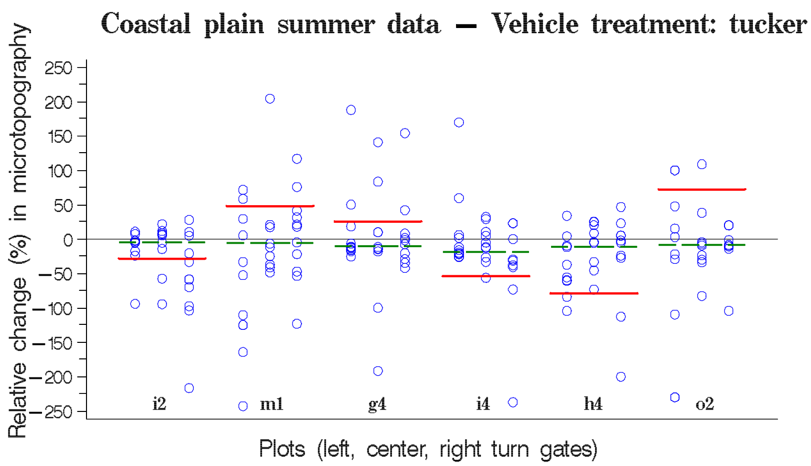


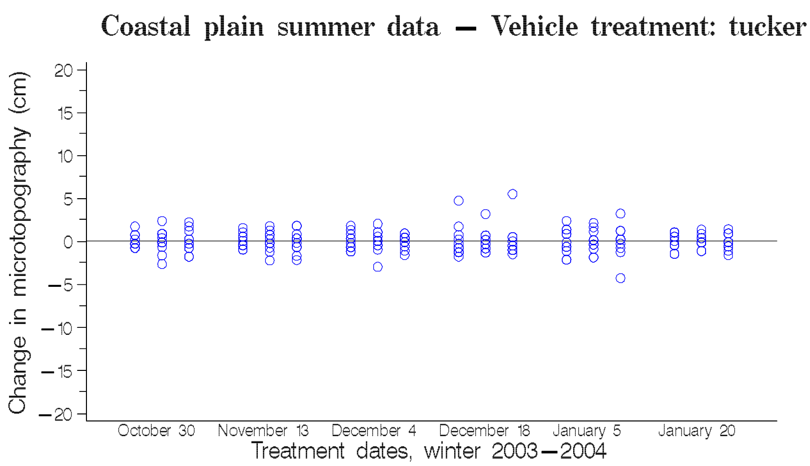
Coastal Plain, summer 2004 - Vehicle treatment: tucker

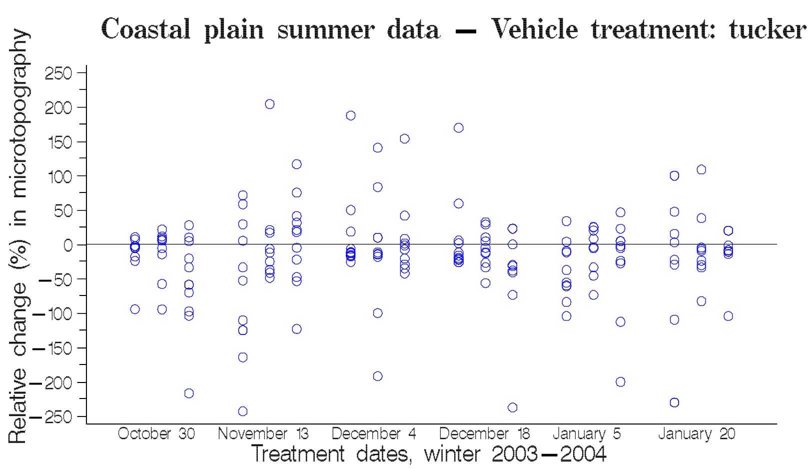


Coastal plain summer data — Vehicle treatment: tucker

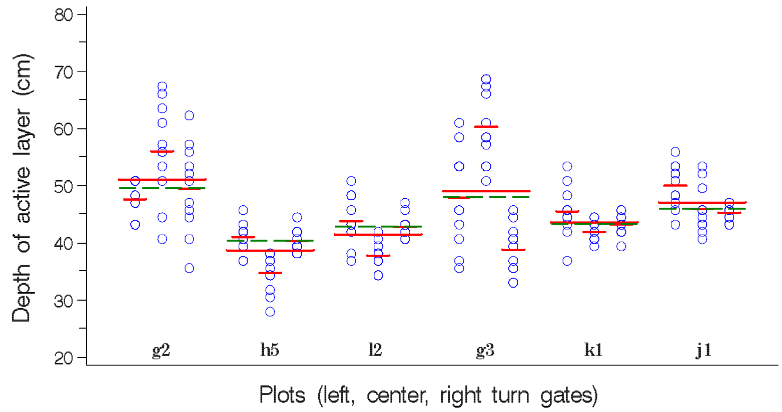



Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
i2
m1
g4
i4
h4
o2
Plots (left, center, right turn gates)

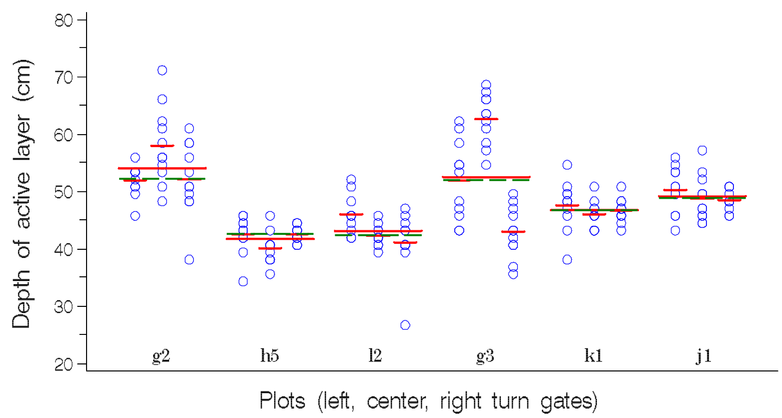

Coastal plain summer data — Vehicle treatment: tucker
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Coastal plain summer data — Vehicle treatment: tucker
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

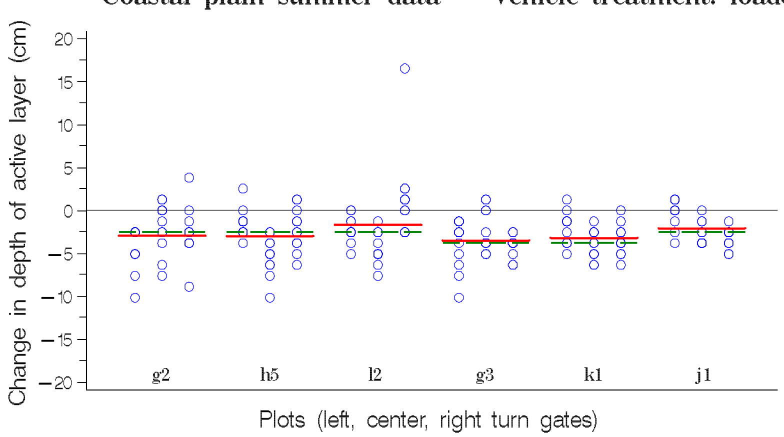
Coastal Plain, summer 2003 – Vehicle treatment: loader



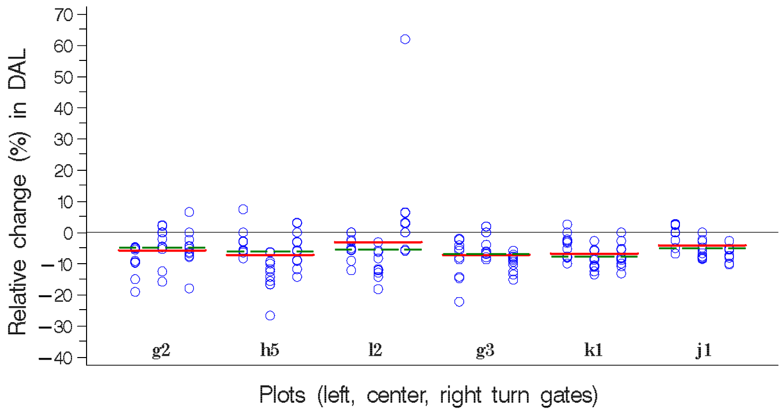
Coastal Plain, summer 2004 – Vehicle treatment: loader



Coastal plain summer data — Vehicle treatment: loader



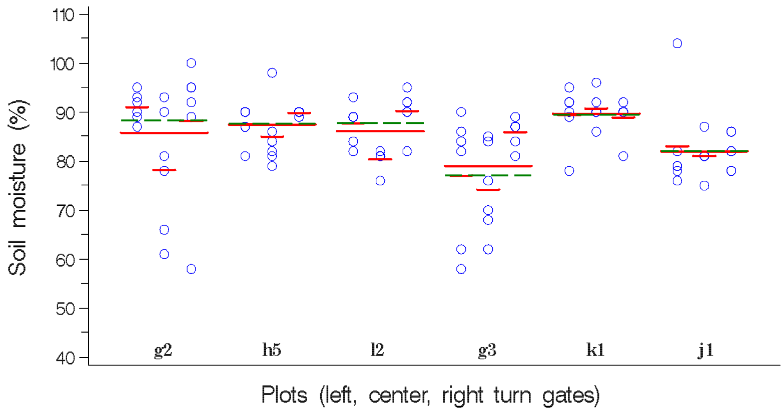
Coastal plain summer data — Vehicle treatment: loader



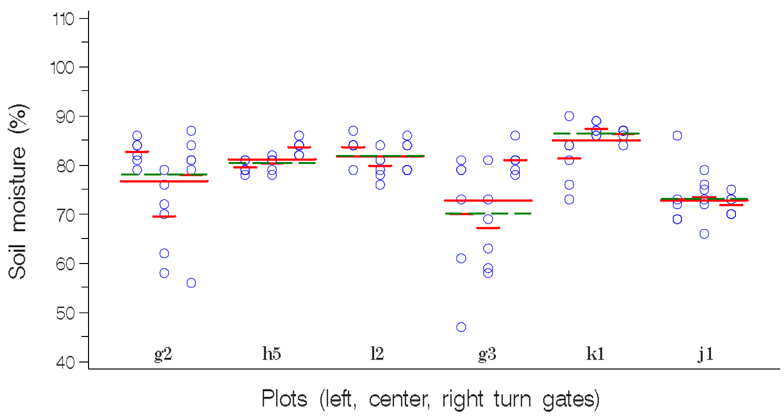
Coastal plain summer data — Vehicle treatment: loader

Coastal plain summer data — Vehicle treatment: loader

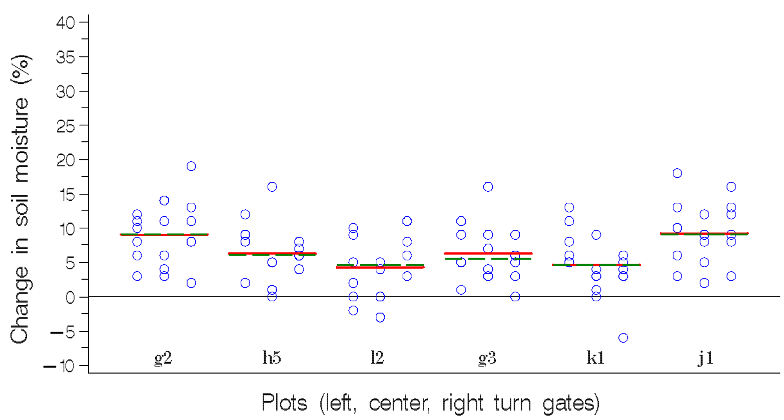
Coastal Plain, summer 2003 – Vehicle treatment: loader

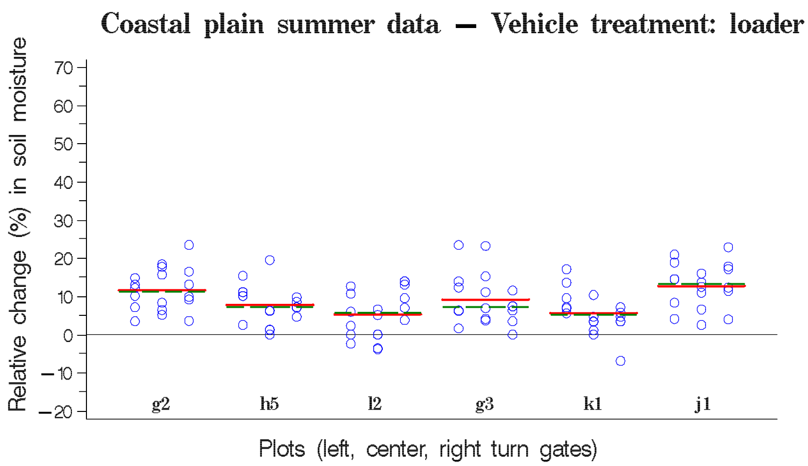


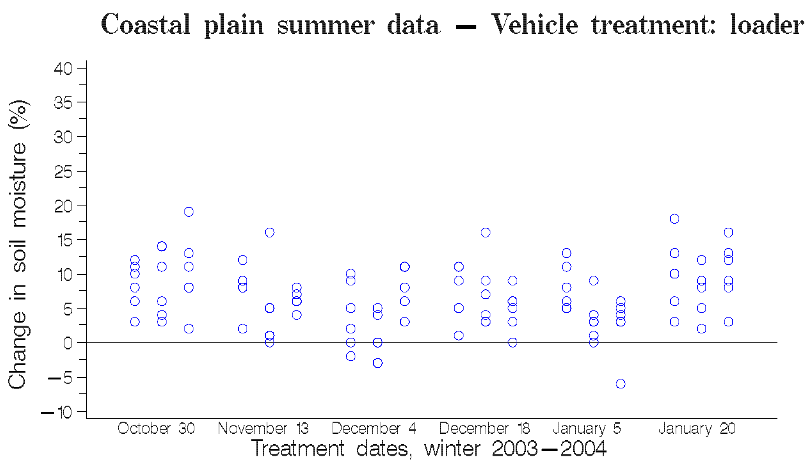
Coastal Plain, summer 2004 – Vehicle treatment: loader

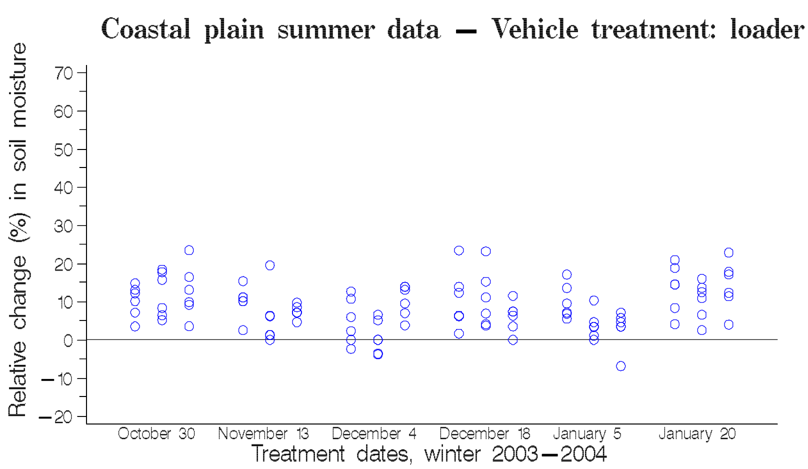


Coastal plain summer data — Vehicle treatment: loader

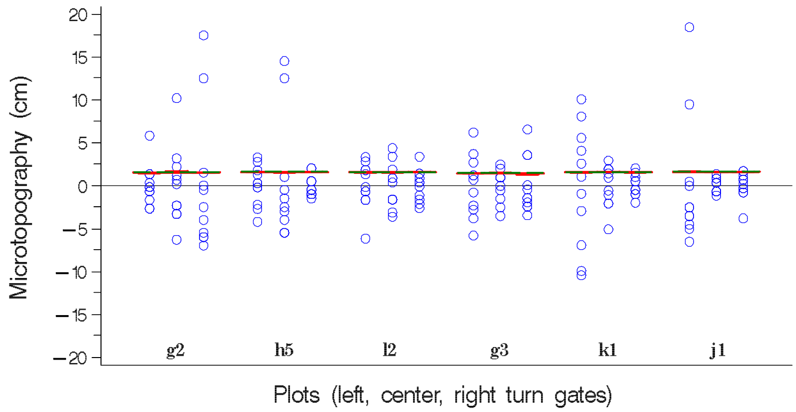



Coastal plain summer data — Vehicle treatment: loader
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
g2
h5
l2
g3
k1
j1
Plots (left, center, right turn gates)

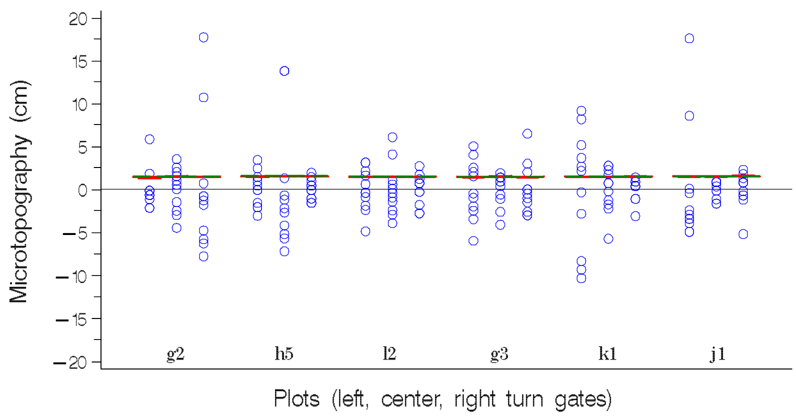

Coastal plain summer data — Vehicle treatment: loader
Change in soil moisture (%)
40
35
30
25
20
15
10
5
0
−5
−10
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003−2004


Coastal plain summer data — Vehicle treatment: loader
Relative change (%) in soil moisture
70
60
50
40
30
20
10
0
−10
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003−2004

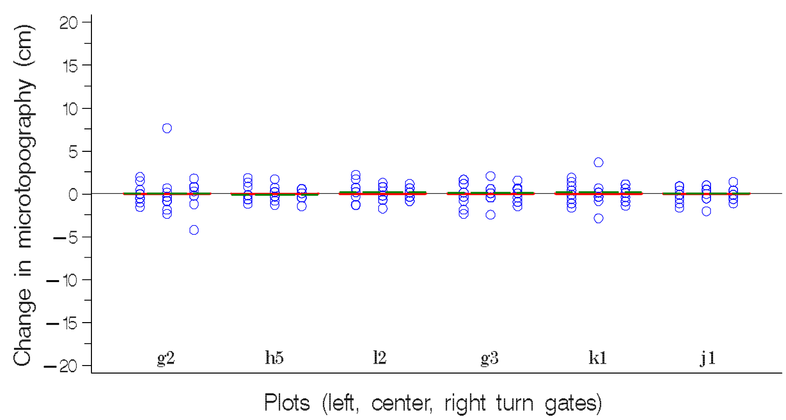
Coastal Plain, summer 2003 - Vehicle treatment: loader

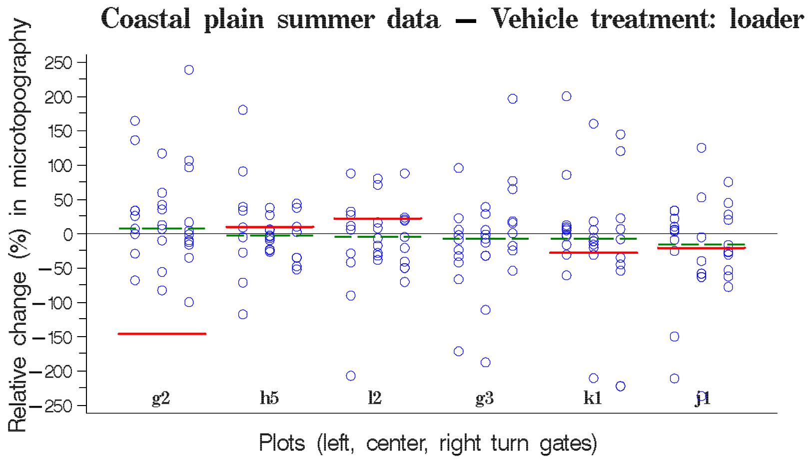


Coastal Plain, summer 2004 - Vehicle treatment: loader

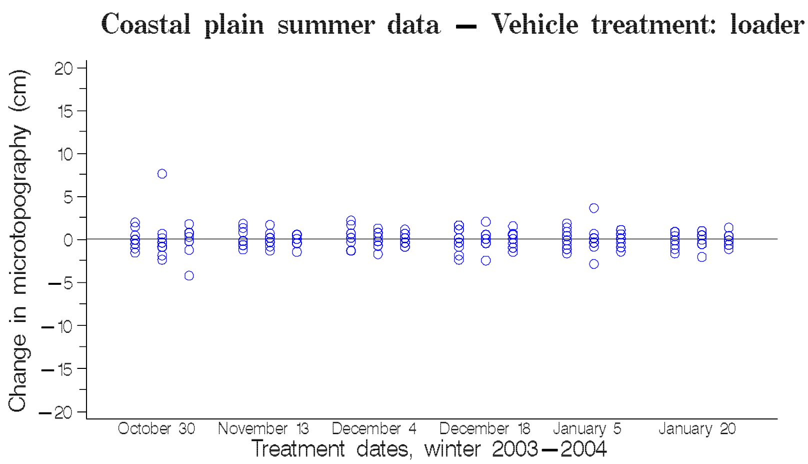


Coastal plain summer data — Vehicle treatment: loader

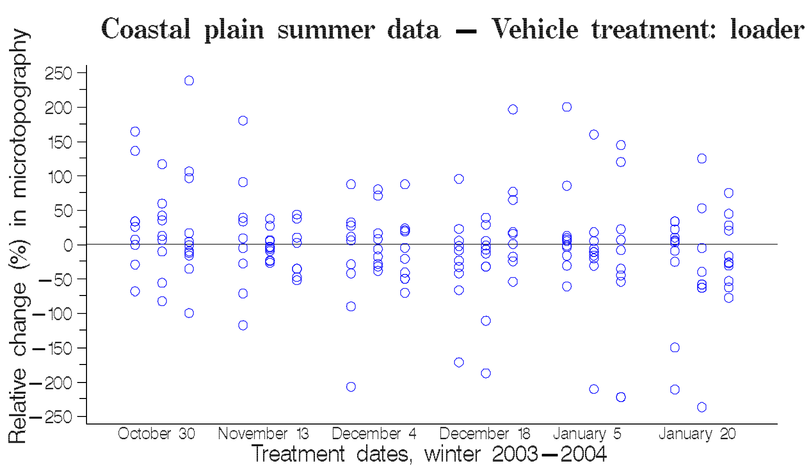




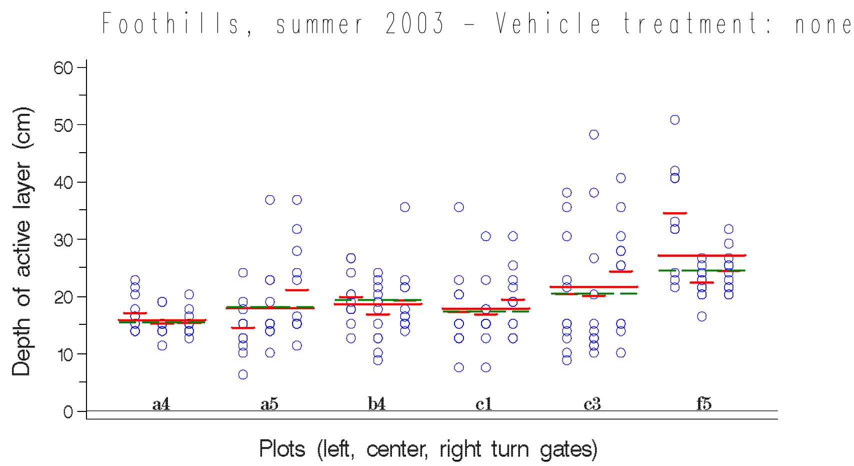
Coastal plain summer data — Vehicle treatment: loader
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
g2
h5
l2
g3
k1
j1
Plots (left, center, right turn gates)

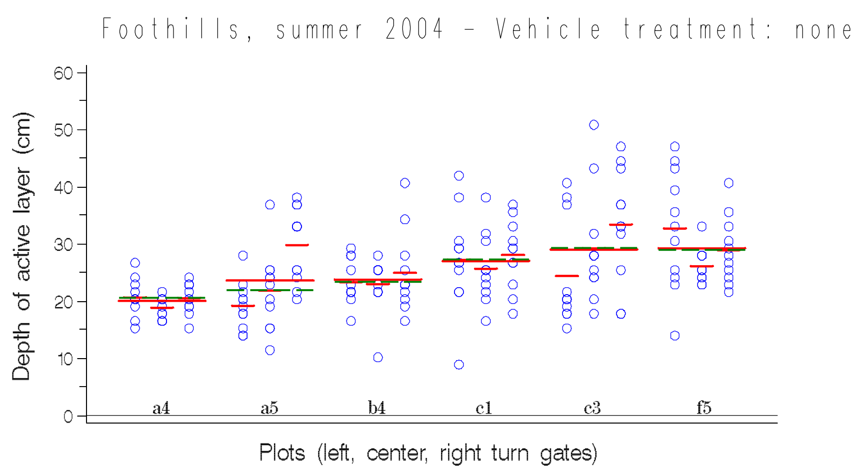


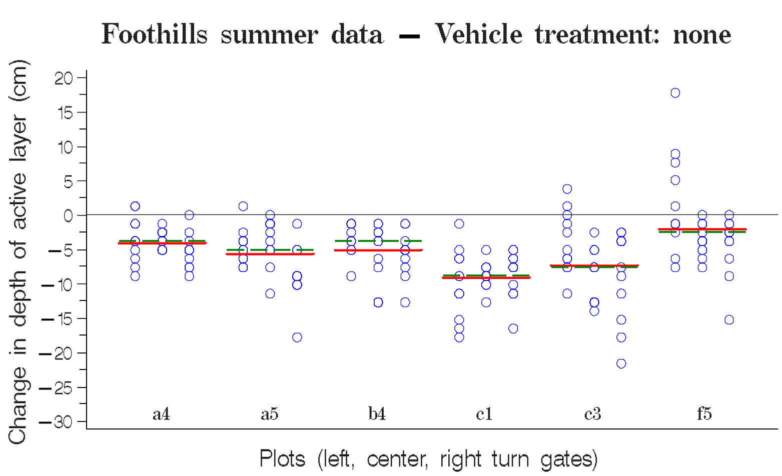
Coastal plain summer data — Vehicle treatment: loader
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004



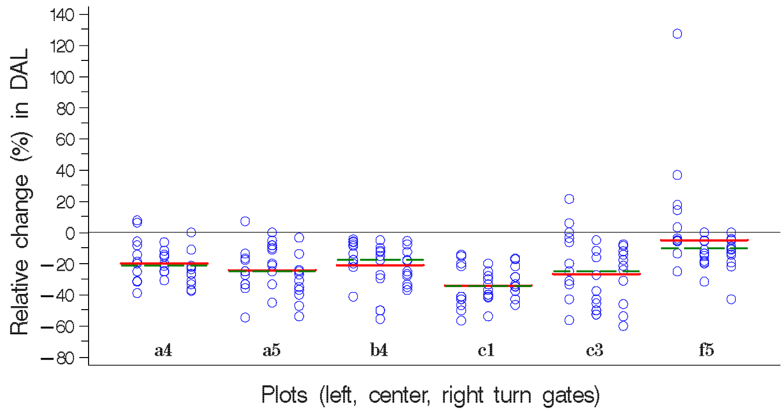
Coastal plain summer data — Vehicle treatment: loader
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Foothills, summer 2003 - Vehicle treatment: none
Depth of active layer (cm)
0
10
20
30
40
50
60
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)

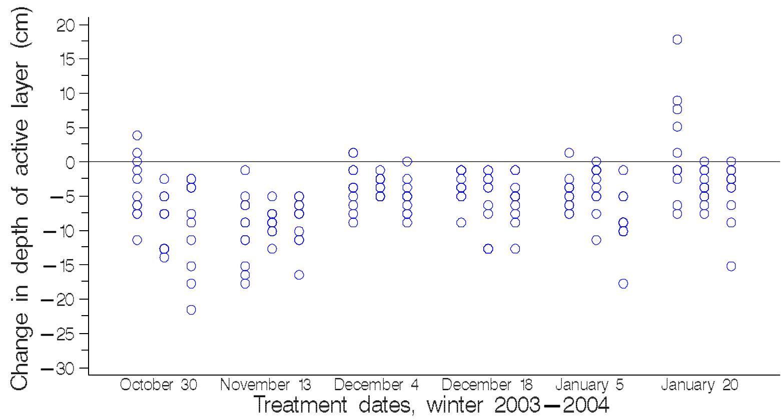

Foothills, summer 2004 - Vehicle treatment: none
Depth of active layer (cm)
0
10
20
30
40
50
60
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)


Foothills summer data — Vehicle treatment: none
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)

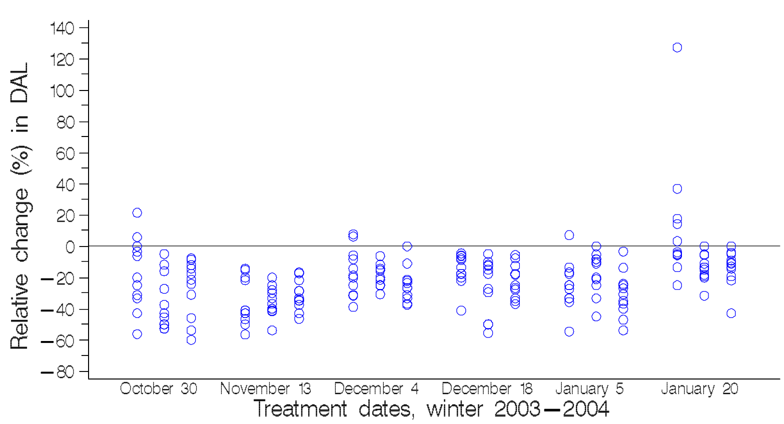
Foothills summer data — Vehicle treatment: none

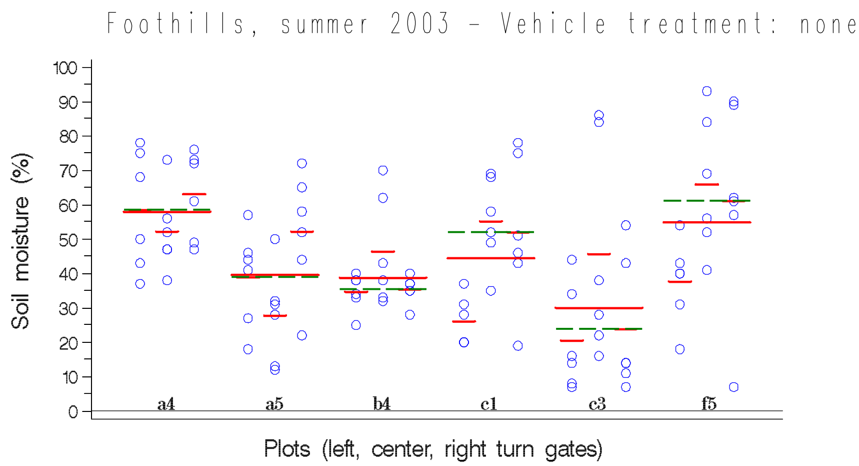


Foothills summer data — Vehicle treatment: none

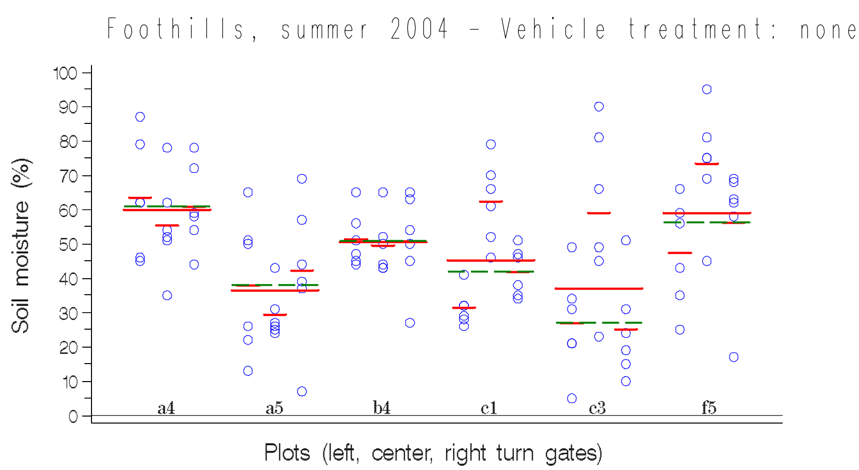


Foothills summer data — Vehicle treatment: none

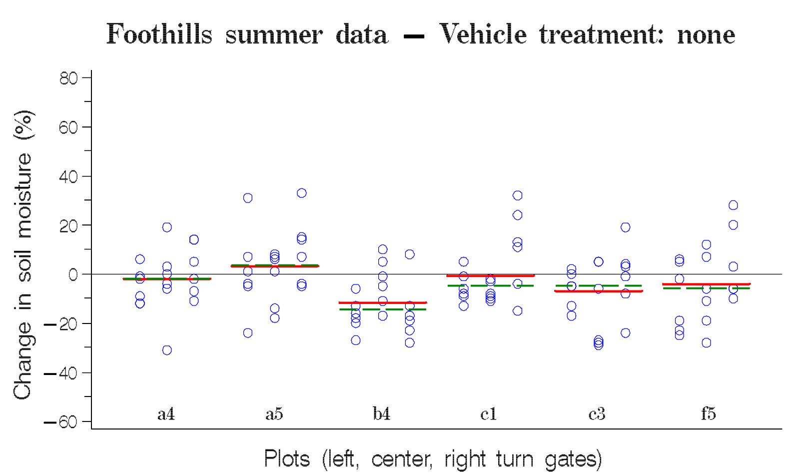




Foothills, summer 2003 - Vehicle treatment: none
Soil moisture (%)
0
10
20
30
40
50
60
70
80
90
100
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)

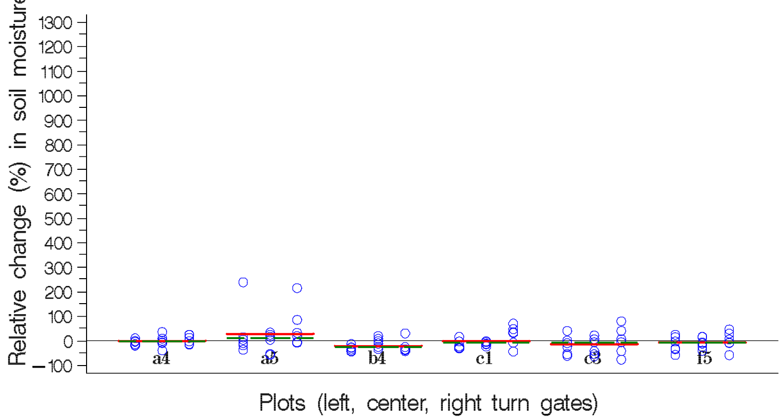


Foothills, summer 2004 - Vehicle treatment: none
Soil moisture (%)
0
10
20
30
40
50
60
70
80
90
100
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)



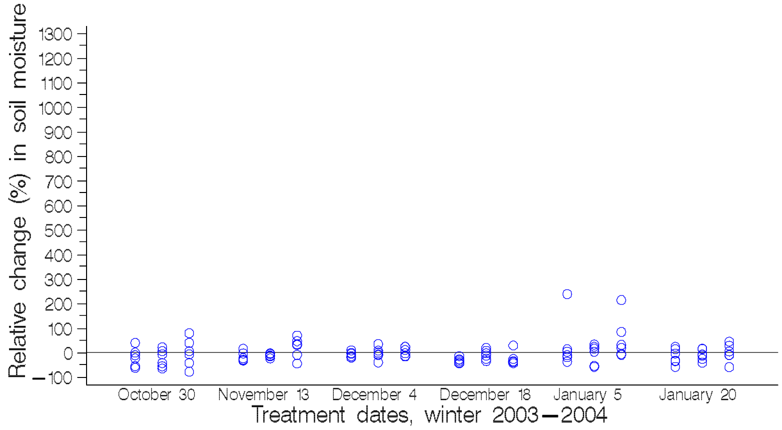
Foothills summer data — Vehicle treatment: none
Change in soil moisture (%)
−60
−40
−20
0
20
40
60
80
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)

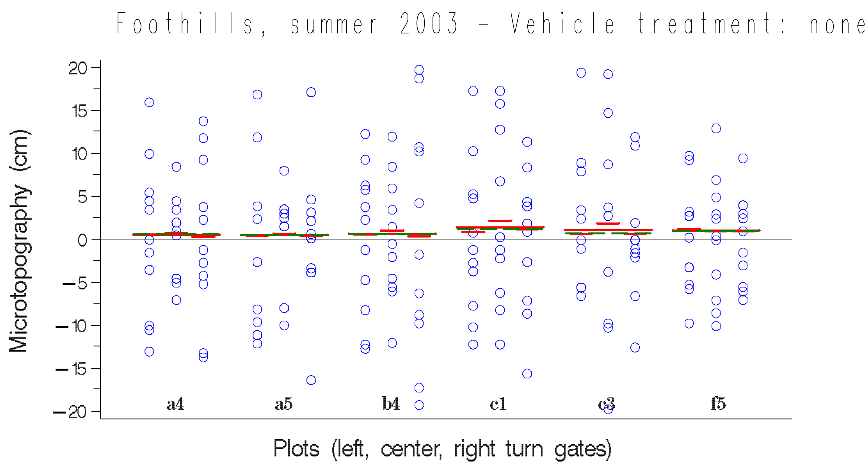
Foothills summer data — Vehicle treatment: none

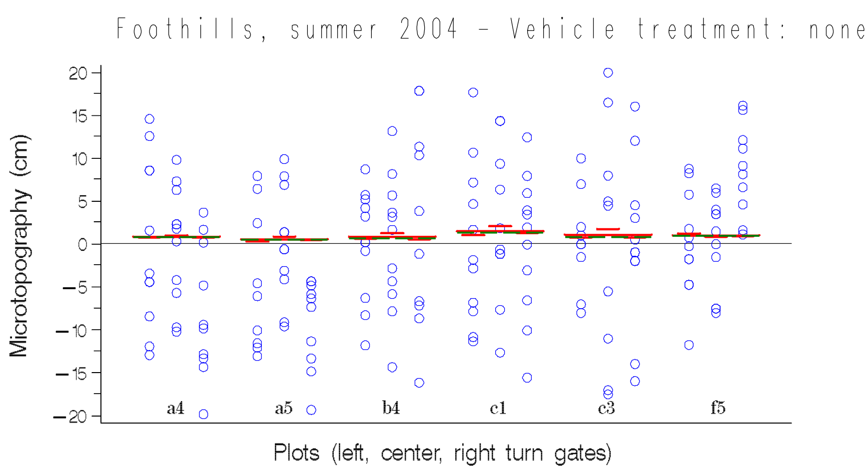


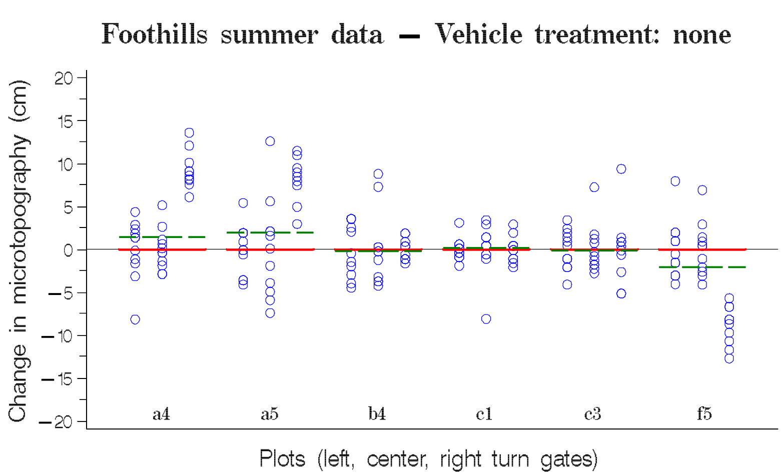
Foothills summer data — Vehicle treatment: none

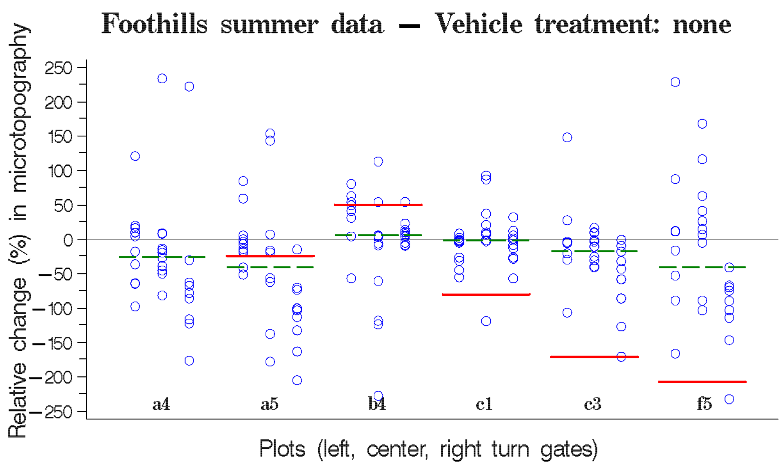
Foothills summer data — Vehicle treatment: none



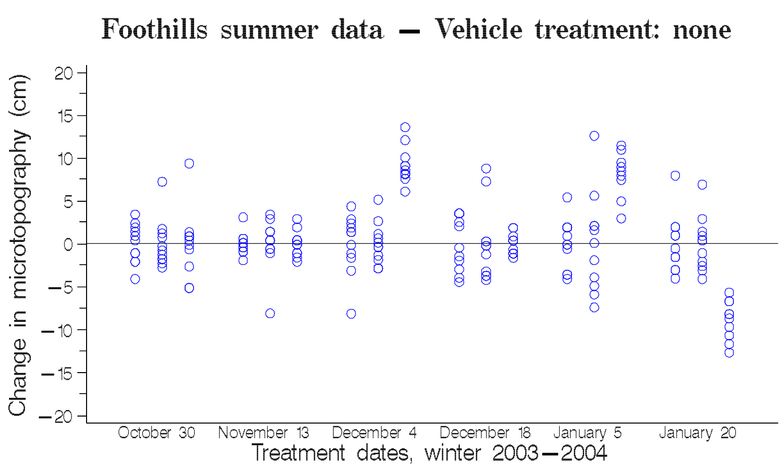

Foothills, summer 2003 - Vehicle treatment: none
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: none
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)

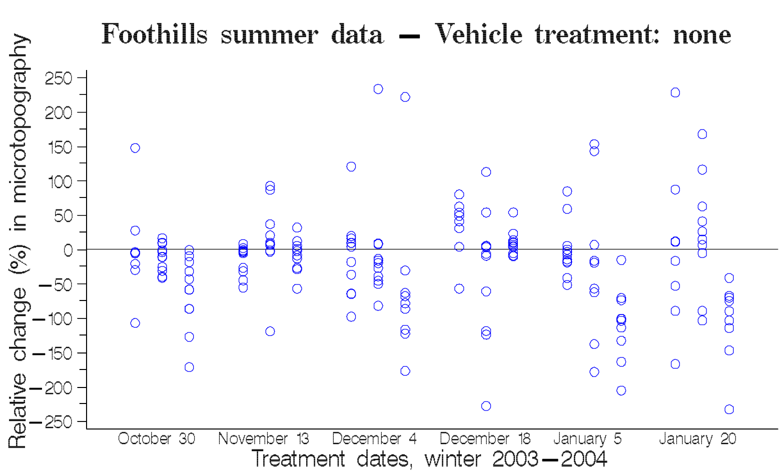

Foothills summer data — Vehicle treatment: none
Change in microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a4
a5
b4
c1
c3
f5
Plots (left, center, right turn gates)



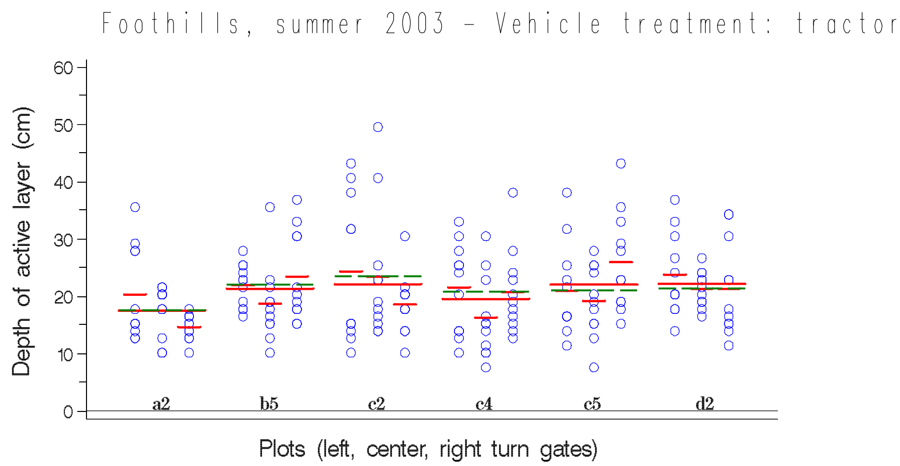
Foothills summer data — Vehicle treatment: none
Relative change (%) in microtopography
Plots (left, center, right turn gates)
a4
a5
b4
c1
c3
f5

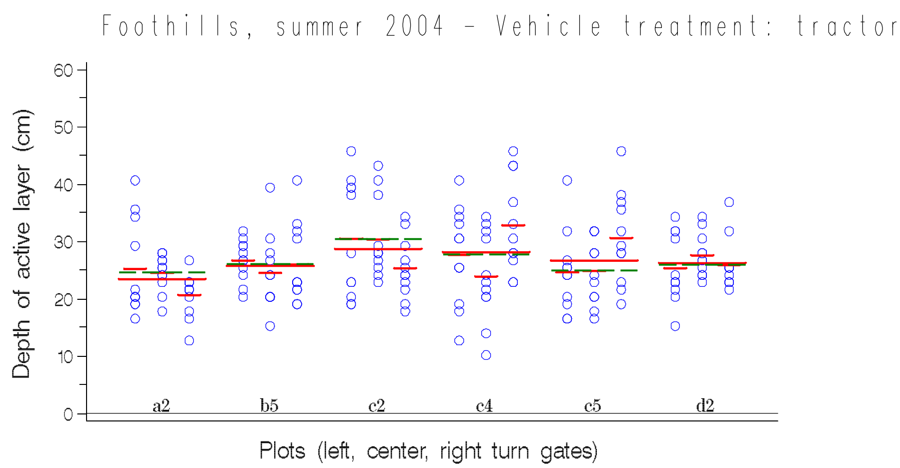


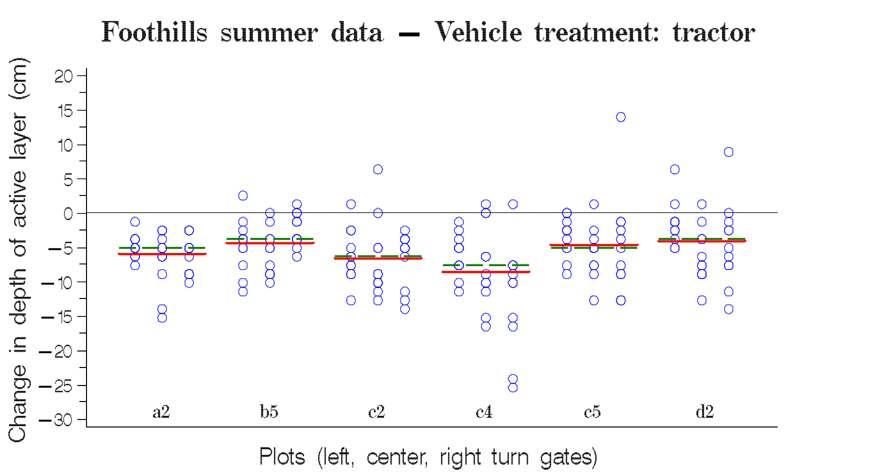
Foothills summer data — Vehicle treatment: none
Change in microtopography (cm)
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

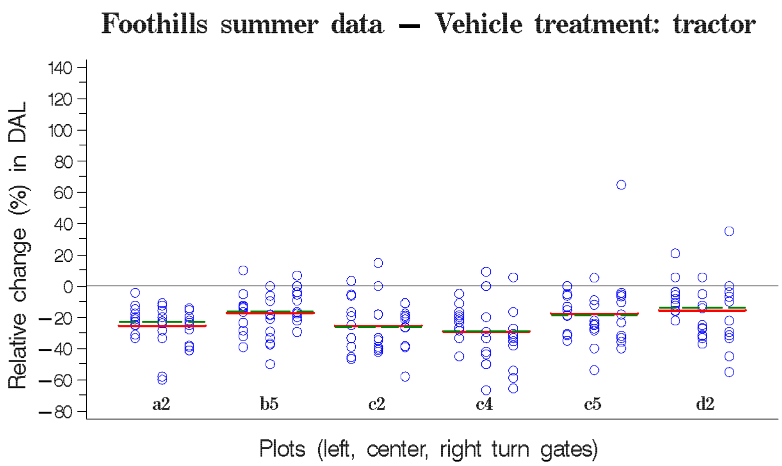


Foothills summer data — Vehicle treatment: none
Relative change (%) in microtopography
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

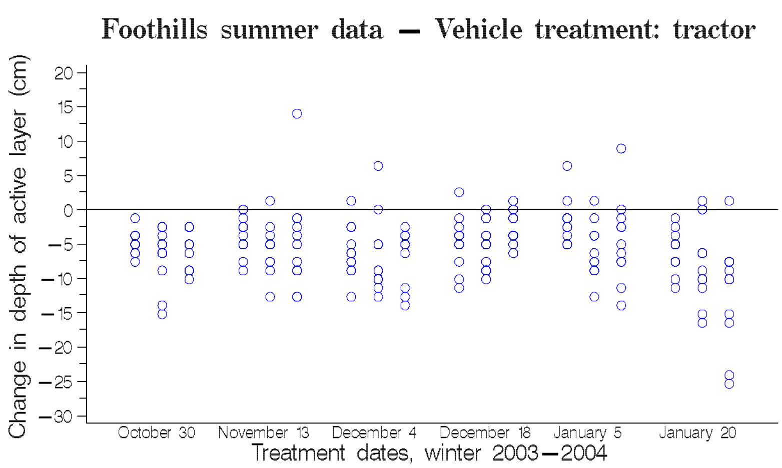

Foothills, summer 2003 - Vehicle treatment: tractor
Depth of active layer (cm)
0
10
20
30
40
50
60
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: tractor
Depth of active layer (cm)
0
10
20
30
40
50
60
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

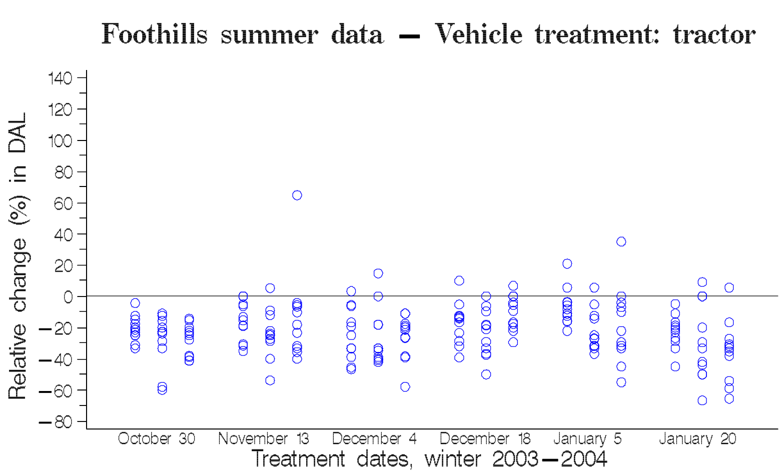

Foothills summer data — Vehicle treatment: tractor
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)



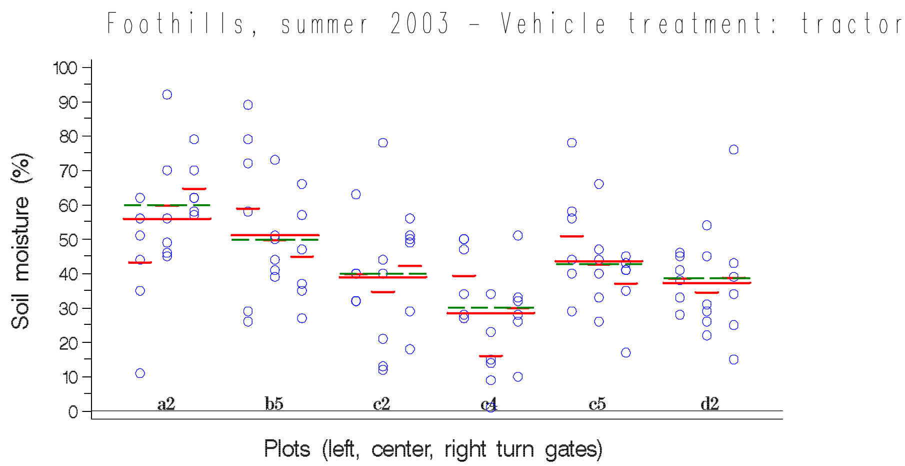
Foothills summer data — Vehicle treatment: tractor
Relative change (%) in DAL
140
120
100
80
60
40
20
0
−20
−40
−60
−80
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

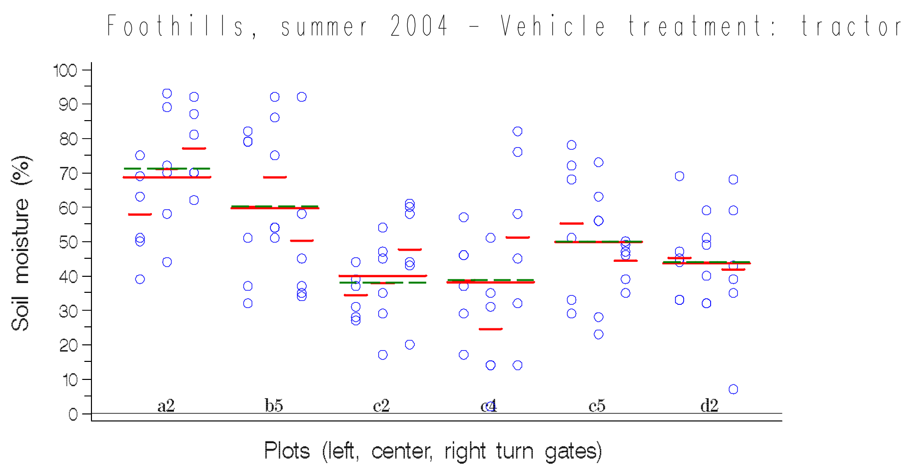


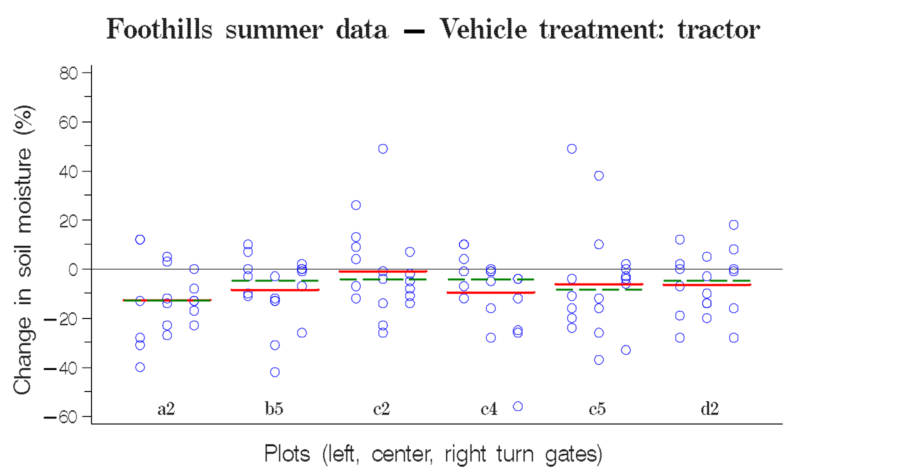
Foothills summer data — Vehicle treatment: tractor
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004



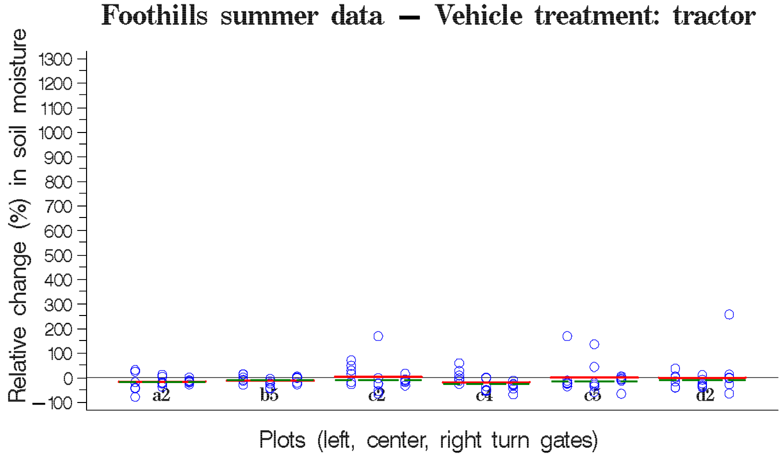
Foothills summer data — Vehicle treatment: tractor
Relative change (%) in DAL
140
120
100
80
60
40
20
0
−20
−40
−60
−80
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Foothills, summer 2003 - Vehicle treatment: tractor
Soil moisture (%)
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: tractor
Soil moisture (%)
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

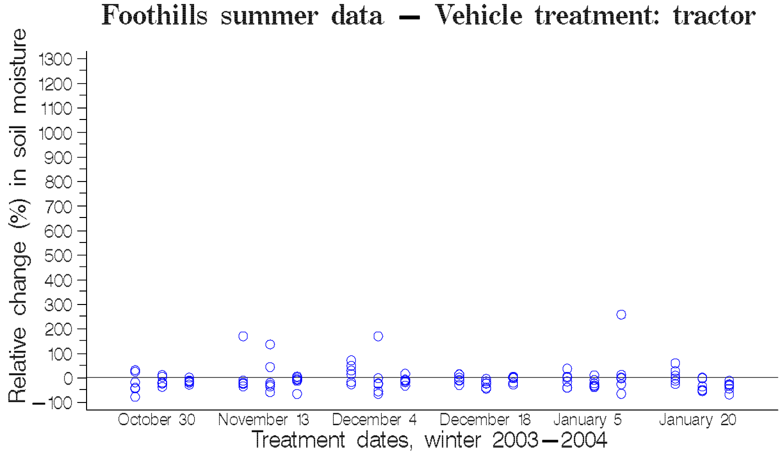

Foothills summer data — Vehicle treatment: tractor
Change in soil moisture (%)
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

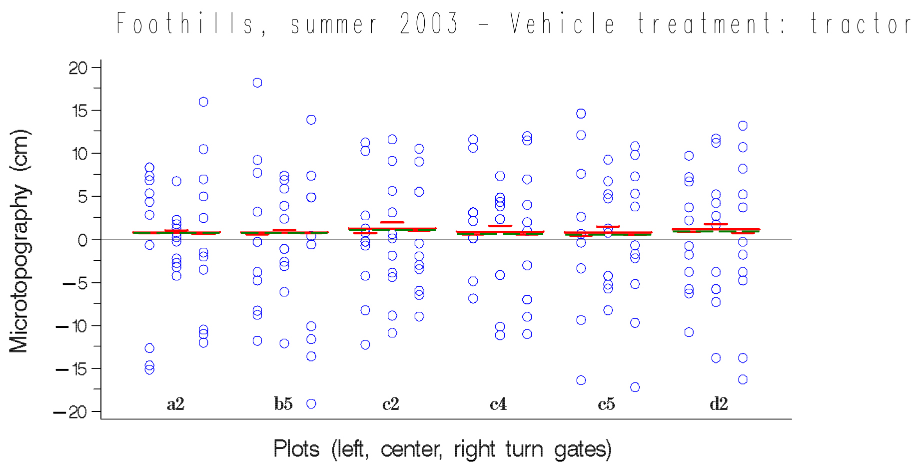
Foothills summer data — Vehicle treatment: tractor

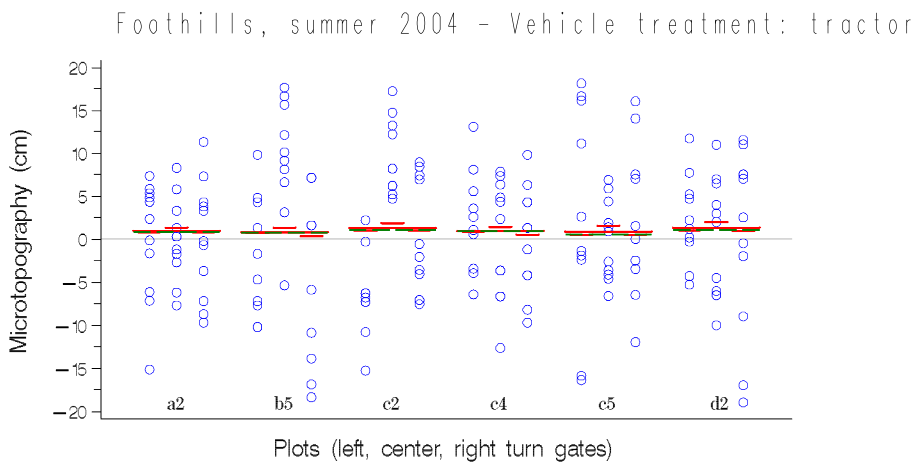


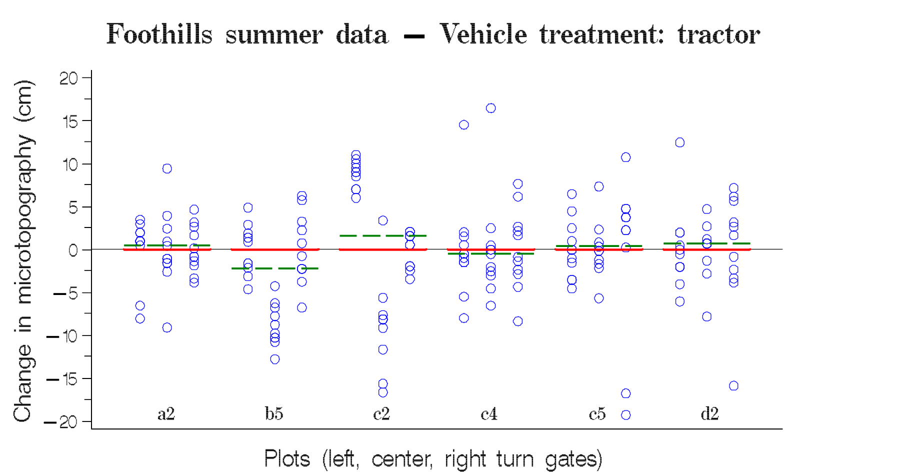
Foothills summer data — Vehicle treatment: tractor

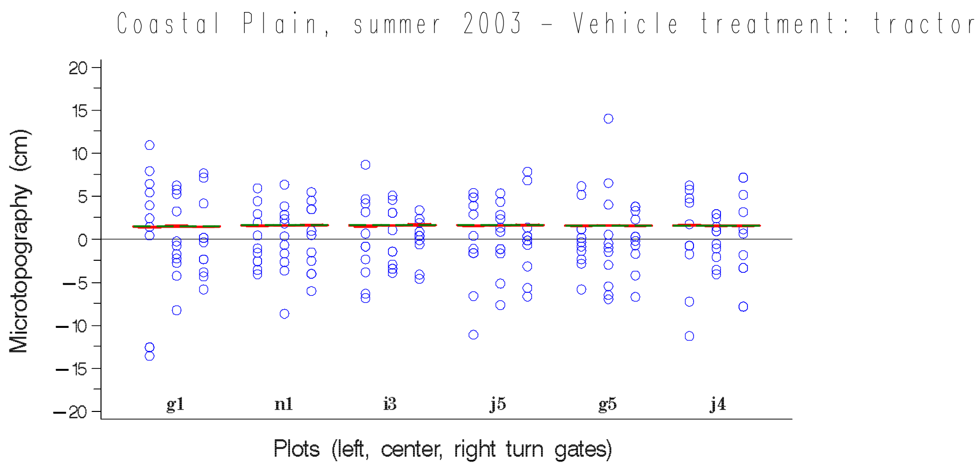
Foothills summer data — Vehicle treatment: tractor

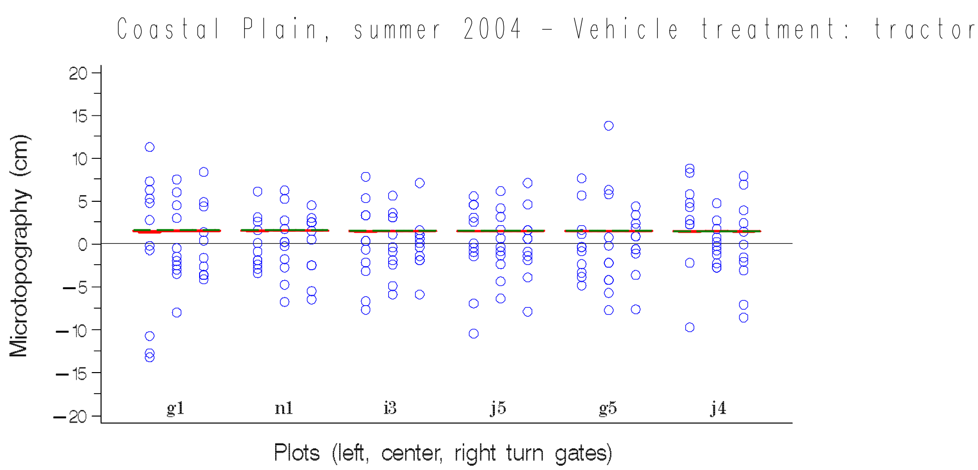


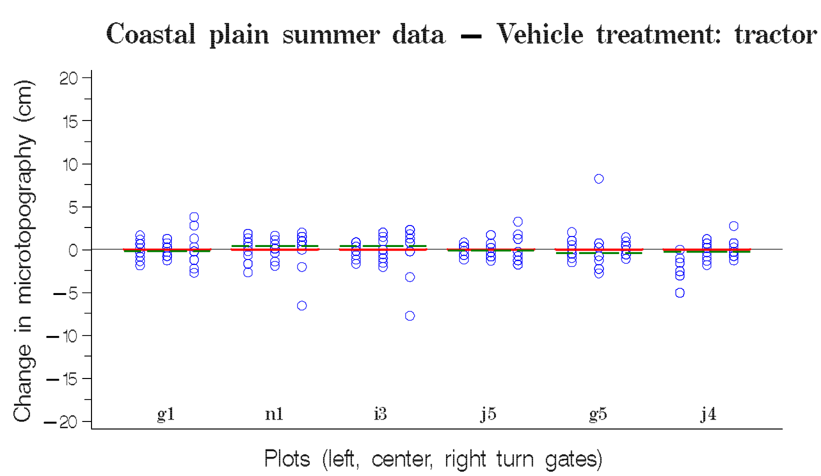

Foothills, summer 2003 – Vehicle treatment: tractor
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

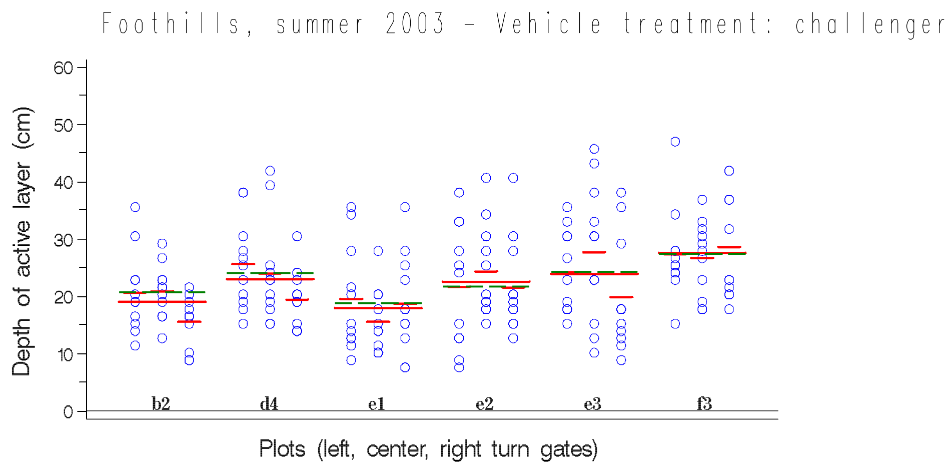

Foothills, summer 2004 – Vehicle treatment: tractor
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

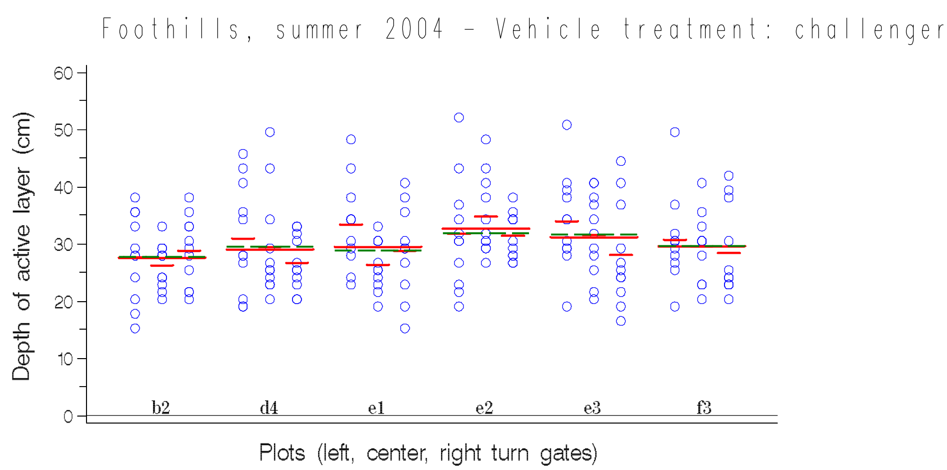

Foothills summer data — Vehicle treatment: tractor
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
a2
b5
c2
c4
c5
d2
Plots (left, center, right turn gates)

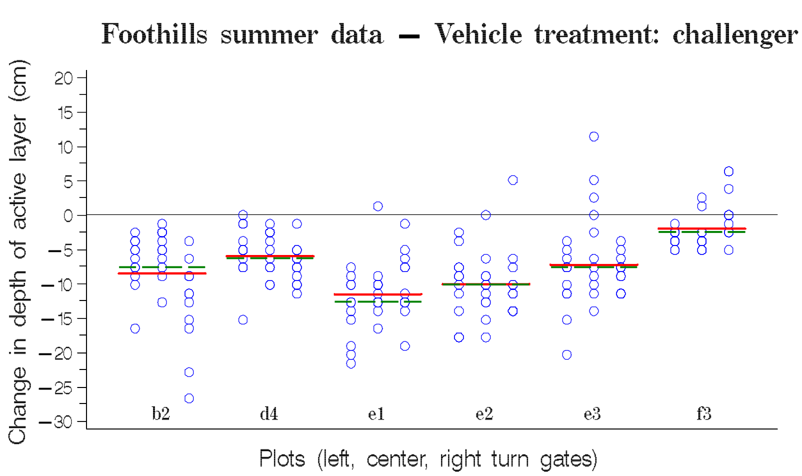

Coastal Plain, summer 2003 – Vehicle treatment: tractor
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
g1
n1
i3
j5
g5
j4
Plots (left, center, right turn gates)


Coastal Plain, summer 2004 – Vehicle treatment: tractor
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
g1
n1
i3
j5
g5
j4
Plots (left, center, right turn gates)

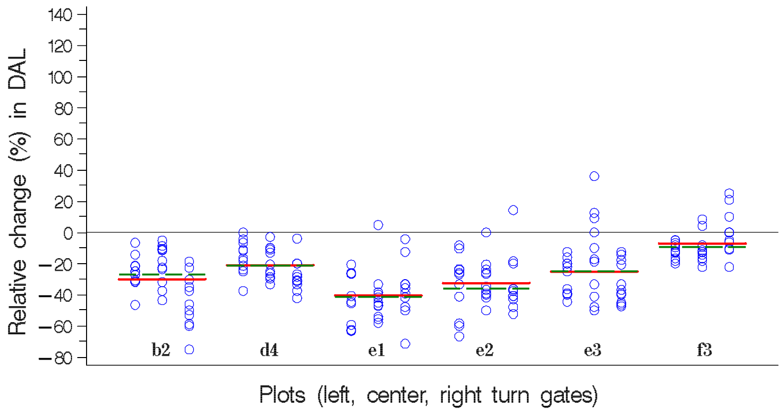

Coastal plain summer data — Vehicle treatment: tractor
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
g1
n1
i3
j5
g5
j4
Plots (left, center, right turn gates)


Foothills, summer 2003 - Vehicle treatment: challenger
Depth of active layer (cm)
60
50
40
30
20
10
0
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: challenger
Depth of active layer (cm)
60
50
40
30
20
10
0
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

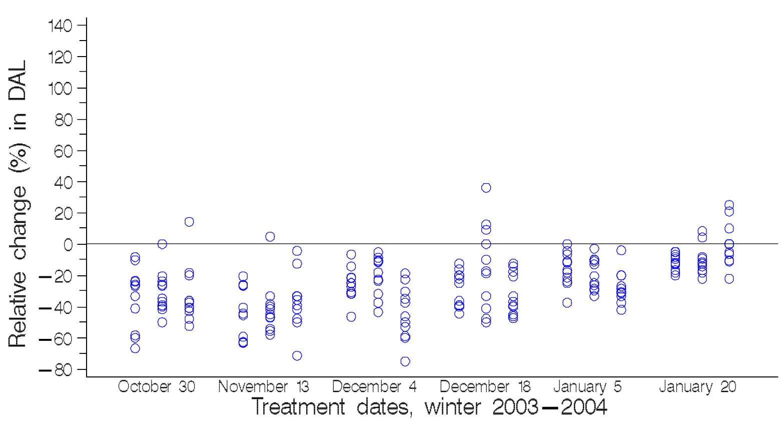

Foothills summer data — Vehicle treatment: challenger
Change in depth of active layer (cm)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

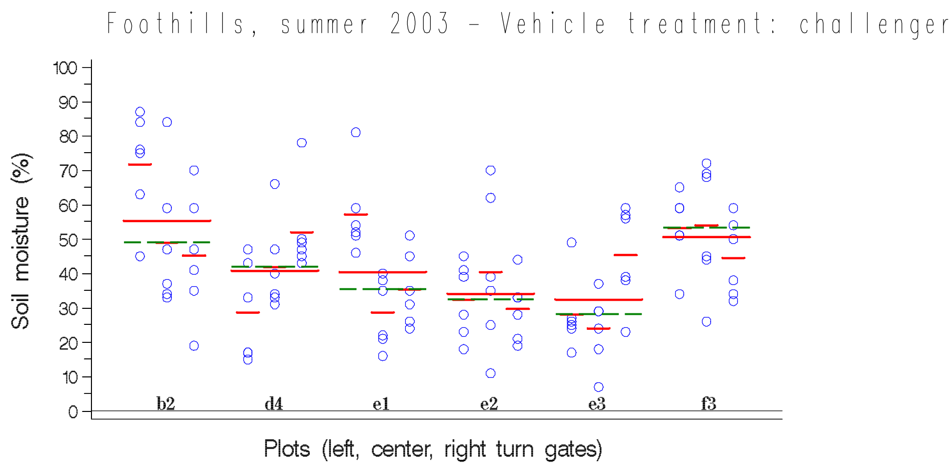
Foothills summer data — Vehicle treatment: challenger

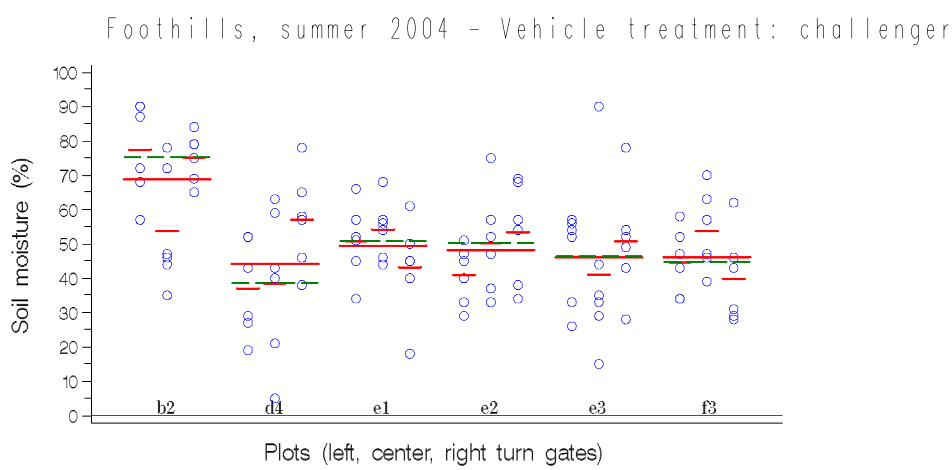


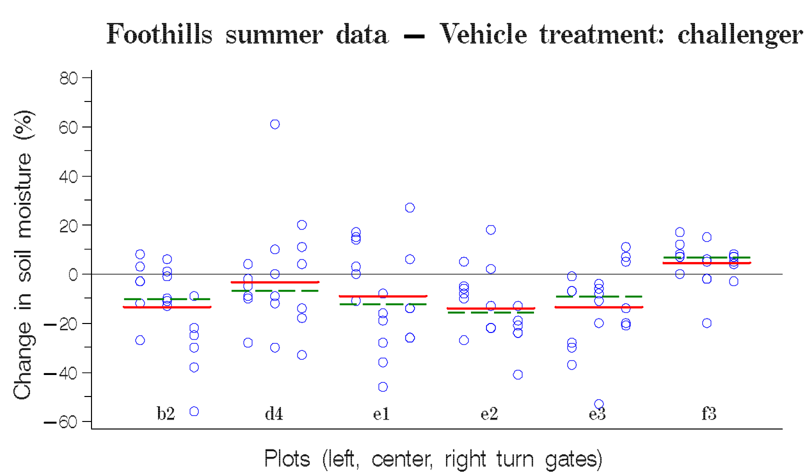
Foothills summer data — Vehicle treatment: challenger

Foothills summer data — Vehicle treatment: challenger

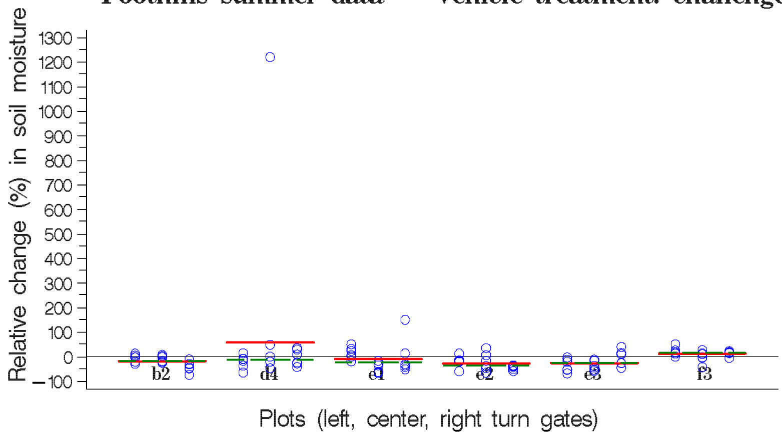



Foothills, summer 2003 - Vehicle treatment: challenger
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: challenger
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

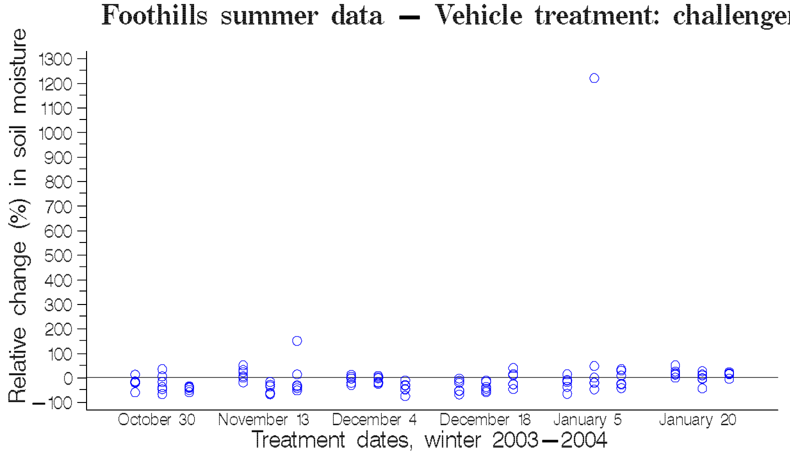

Foothills summer data — Vehicle treatment: challenger
Change in soil moisture (%)
80
60
40
20
0
−20
−40
−60
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

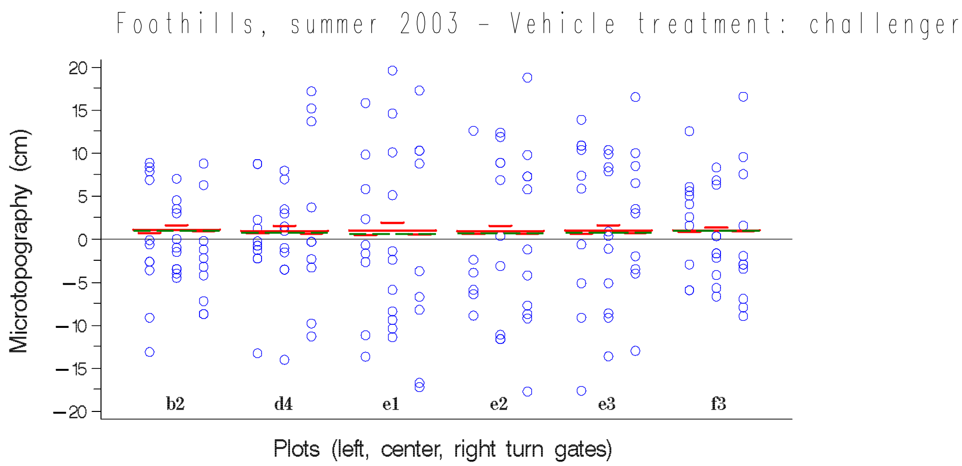
Foothills summer data — Vehicle treatment: challenger

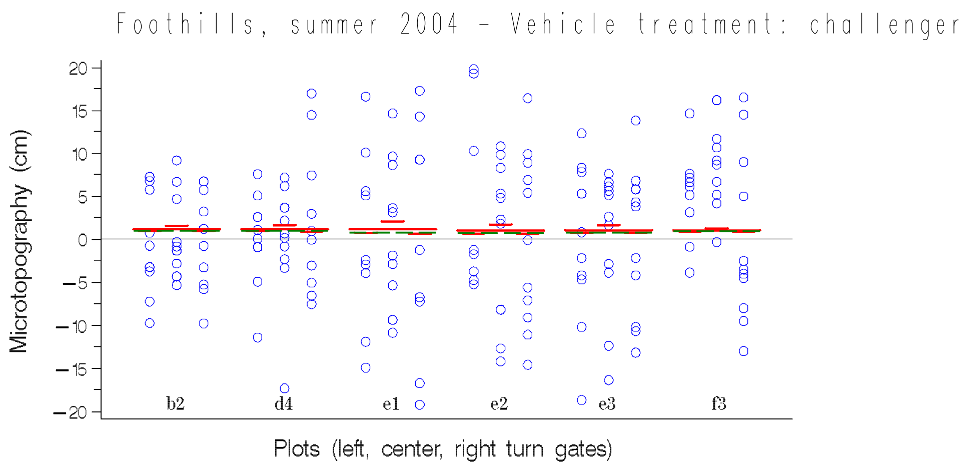


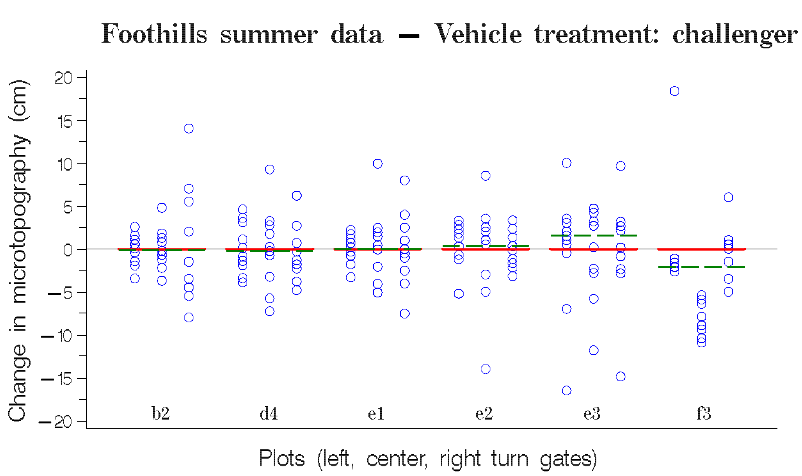
Foothills summer data — Vehicle treatment: challenger

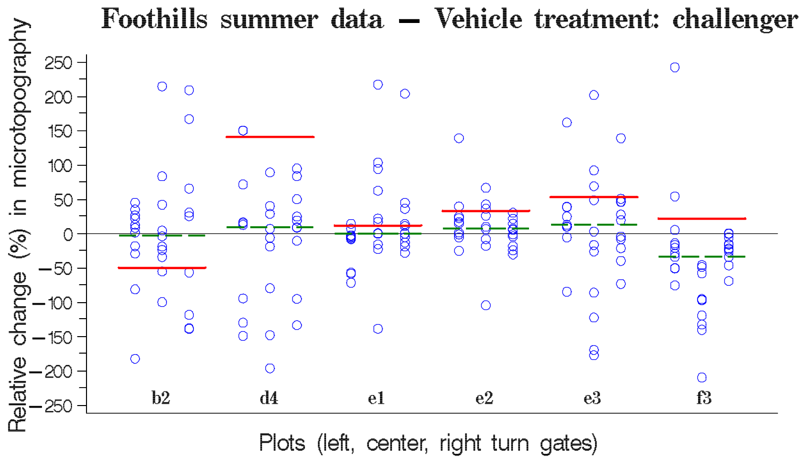
Foothills summer data — Vehicle treatment: challenger

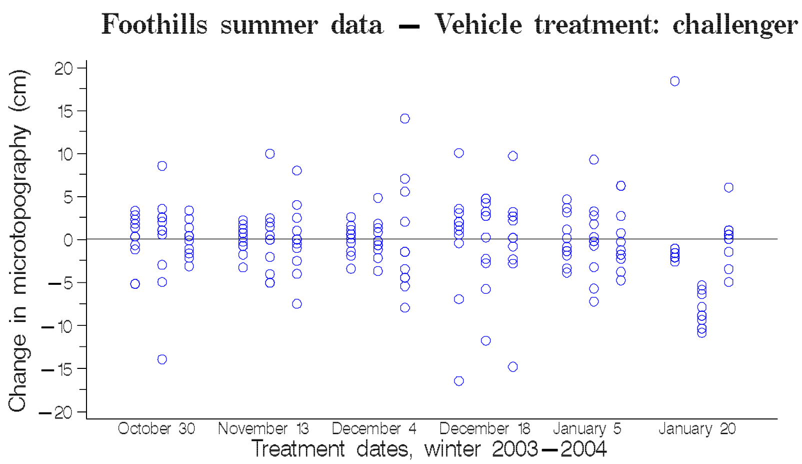


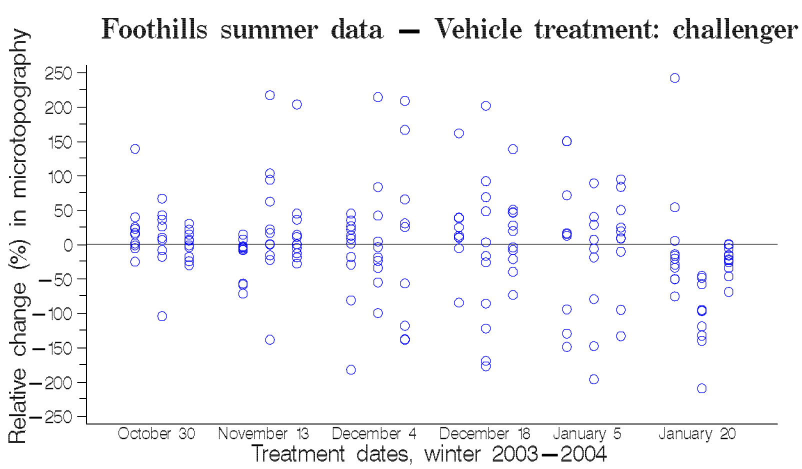

Foothills, summer 2003 - Vehicle treatment: challenger
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

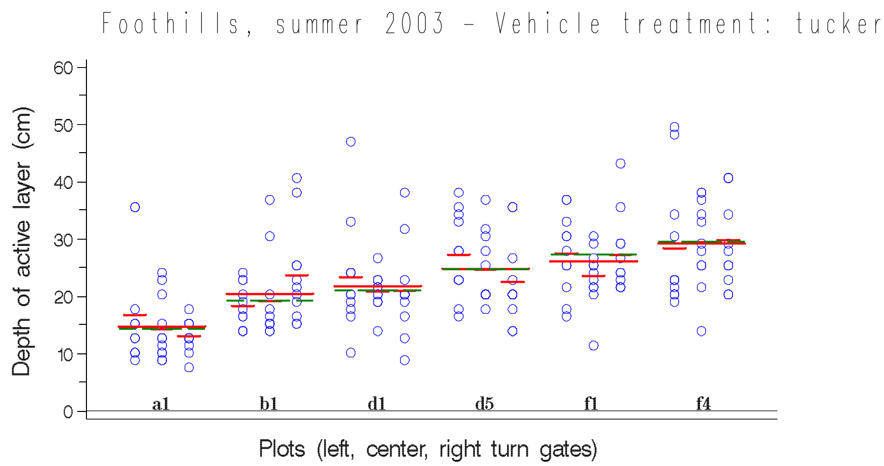

Foothills, summer 2004 - Vehicle treatment: challenger
Microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

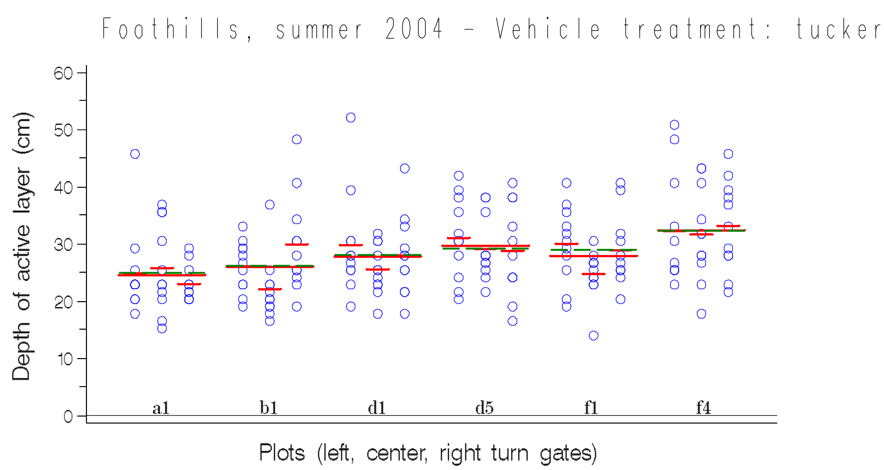

Foothills summer data — Vehicle treatment: challenger
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

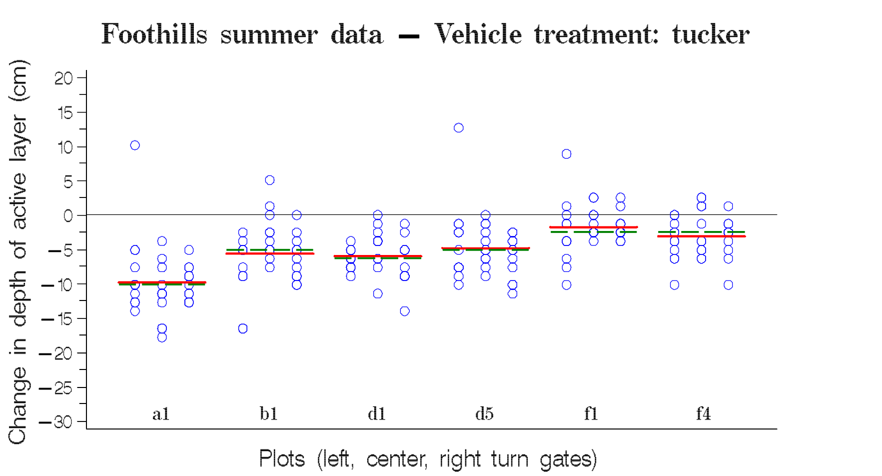

Foothills summer data — Vehicle treatment: challenger
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
b2
d4
e1
e2
e3
f3
Plots (left, center, right turn gates)

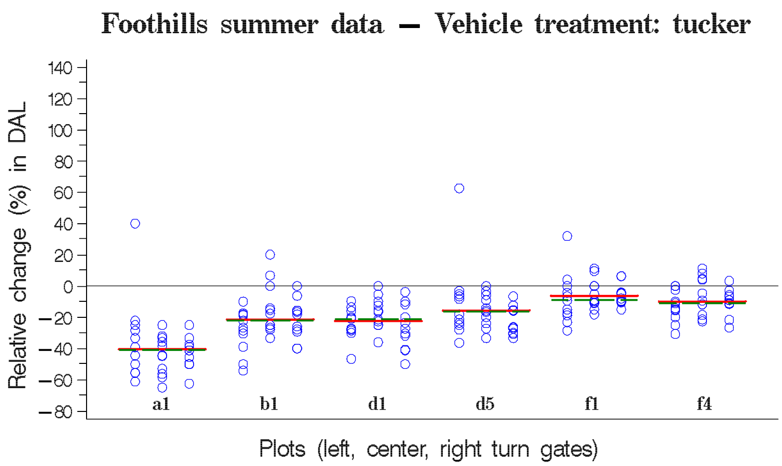

Foothills summer data — Vehicle treatment: challenger
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003−2004


Foothills summer data — Vehicle treatment: challenger
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003−2004

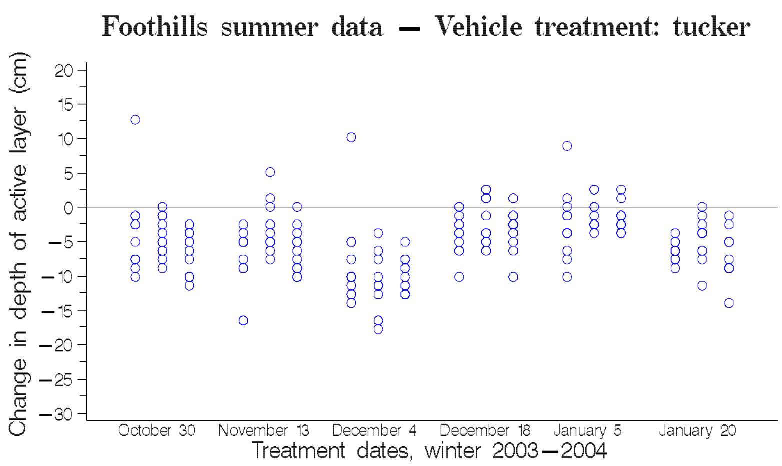

Foothills, summer 2003 - Vehicle treatment: tucker
Depth of active layer (cm)
0
10
20
30
40
50
60
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: tucker
Depth of active layer (cm)
0
10
20
30
40
50
60
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

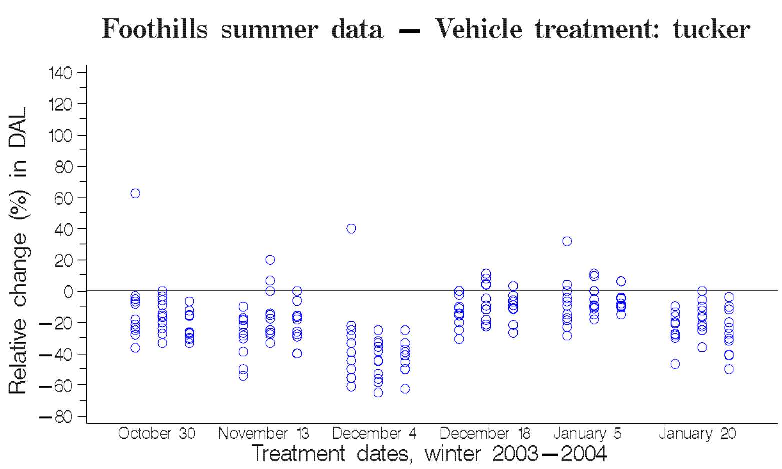

Foothills summer data — Vehicle treatment: tucker
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)



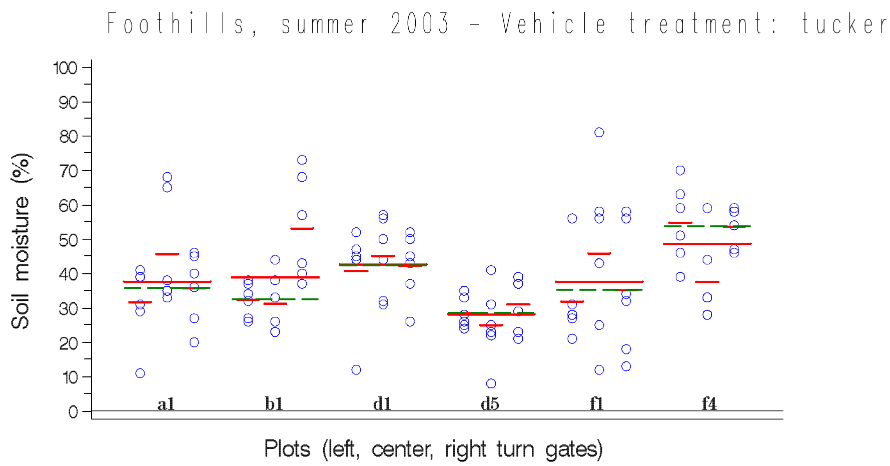
Foothills summer data — Vehicle treatment: tucker
Relative change (%) in DAL
140
120
100
80
60
40
20
0
−20
−40
−60
−80
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

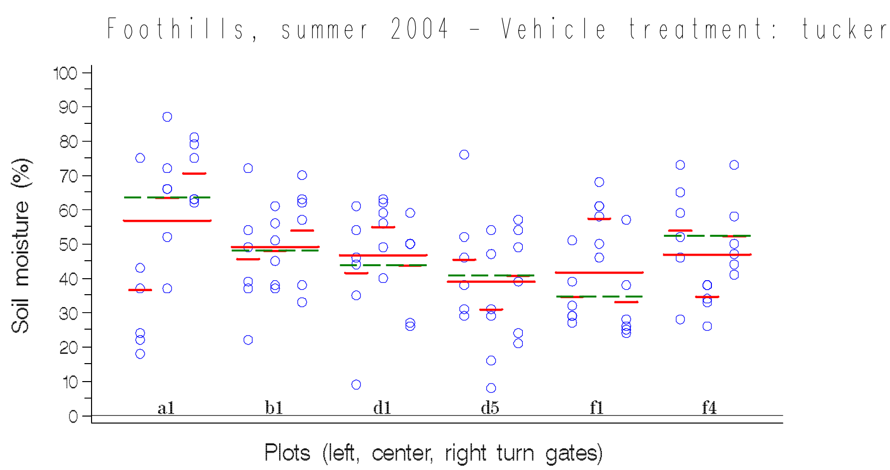


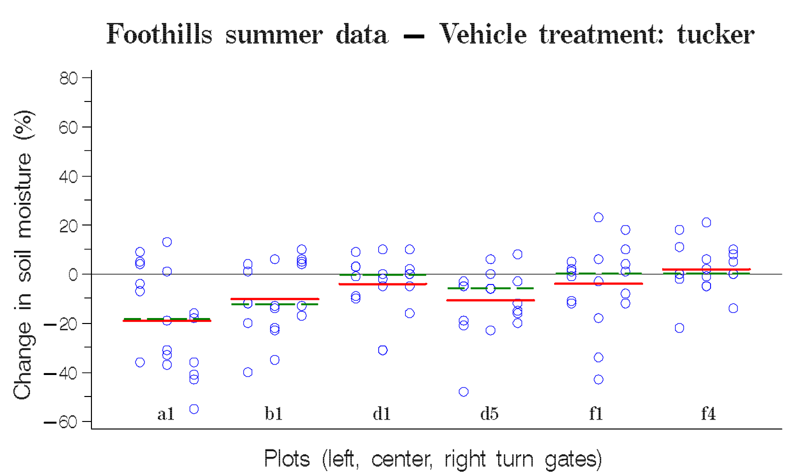
Foothills summer data — Vehicle treatment: tucker
Change in depth of active layer (cm)
20
15
10
5
0
−5
−10
−15
−20
−25
−30
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

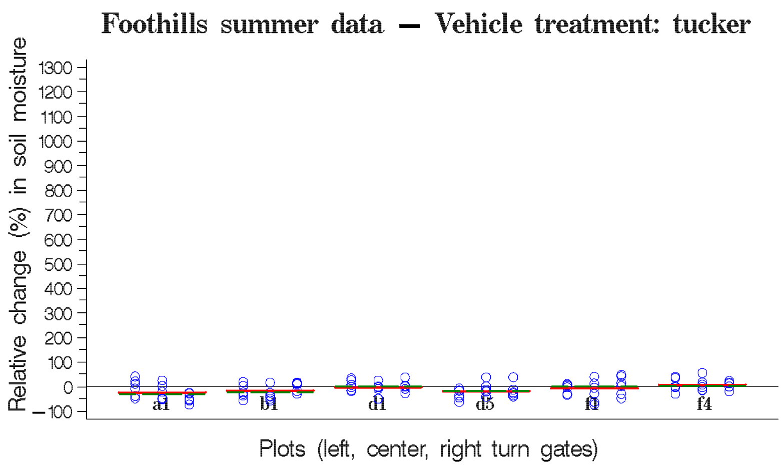


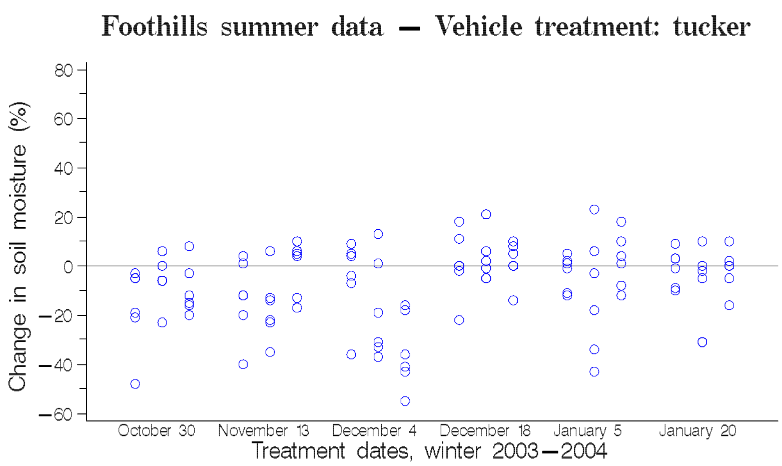
Foothills summer data — Vehicle treatment: tucker
Relative change (%) in DAL
140
120
100
80
60
40
20
0
−20
−40
−60
−80
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

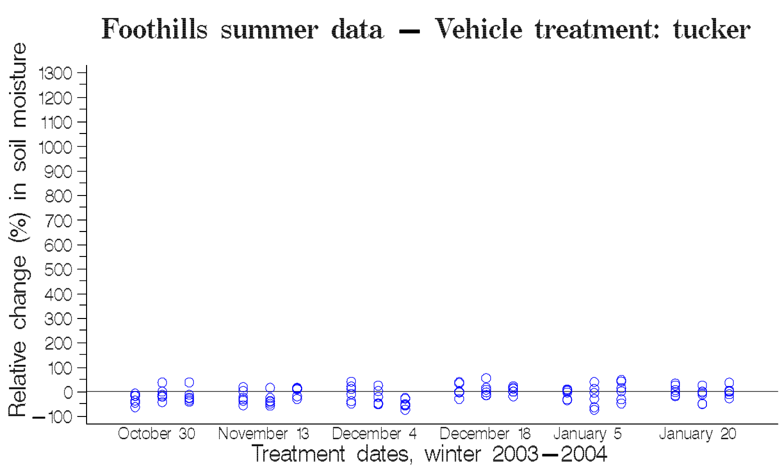

Foothills, summer 2003 - Vehicle treatment: tucker
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

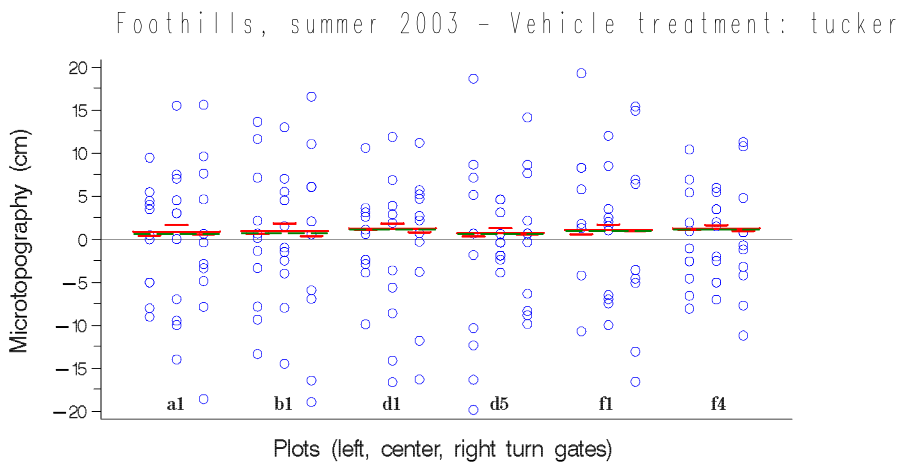

Foothills, summer 2004 - Vehicle treatment: tucker
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

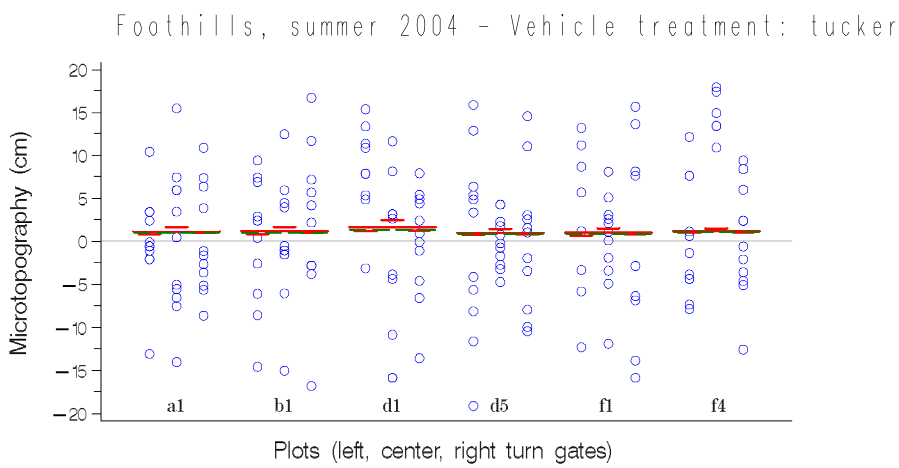

Foothills summer data — Vehicle treatment: tucker
Change in soil moisture (%)
80
60
40
20
0
−20
−40
−60
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

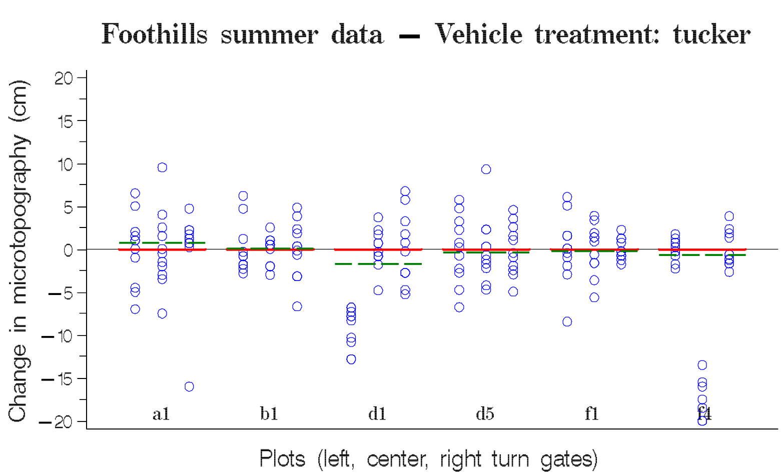

Foothills summer data — Vehicle treatment: tucker
Relative change (%) in soil moisture
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
−100
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

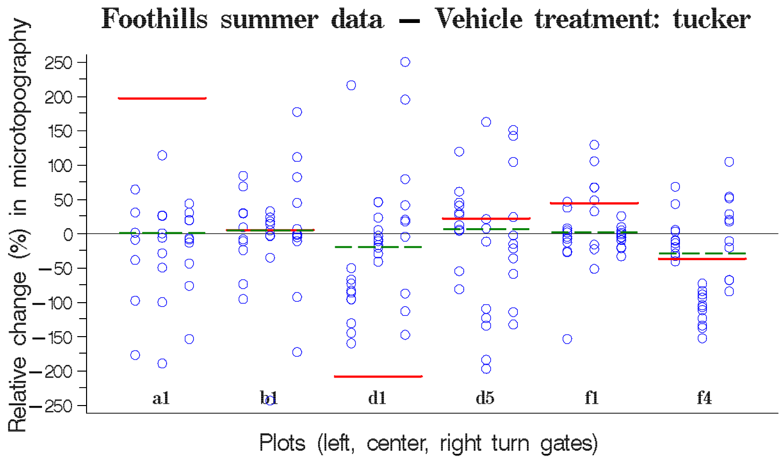

Foothills summer data — Vehicle treatment: tucker
Change in soil moisture (%)
80
60
40
20
0
−20
−40
−60
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

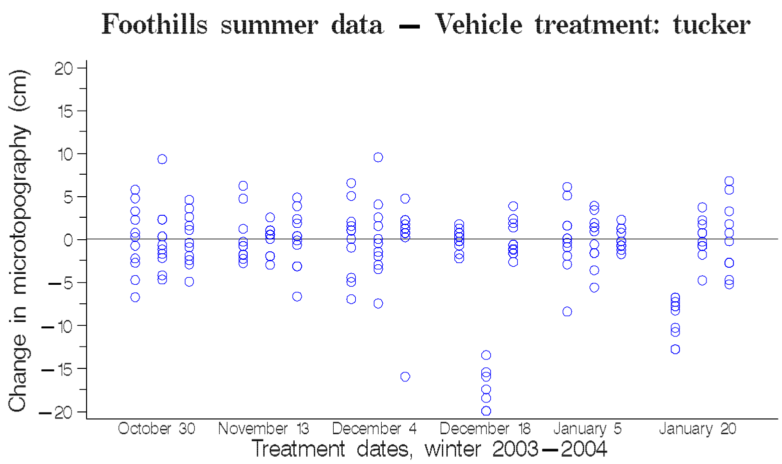

Foothills summer data — Vehicle treatment: tucker
Relative change (%) in soil moisture
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
−100
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

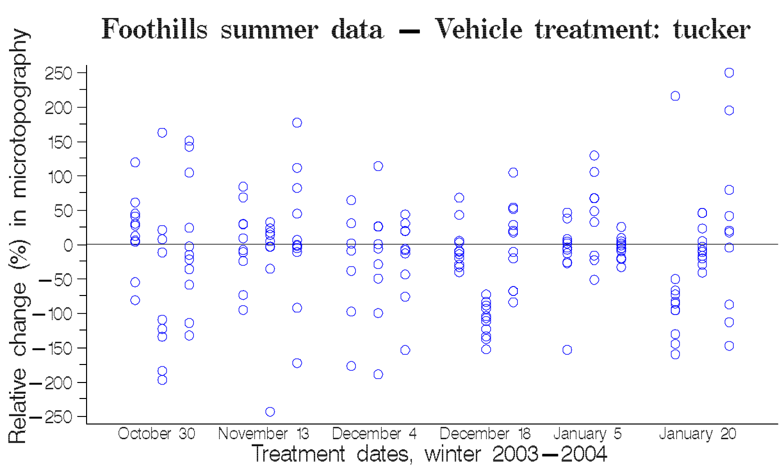

Foothills, summer 2003 - Vehicle treatment: tucker
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

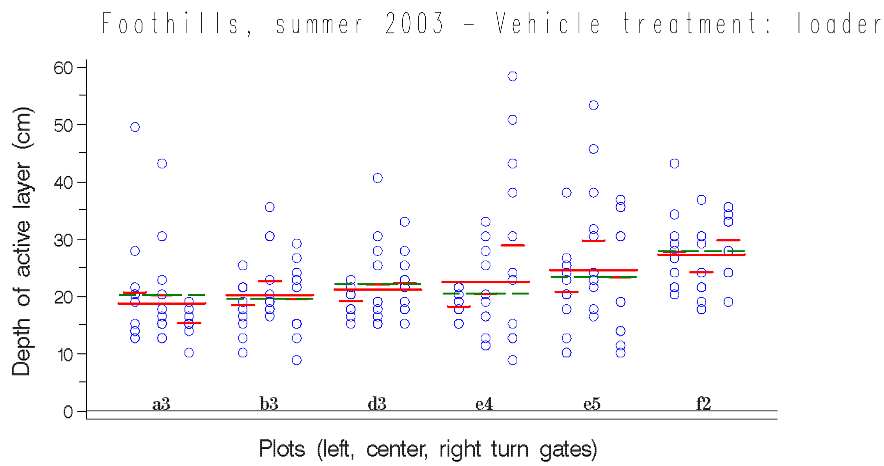

Foothills, summer 2004 - Vehicle treatment: tucker
Microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

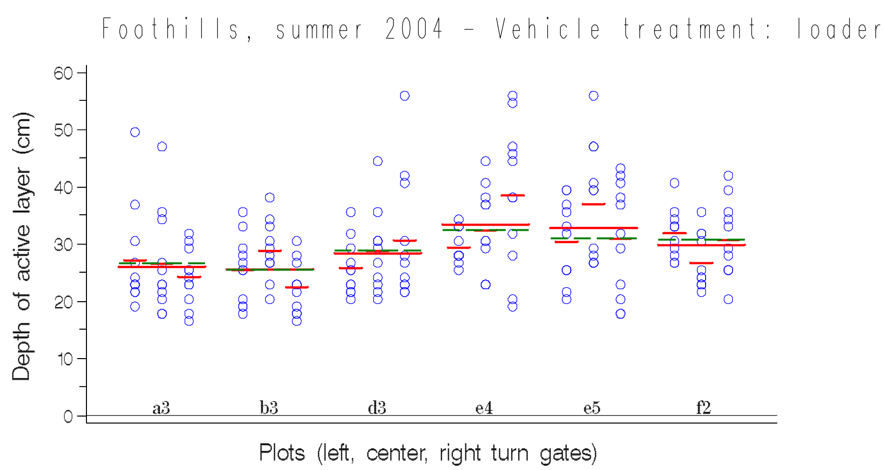

Foothills summer data — Vehicle treatment: tucker
Change in microtopography (cm)
20
15
10
5
0
-5
-10
-15
-20
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)

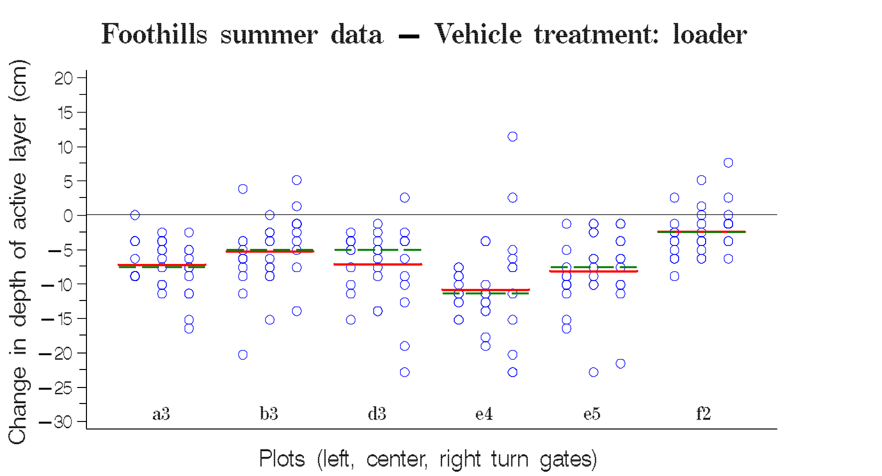

Foothills summer data — Vehicle treatment: tucker
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
a1
b1
d1
d5
f1
f4
Plots (left, center, right turn gates)


Foothills summer data — Vehicle treatment: tucker
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

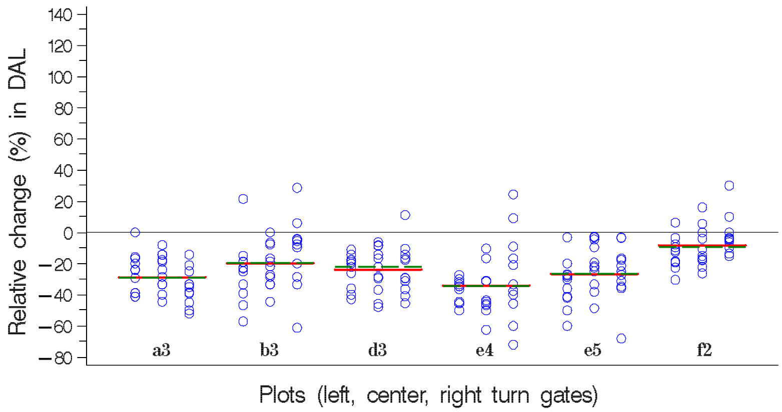

Foothills summer data — Vehicle treatment: tucker
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Foothills, summer 2003 - Vehicle treatment: loader
Depth of active layer (cm)
0
10
20
30
40
50
60
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)


Foothills, summer 2004 - Vehicle treatment: loader
Depth of active layer (cm)
0
10
20
30
40
50
60
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

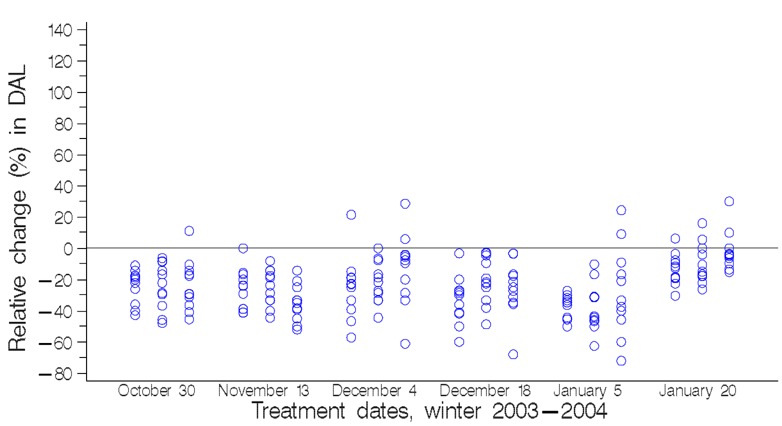

Foothills summer data — Vehicle treatment: loader
Change in depth of active layer (cm)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

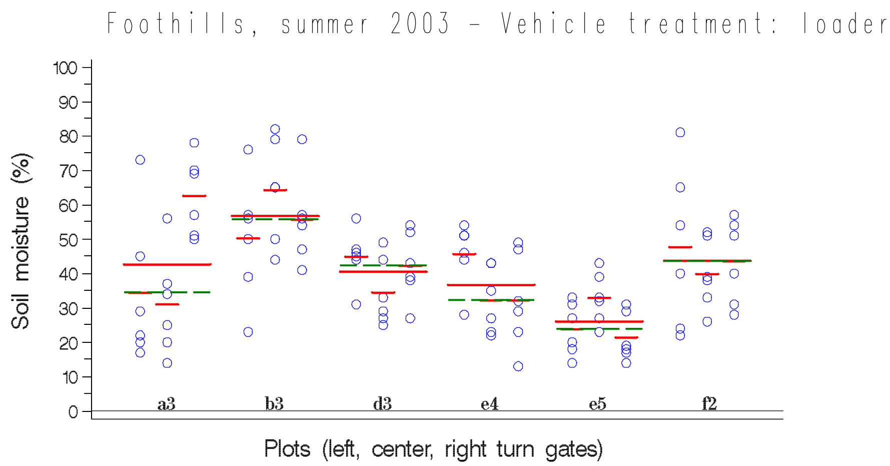
Foothills summer data — Vehicle treatment: loader

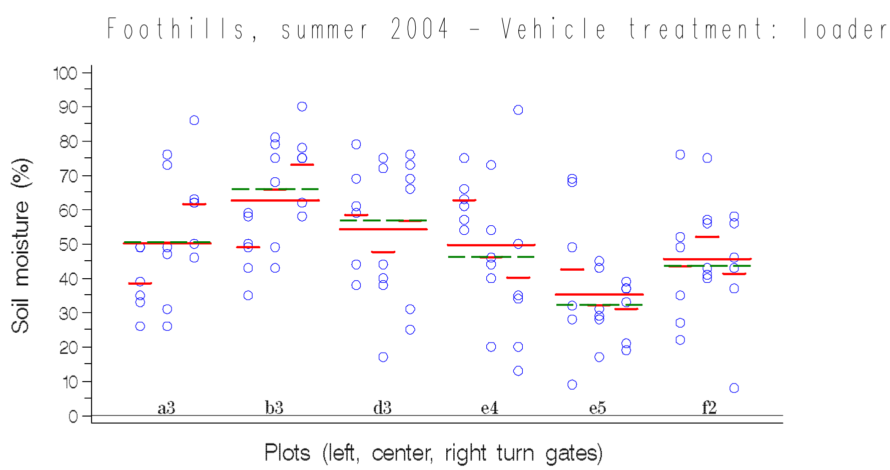


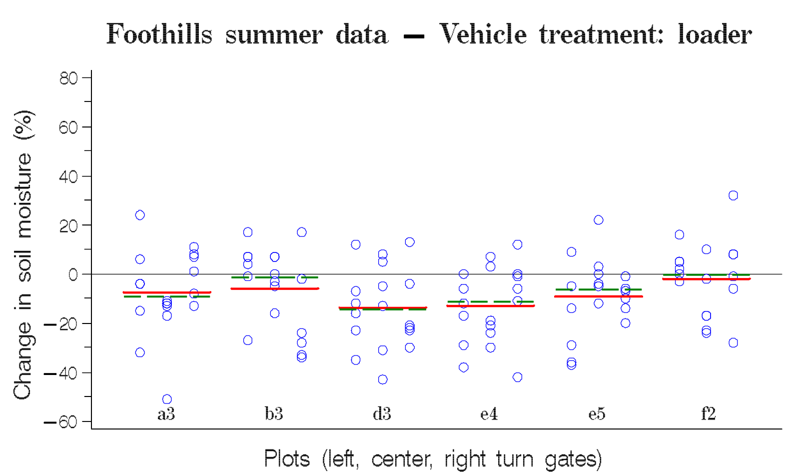
Foothills summer data — Vehicle treatment: loader

Foothills summer data — Vehicle treatment: loader

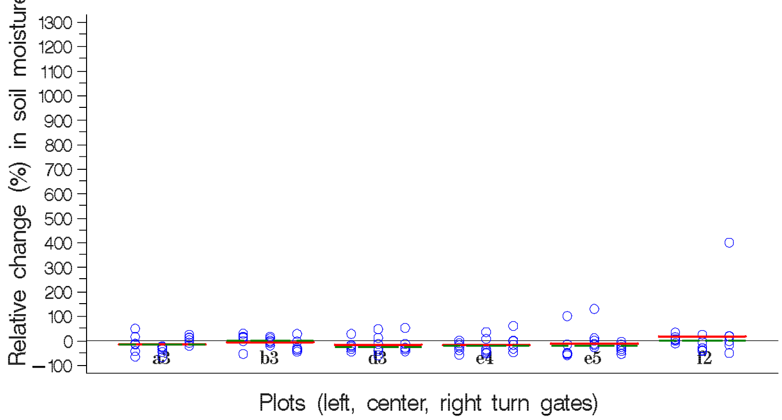



Foothills, summer 2003 - Vehicle treatment: loader
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

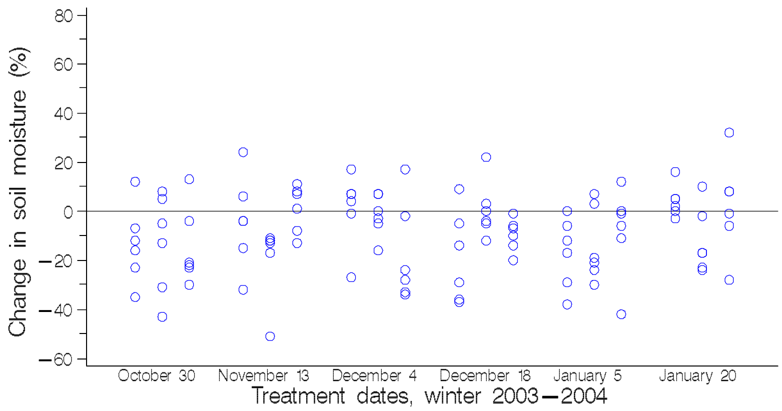

Foothills, summer 2004 - Vehicle treatment: loader
Soil moisture (%)
100
90
80
70
60
50
40
30
20
10
0
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)


Foothills summer data — Vehicle treatment: loader
Change in soil moisture (%)
80
60
40
20
0
−20
−40
−60
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

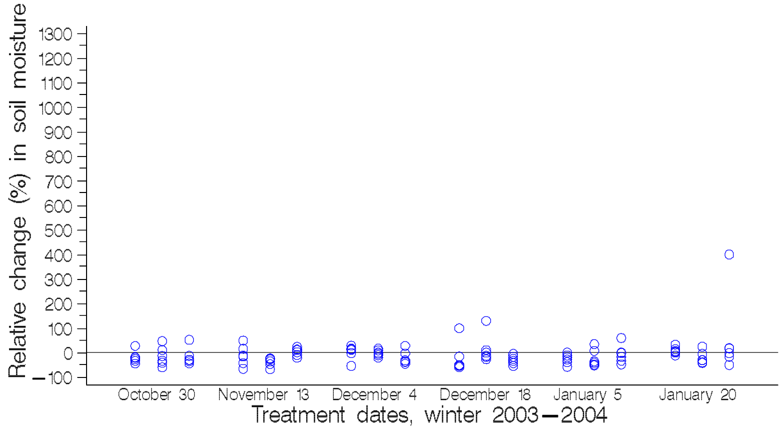
Foothills summer data — Vehicle treatment: loader

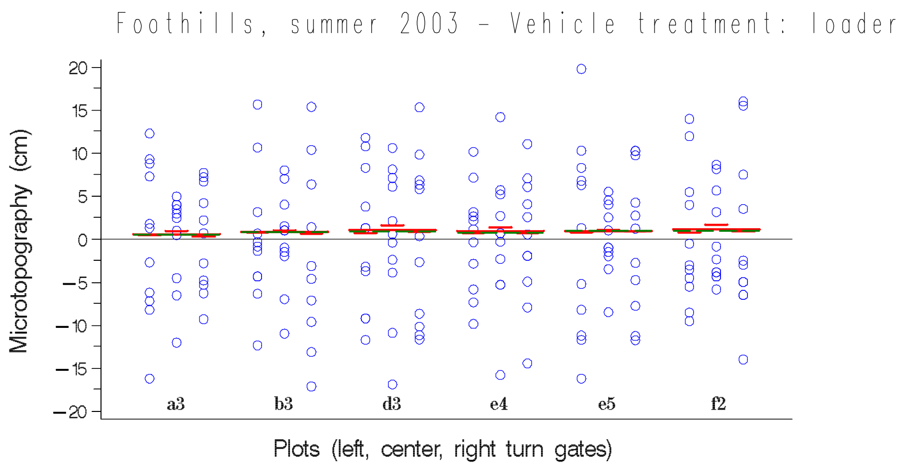


Foothills summer data — Vehicle treatment: loader

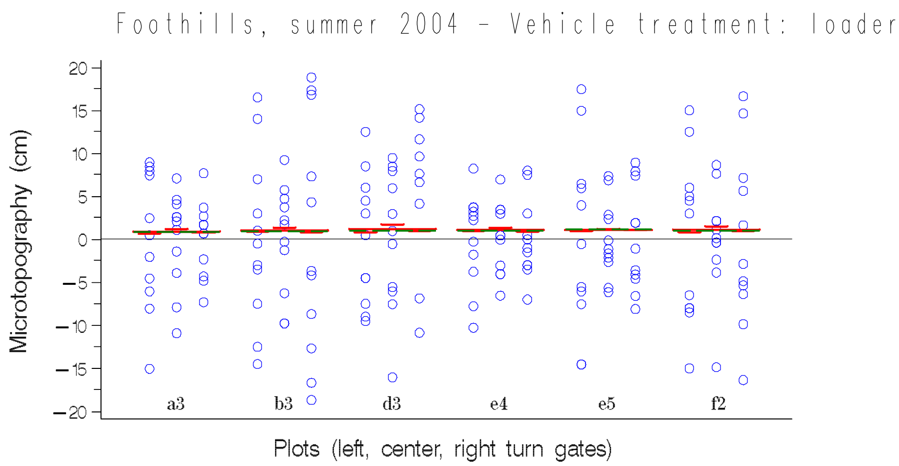


Foothills summer data — Vehicle treatment: loader

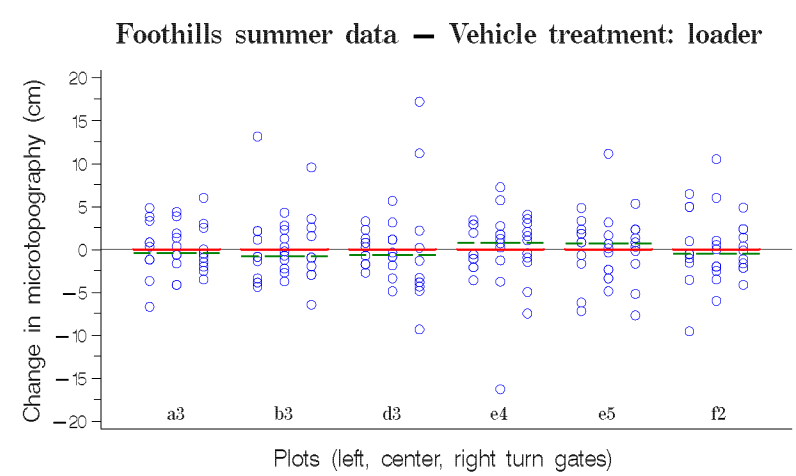




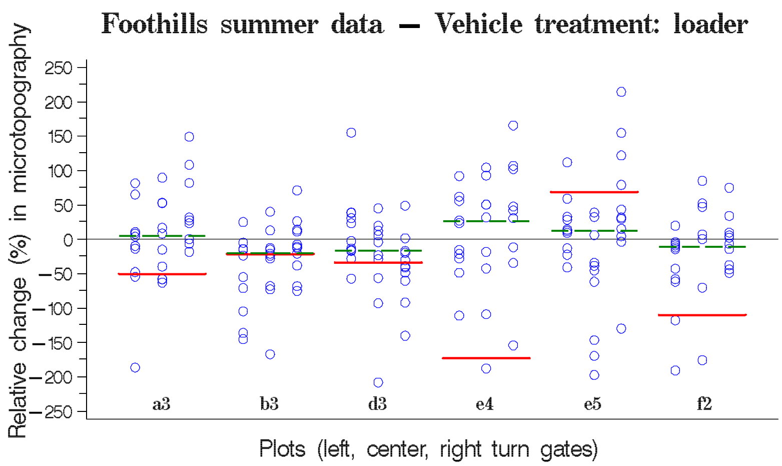
Foothills, summer 2003 - Vehicle treatment: loader
Microtopography (cm)
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

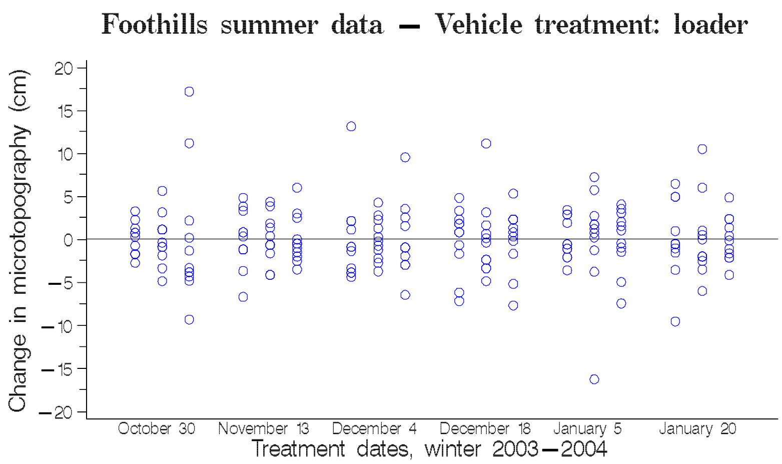


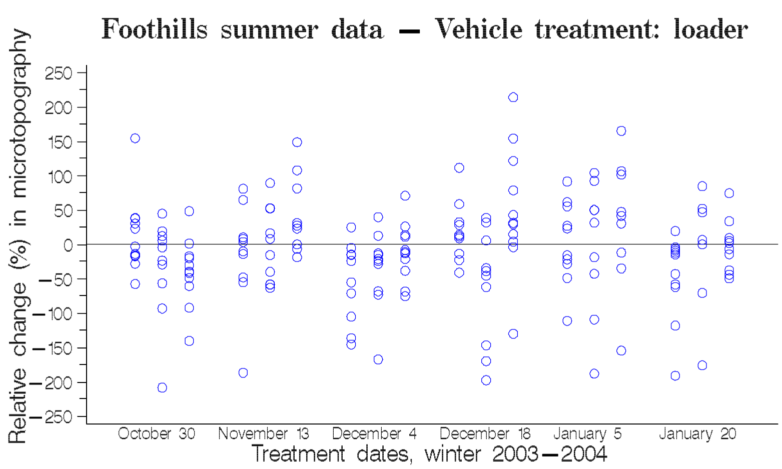
Foothills, summer 2004 - Vehicle treatment: loader
Microtopography (cm)
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)



Foothills summer data — Vehicle treatment: loader
Change in microtopography (cm)
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)

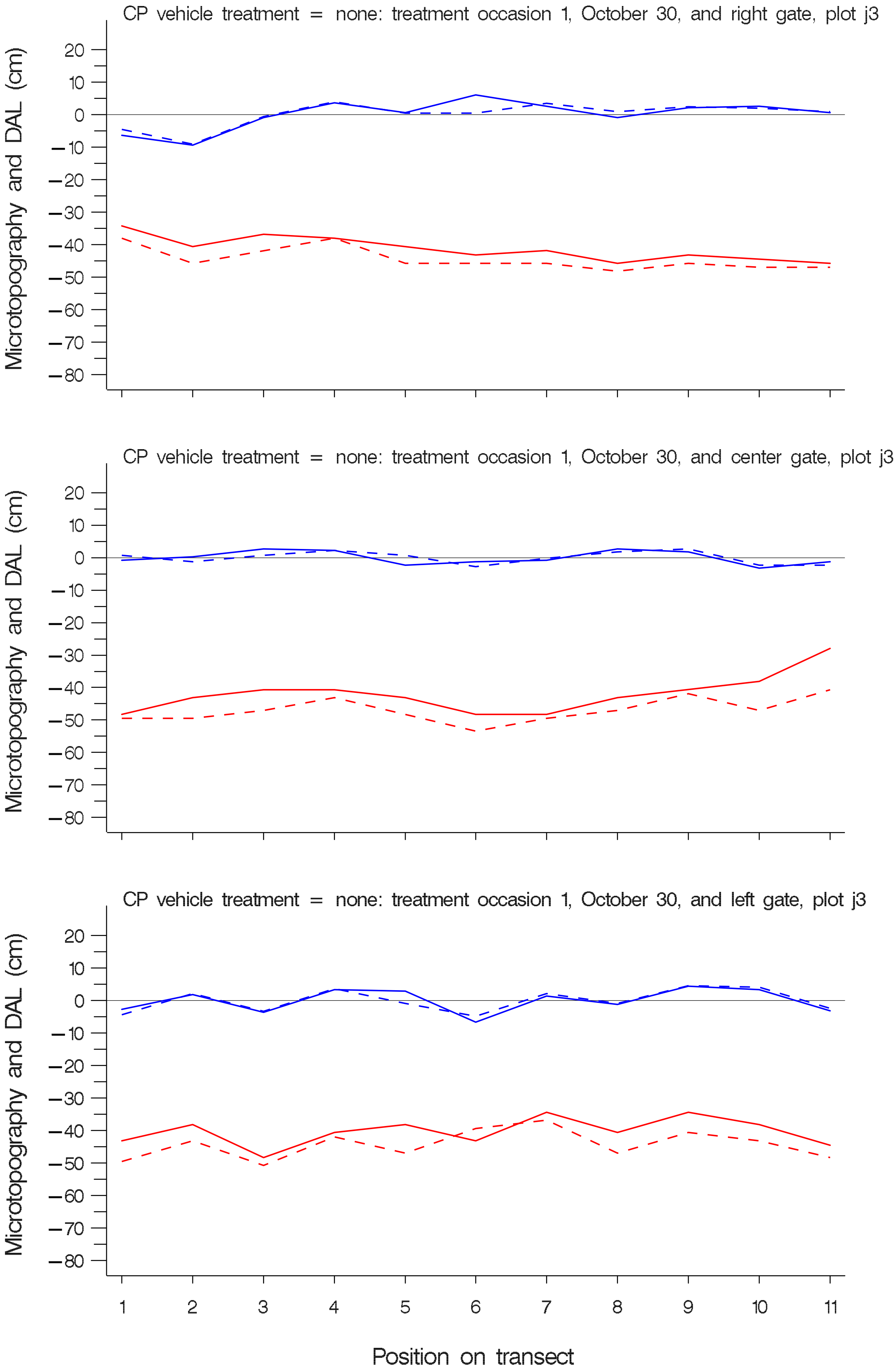

Foothills summer data — Vehicle treatment: loader
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
a3
b3
d3
e4
e5
f2
Plots (left, center, right turn gates)


Foothills summer data — Vehicle treatment: loader
Change in microtopography (cm)
20
15
10
5
0
−5
−10
−15
−20
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004


Foothills summer data — Vehicle treatment: loader
Relative change (%) in microtopography
250
200
150
100
50
0
−50
−100
−150
−200
−250
October 30
November 13
December 4
December 18
January 5
January 20
Treatment dates, winter 2003—2004

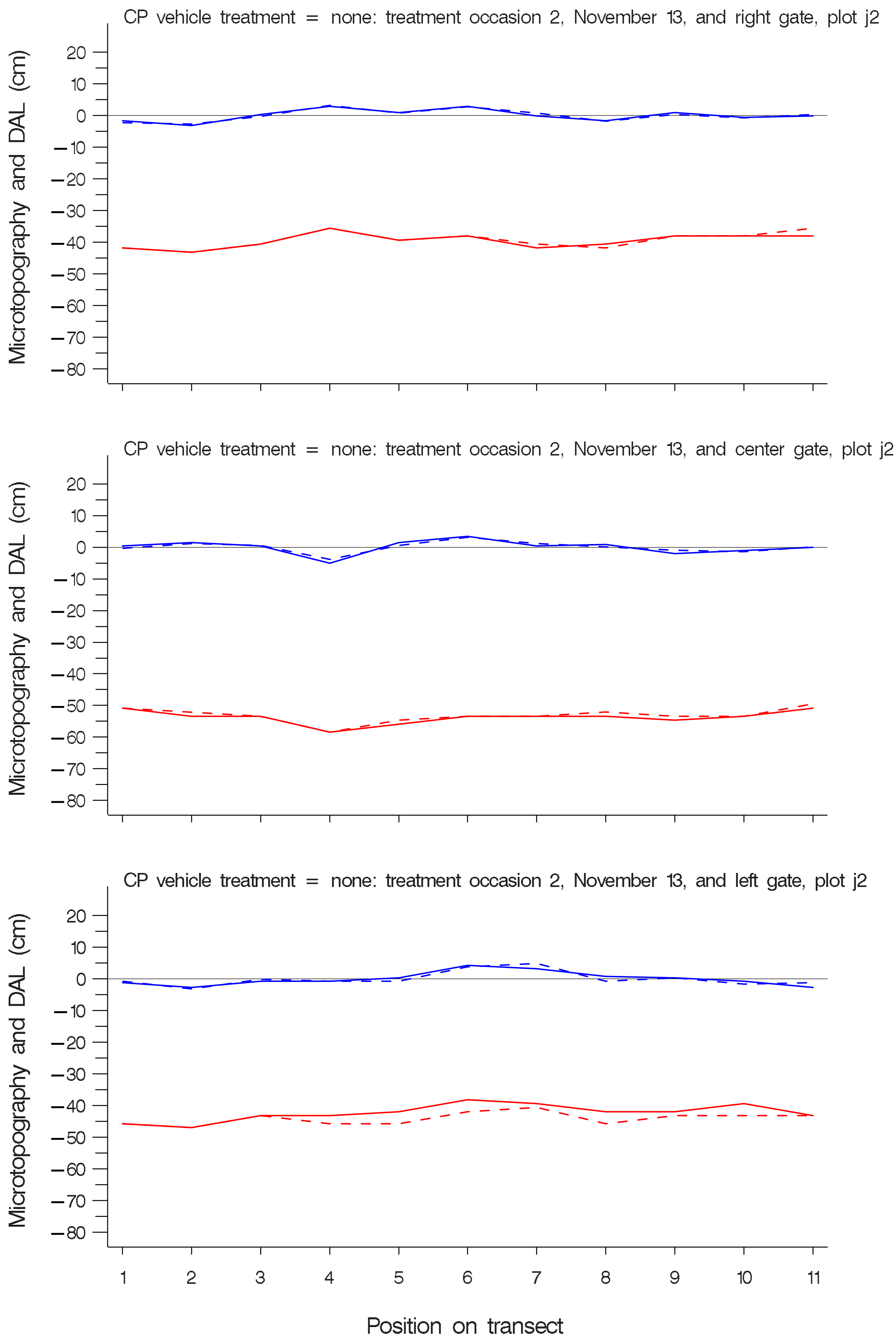
APPENDIX G:
MICRO-TOPOGRAPHY AND PERMAFROST PROFILES

The following graphs portray microtopographical relief and active layer depth profiles for each transect in each treatment plot. The solid lines represent year 2003 measurements and the dashed lines represent year 2004 measurements. The topmost pair of lines portray the ground surface relief. The bottom pair of lines portray the top of the permafrost, thereby demarcating the active layer depth. Comparison of the two sets of lines offers a visual portrayal of the change from 2003 to 2004 in all plots.



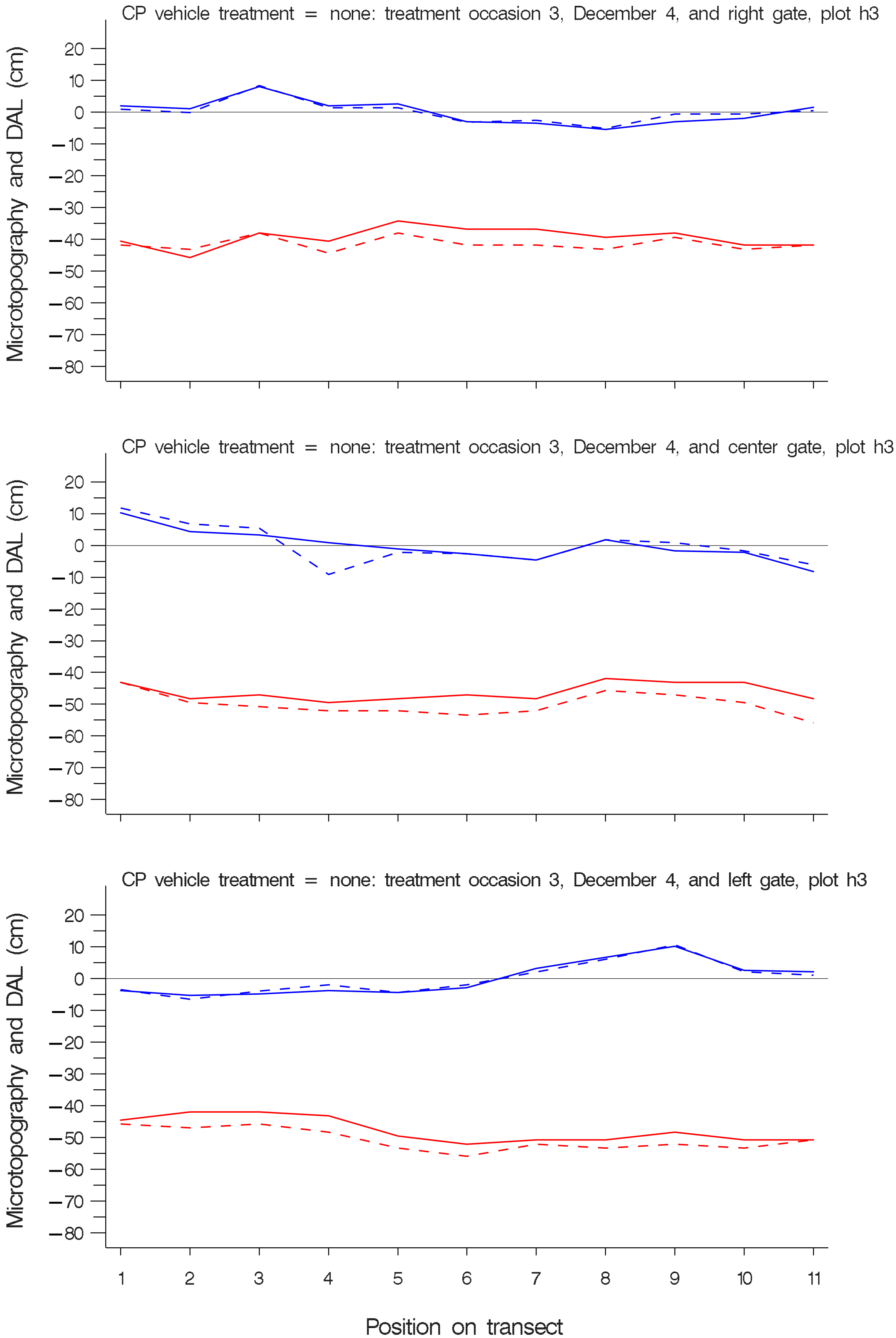
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



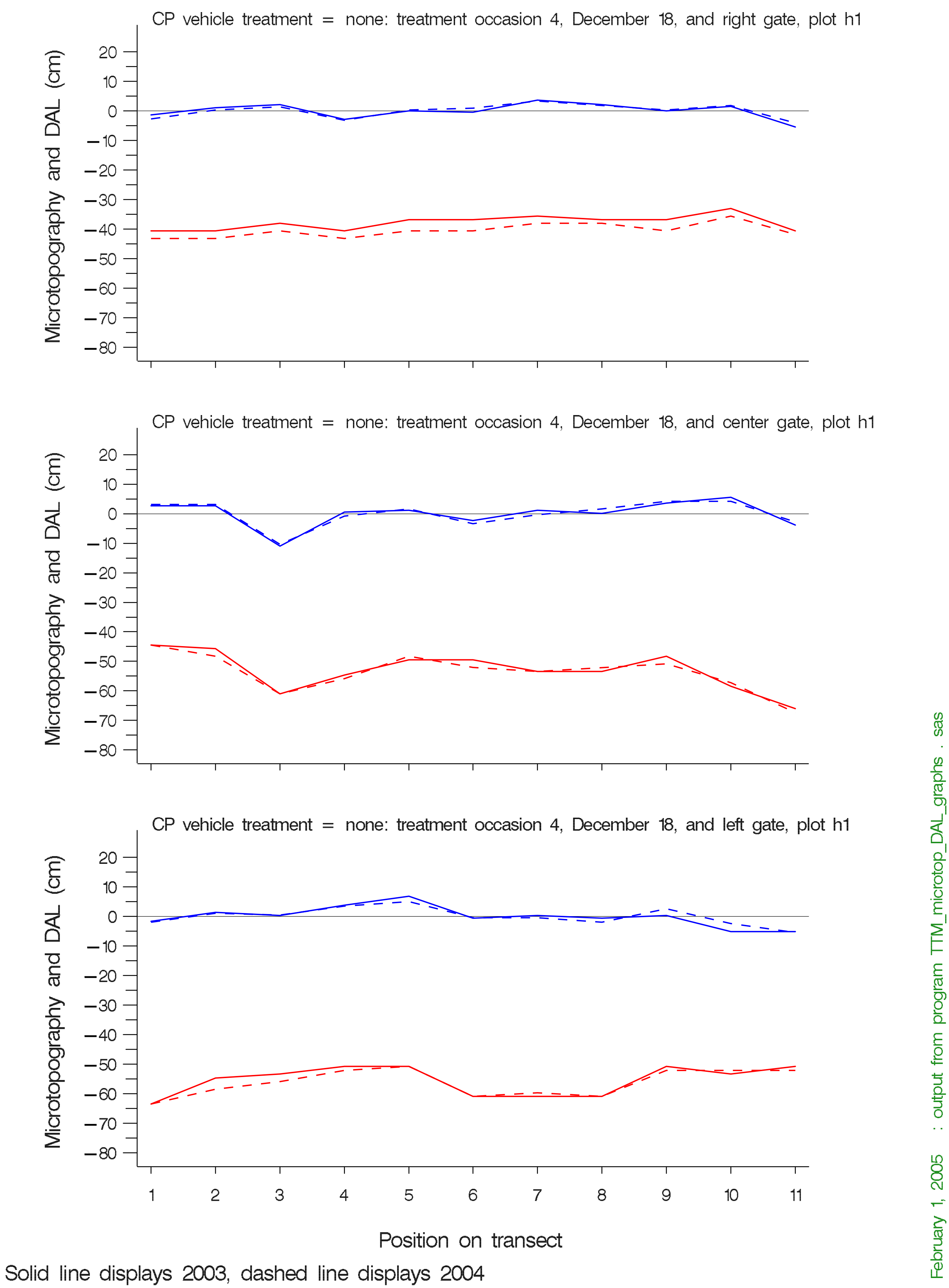
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

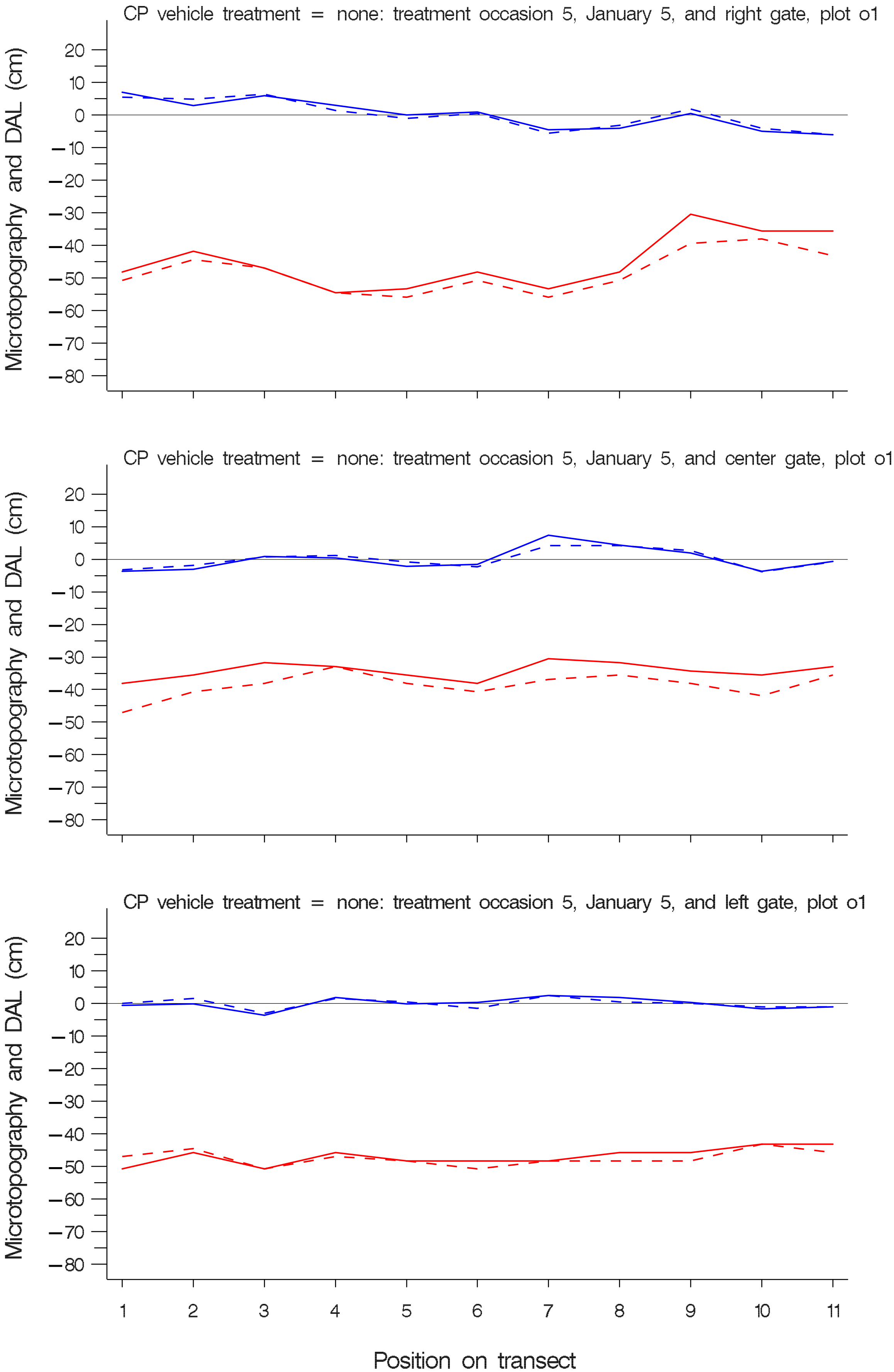


Solid line displays 2003, dashed line displays 2004

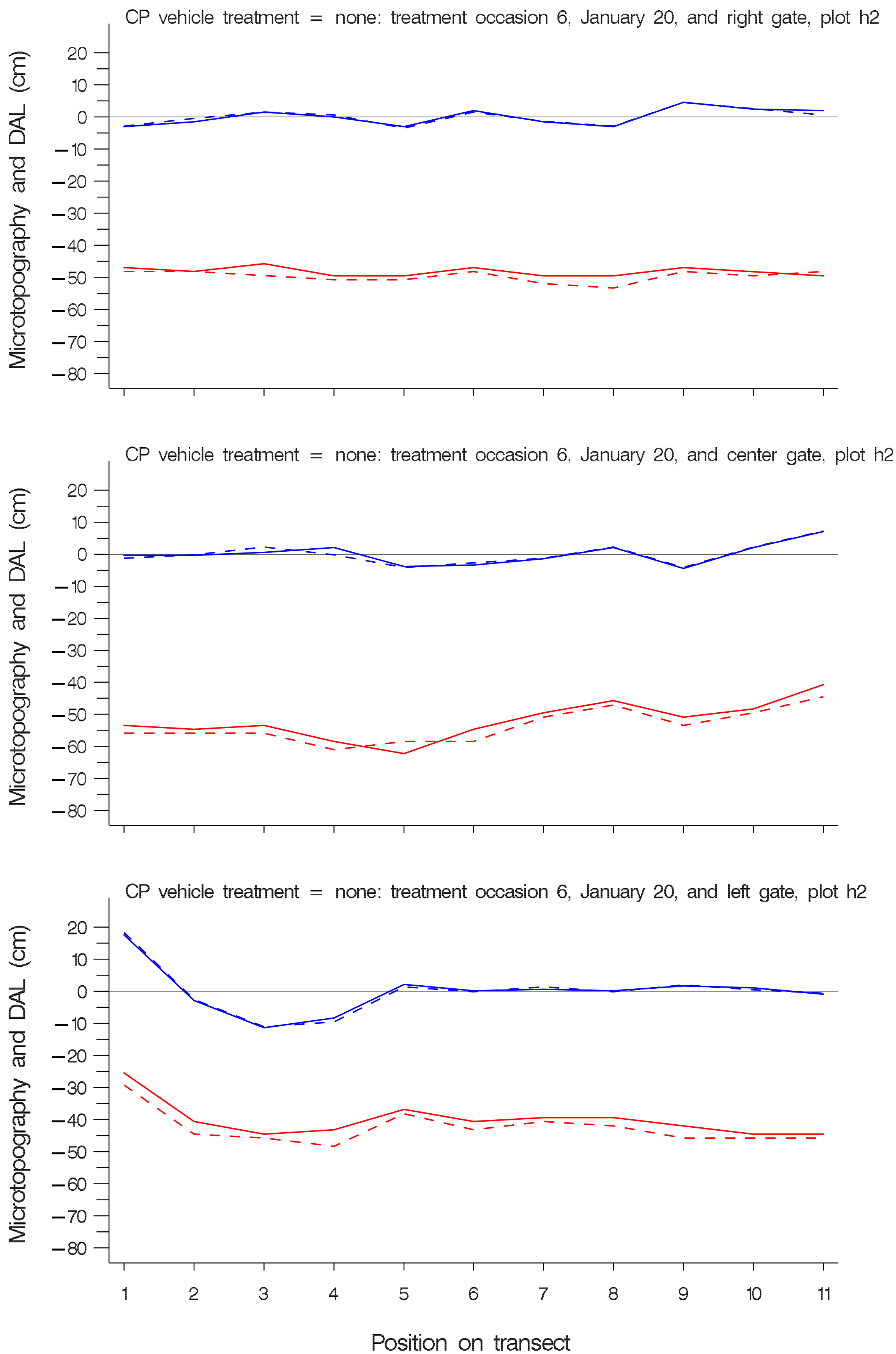
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



CP vehicle treatment = none: treatment occasion 4, December 18, and right gate, plot h1
CP vehicle treatment = none: treatment occasion 4, December 18, and center gate, plot h1
CP vehicle treatment = none: treatment occasion 4, December 18, and left gate, plot h1
Microtopography and DAL (cm)
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
1 2 3 4 5 6 7 8 9 10 11
Position on transect
Solid line displays 2003, dashed line displays 2004
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

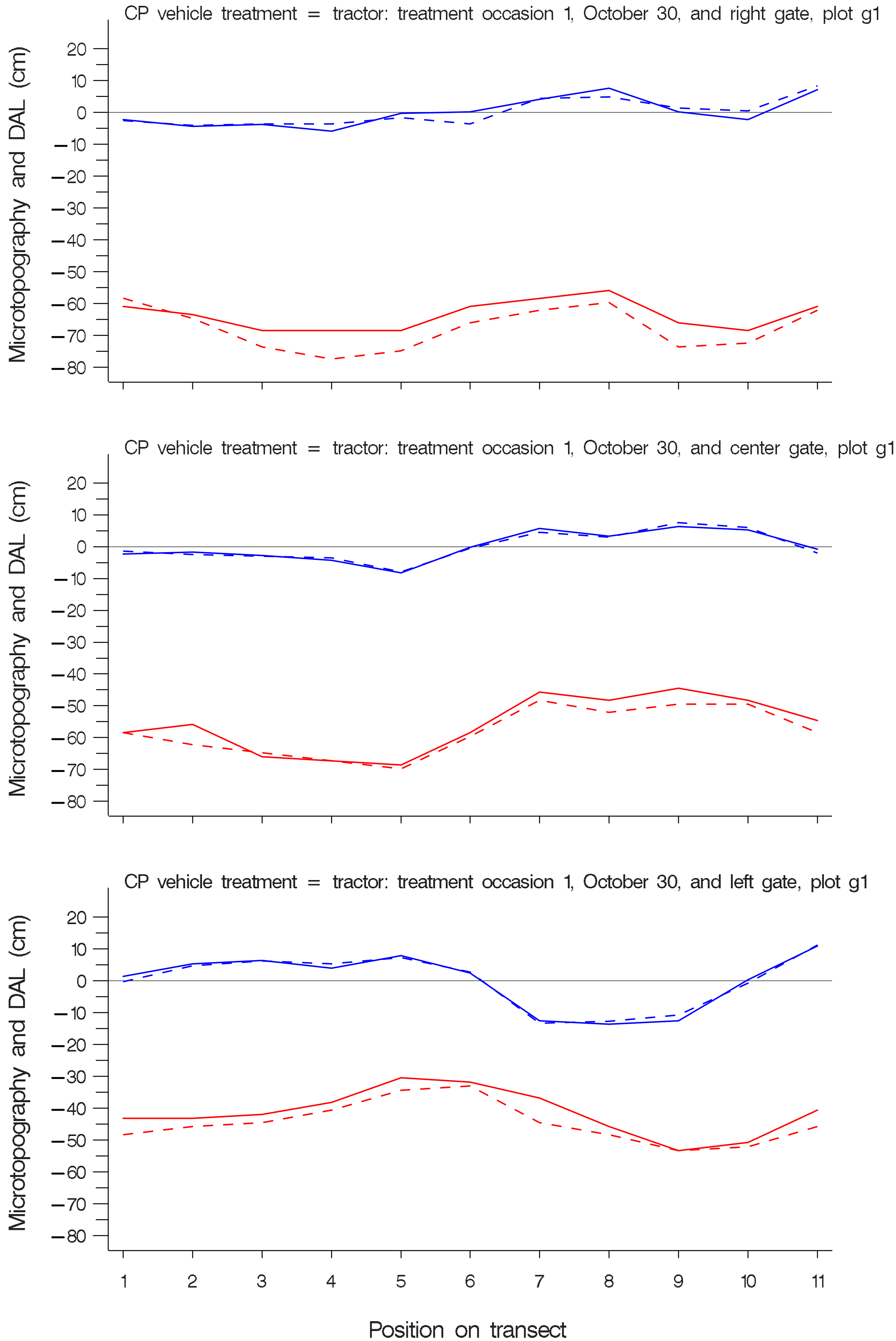


Solid line displays 2003, dashed line displays 2004



Solid line displays 2003, dashed line displays 2004

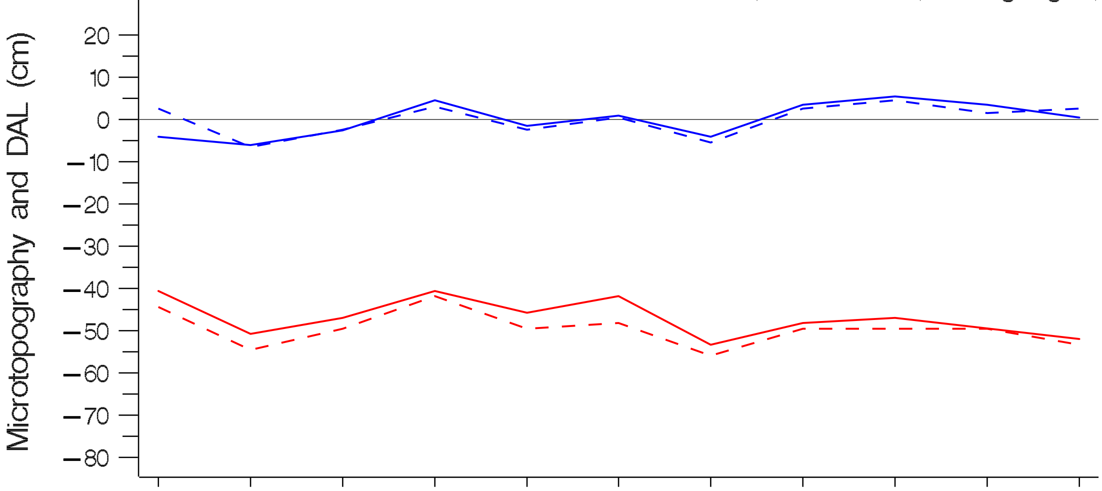
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



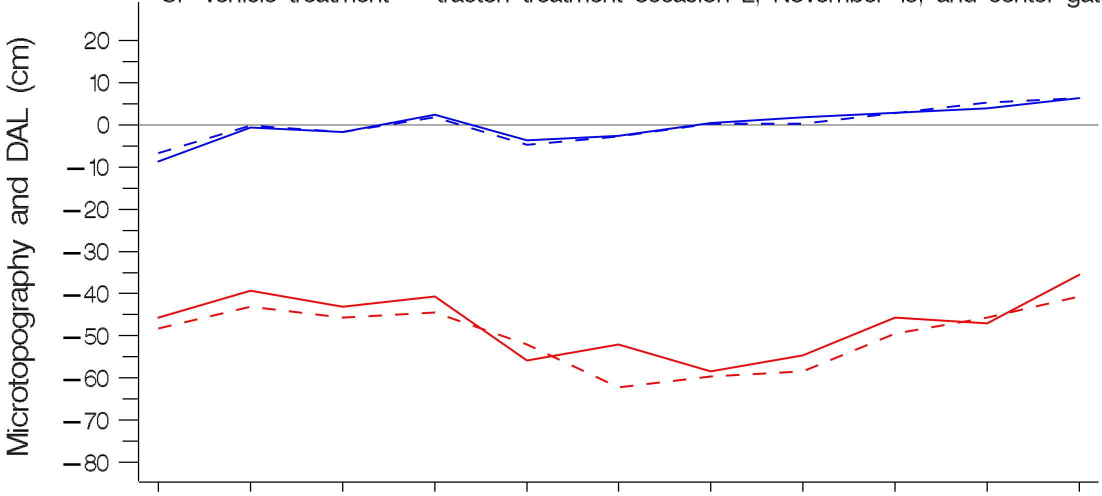
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

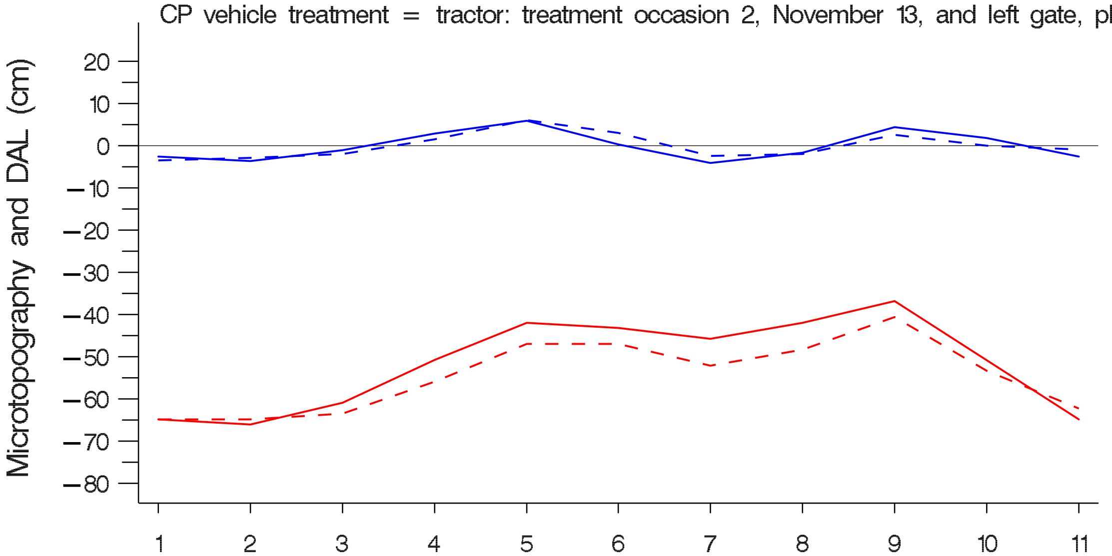
CP vehicle treatment = tractor: treatment occasion 2, November 13, and right gate, plot n1



CP vehicle treatment = tractor: treatment occasion 2, November 13, and center gate, plot n1



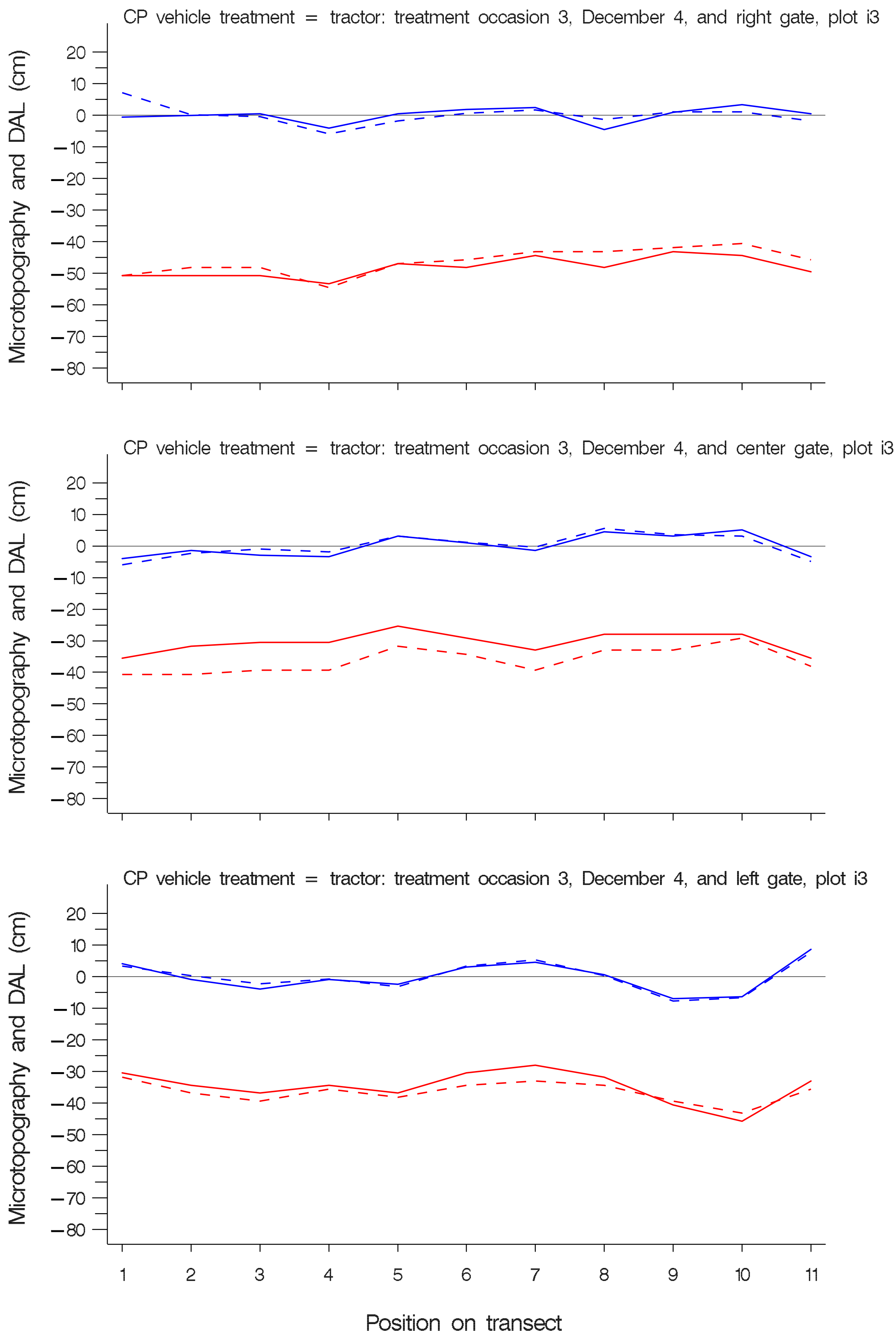
CP vehicle treatment = tractor: treatment occasion 2, November 13, and left gate, plot n1



Position on transect

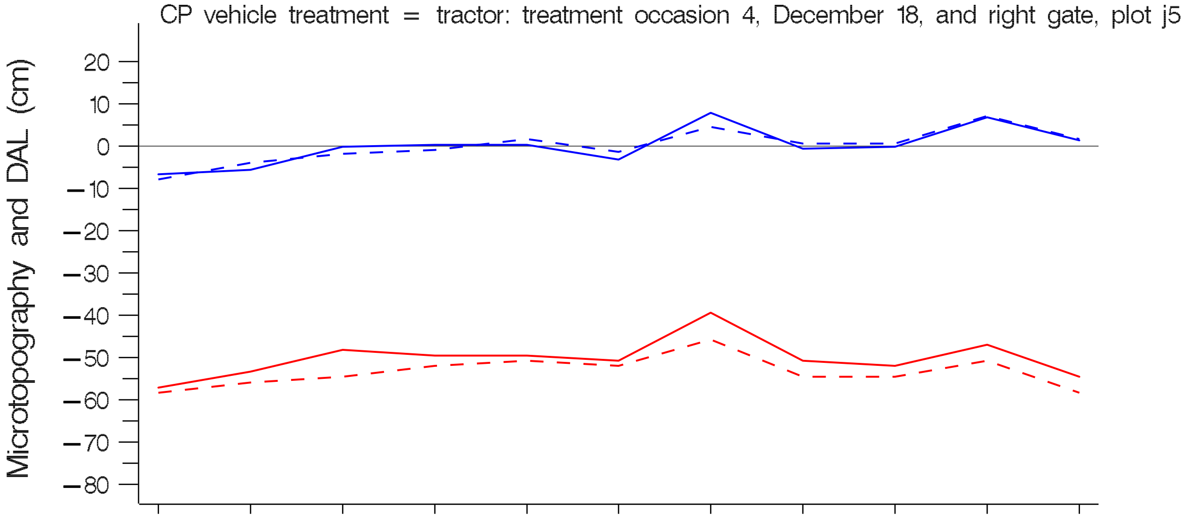
Solid line displays 2003, dashed line displays 2004

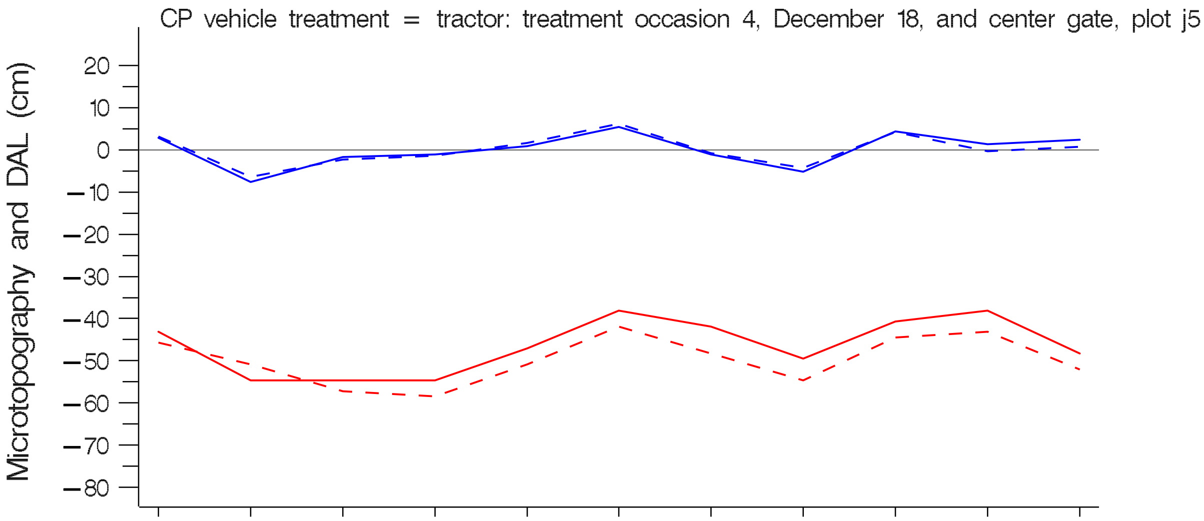
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

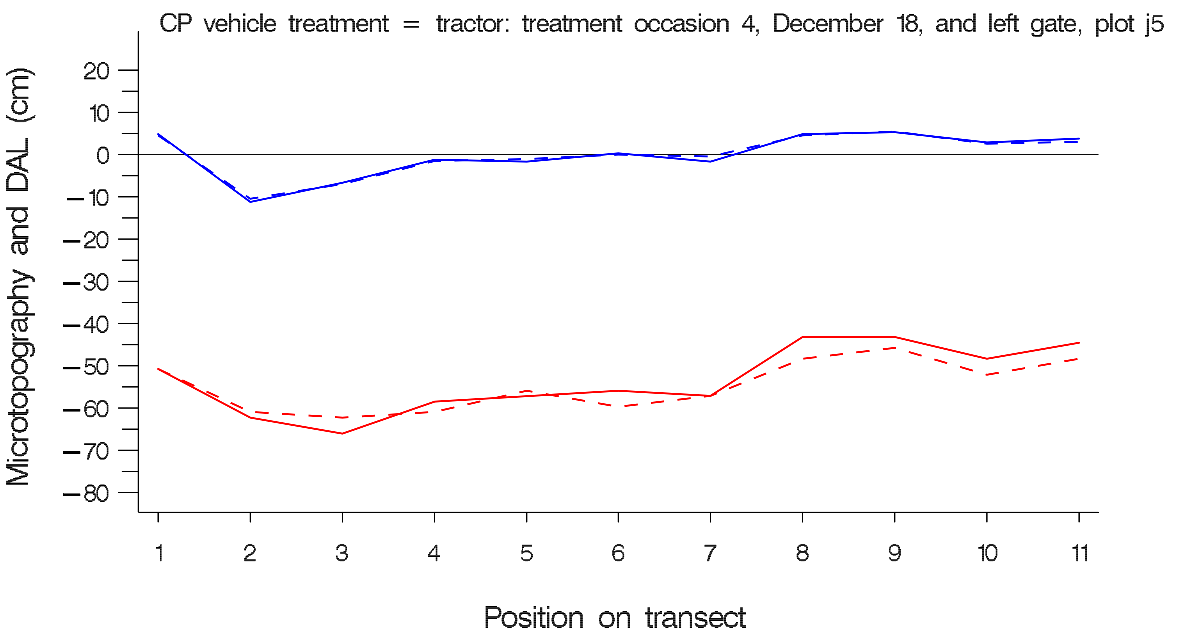


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

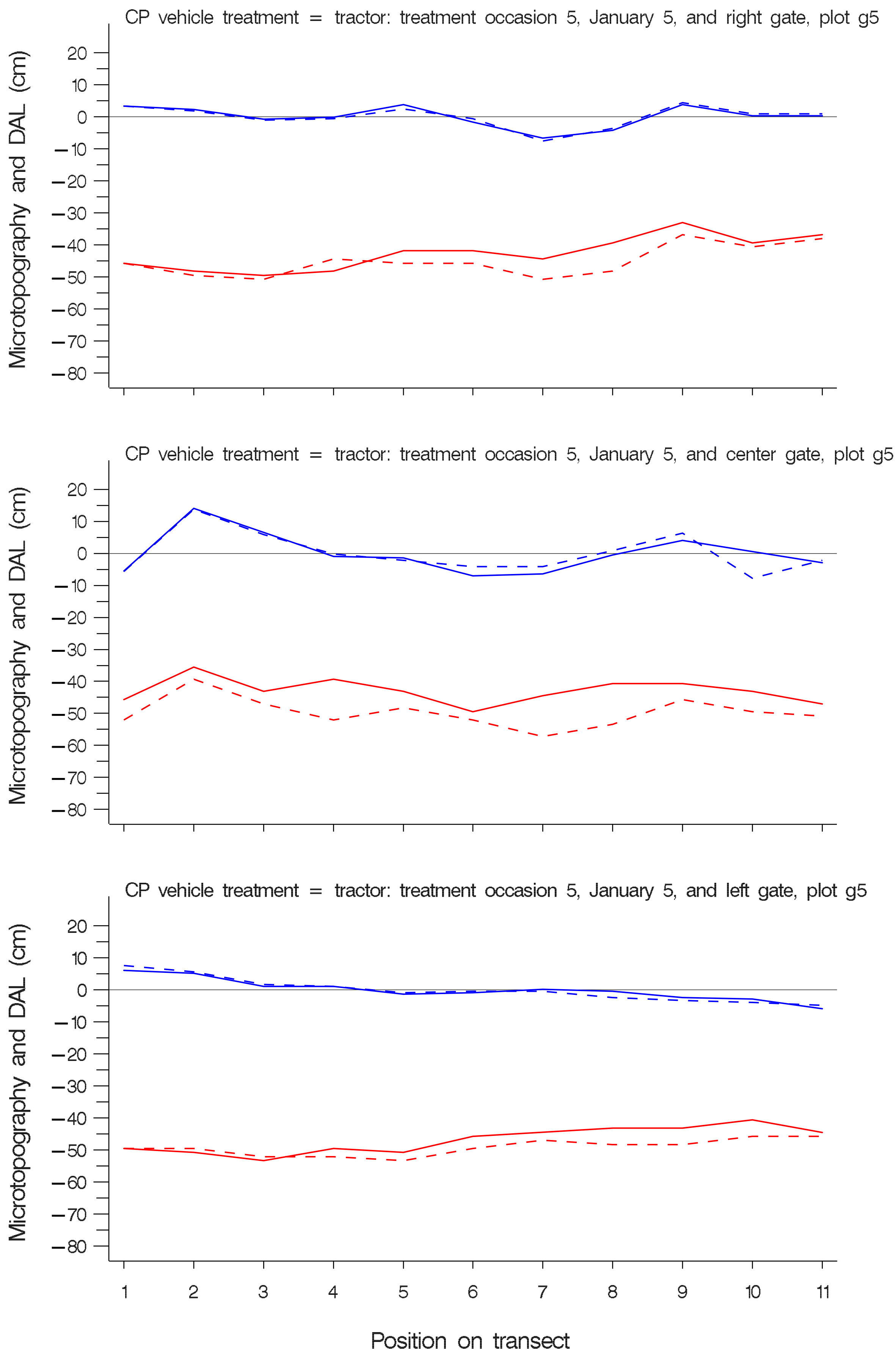






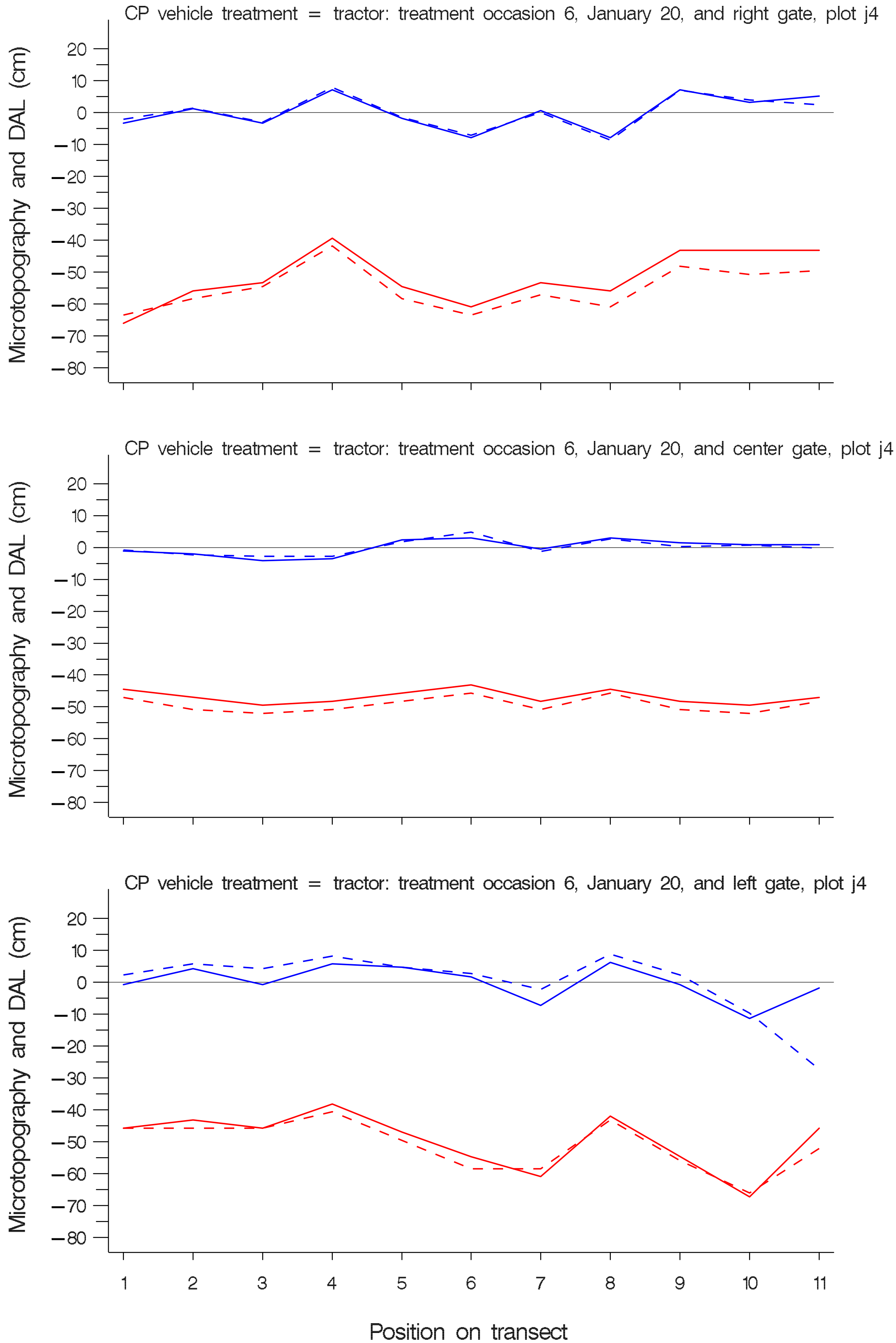
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



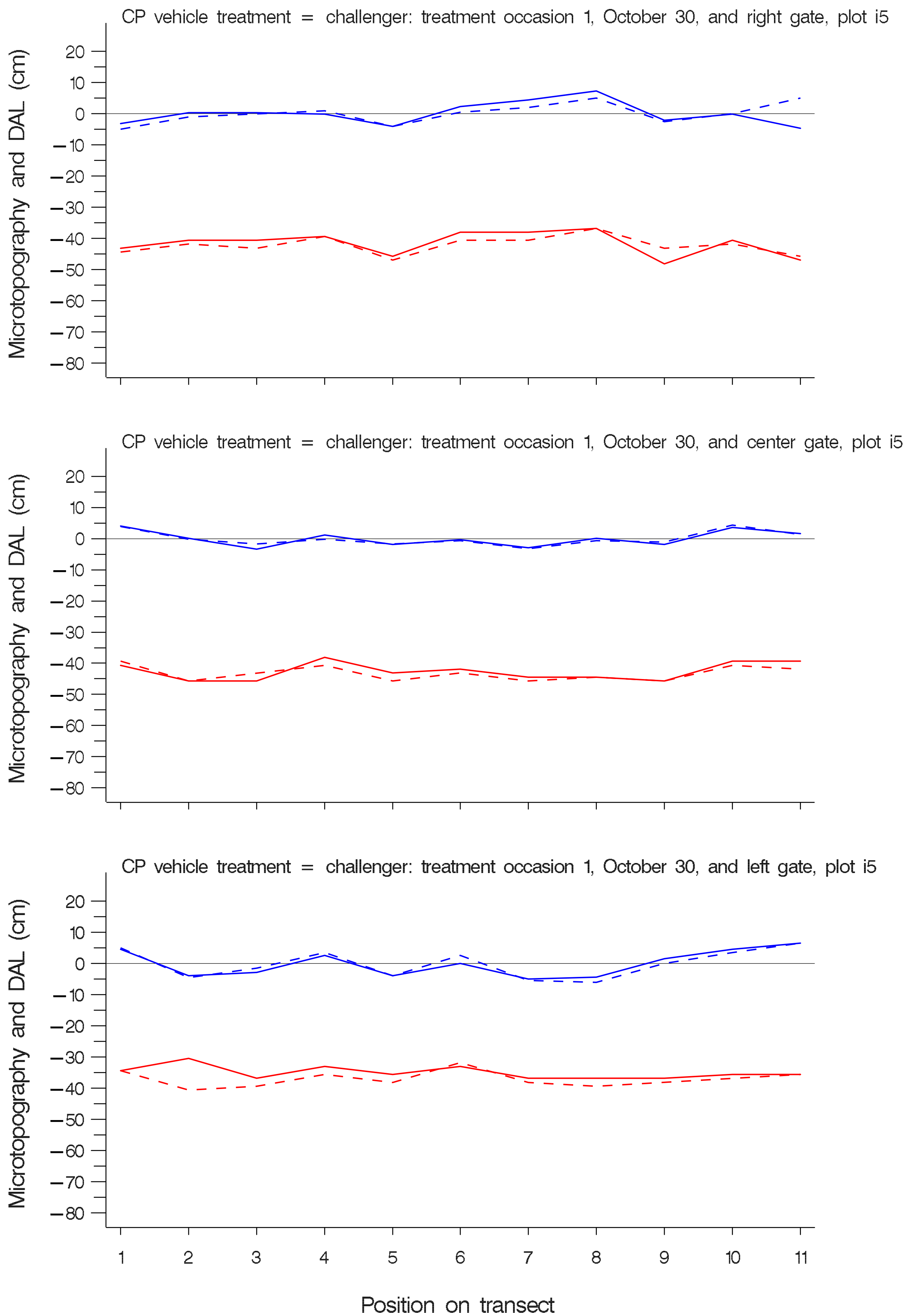
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



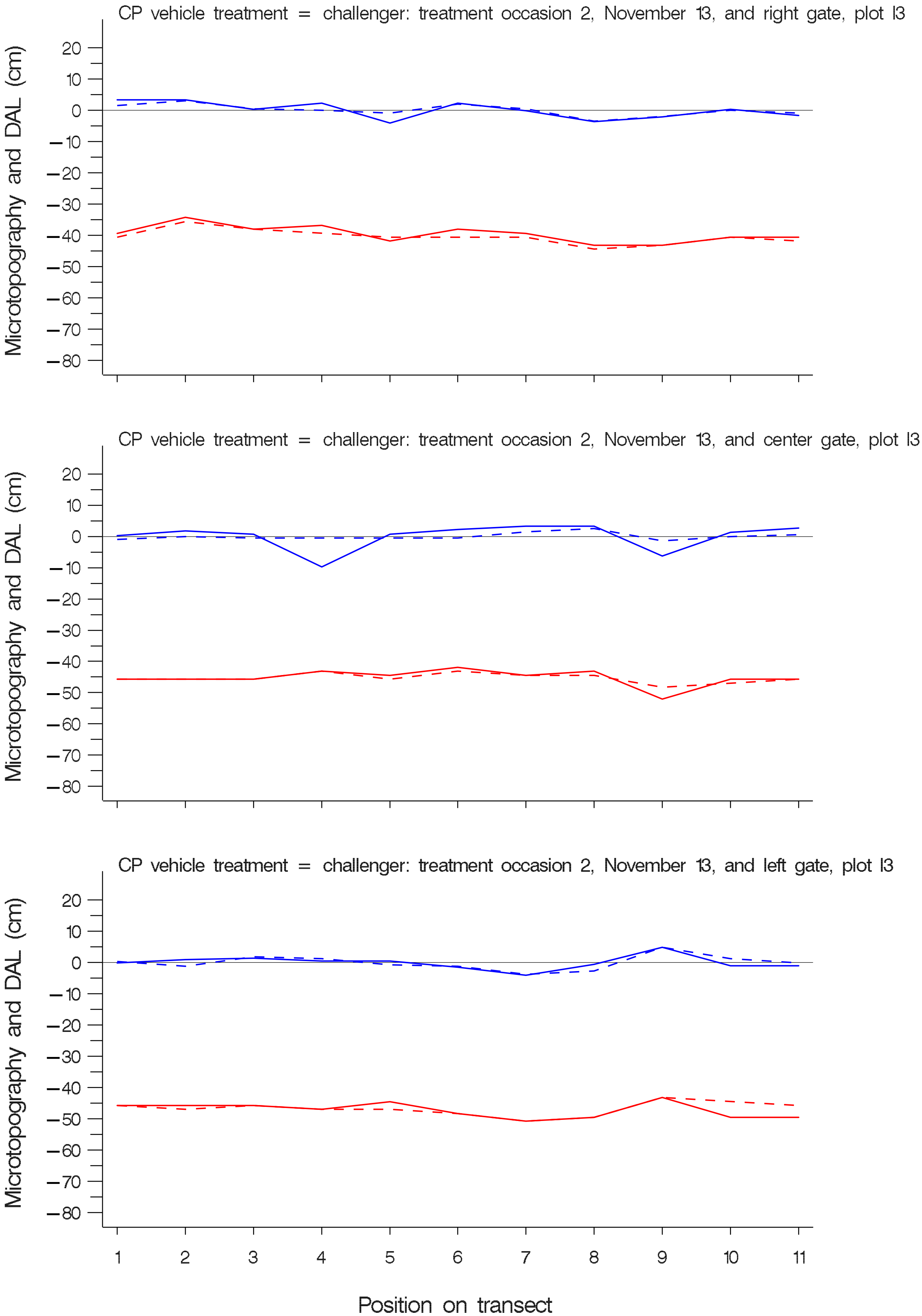
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



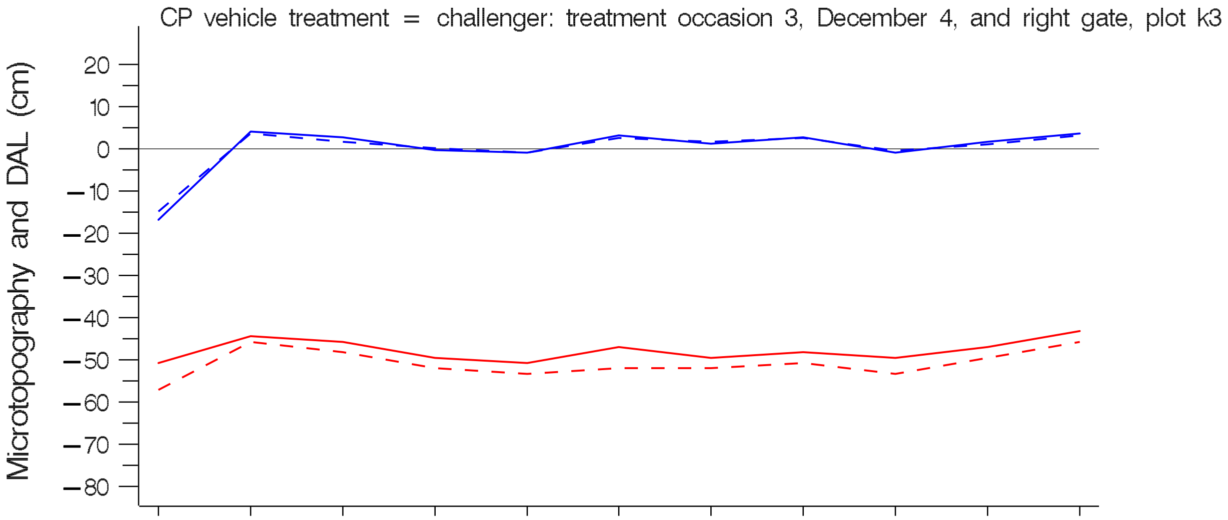
Solid line displays 2003, dashed line displays 2004

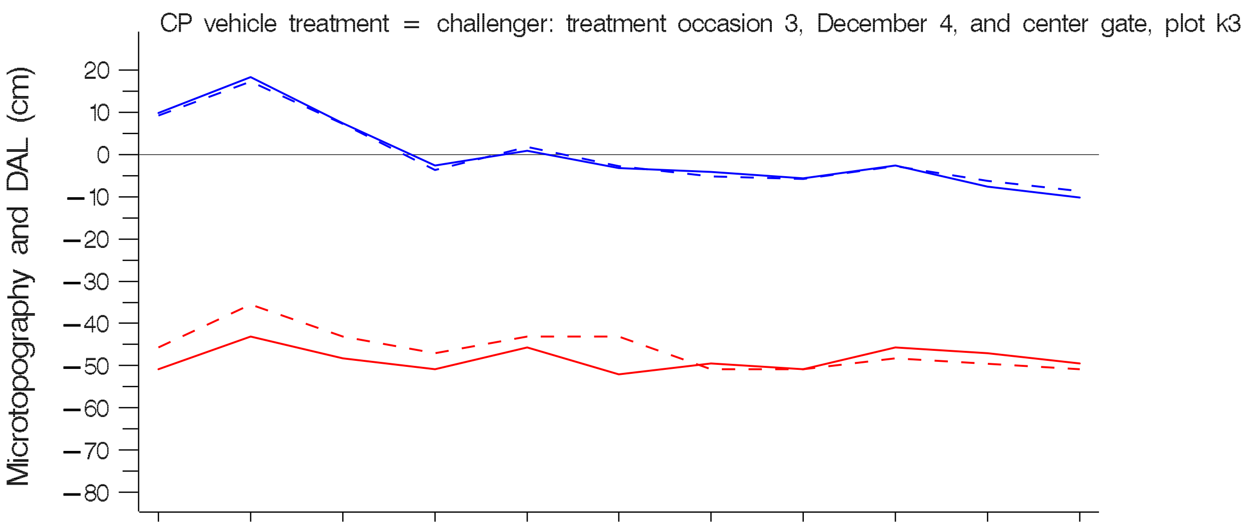
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

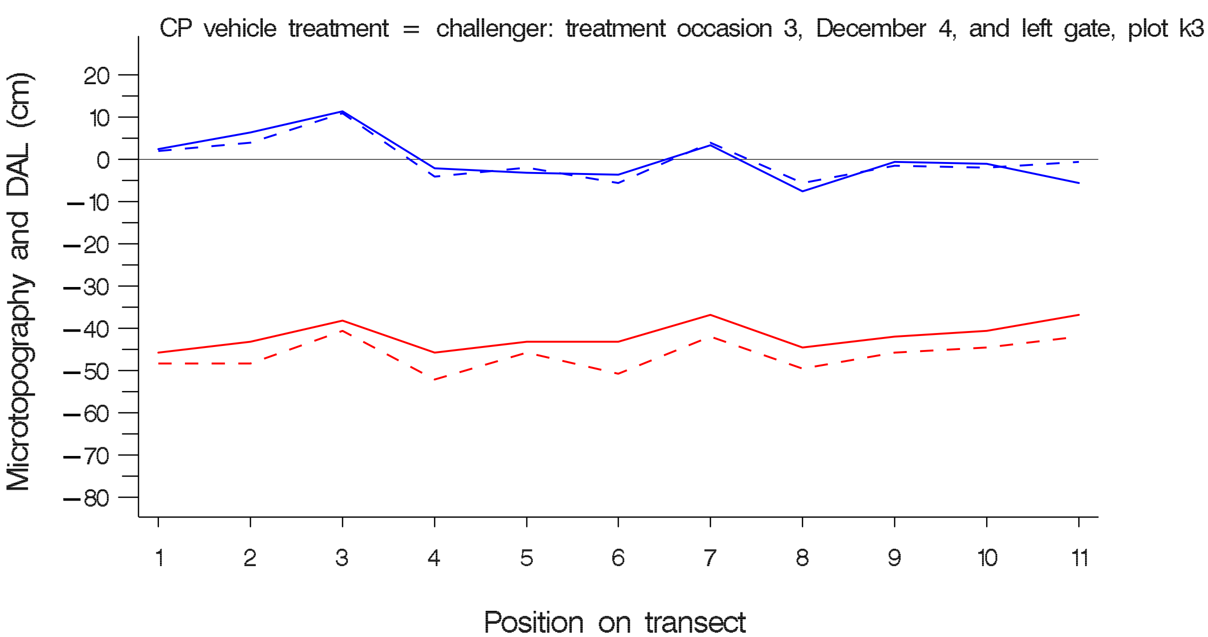


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

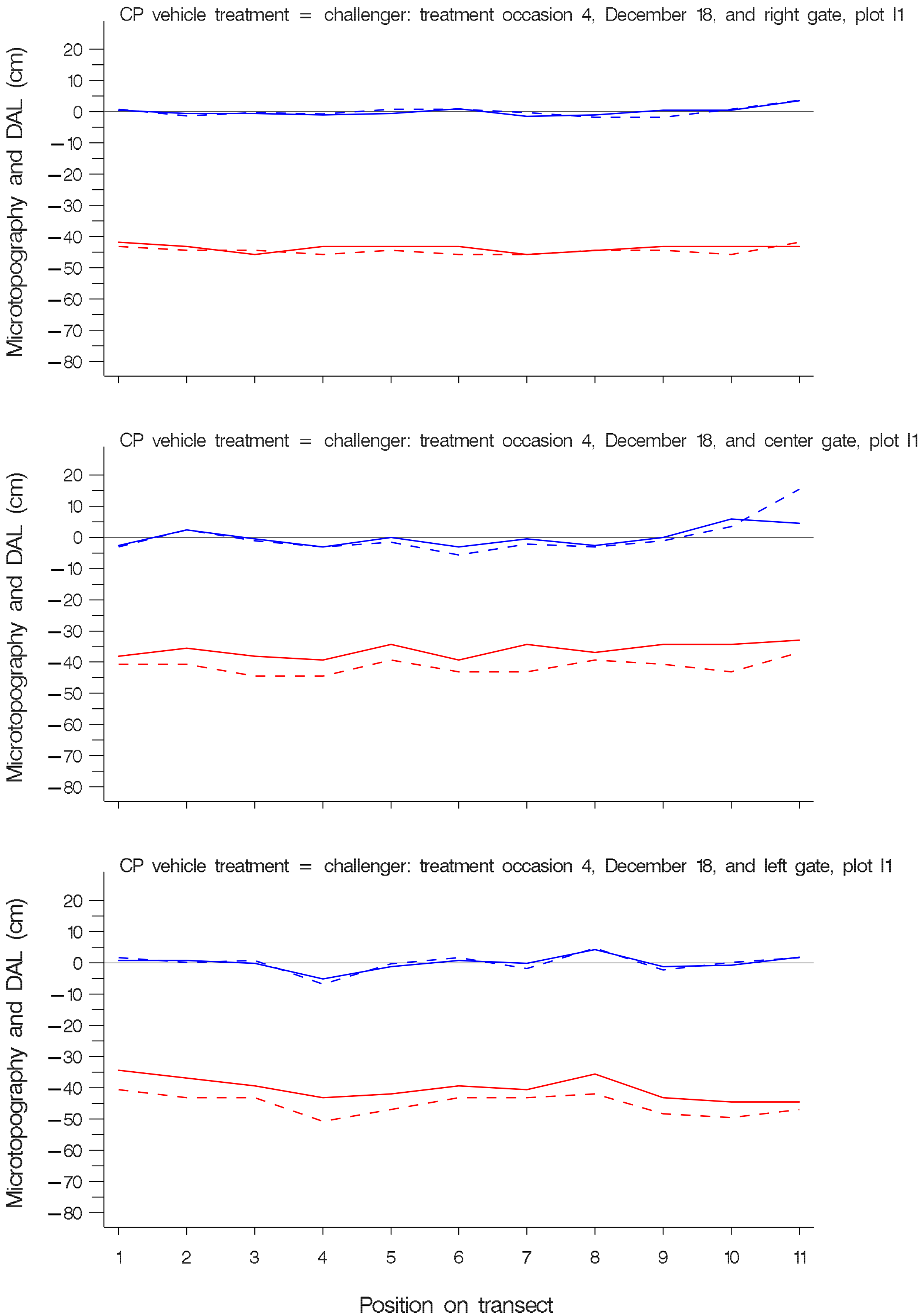






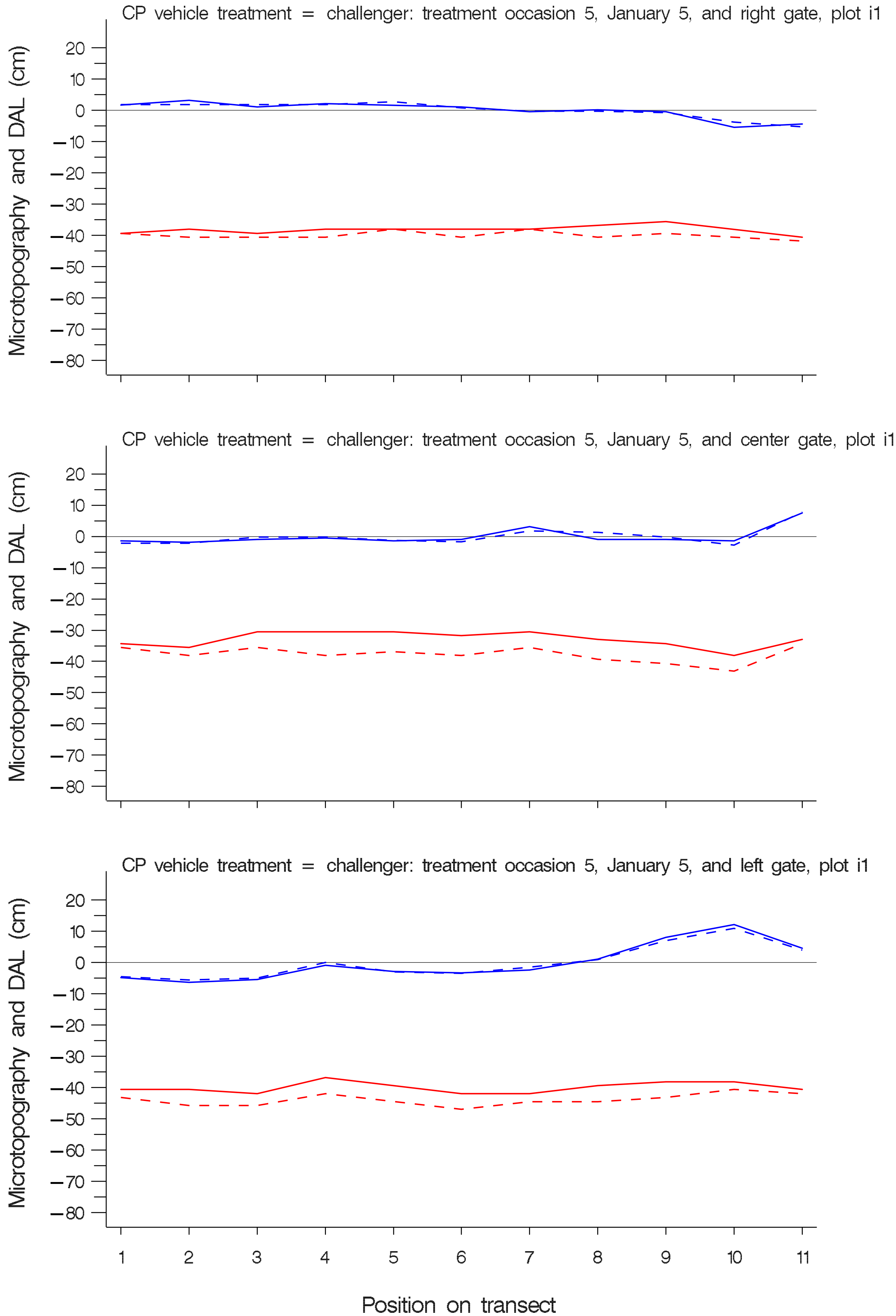
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



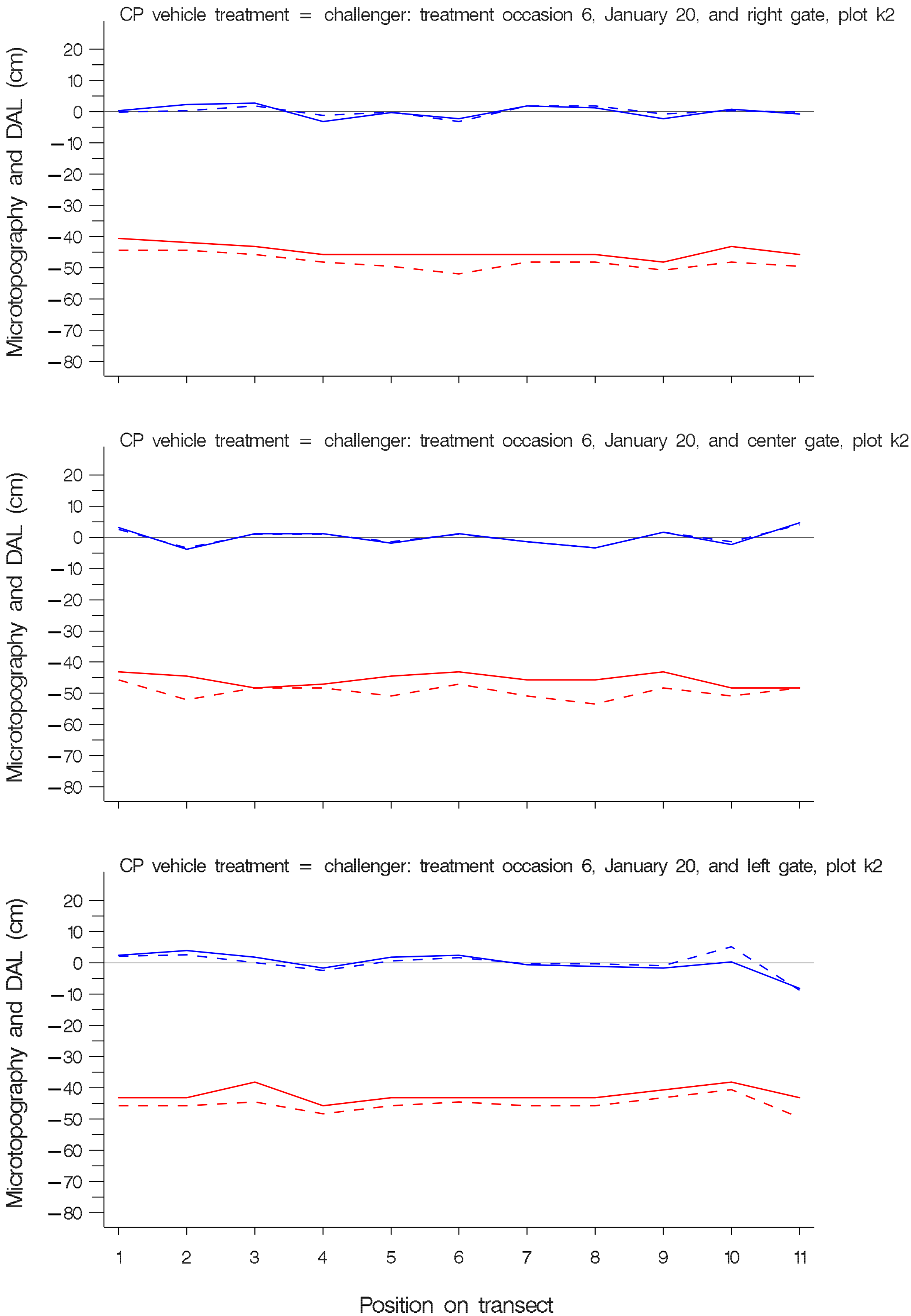
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



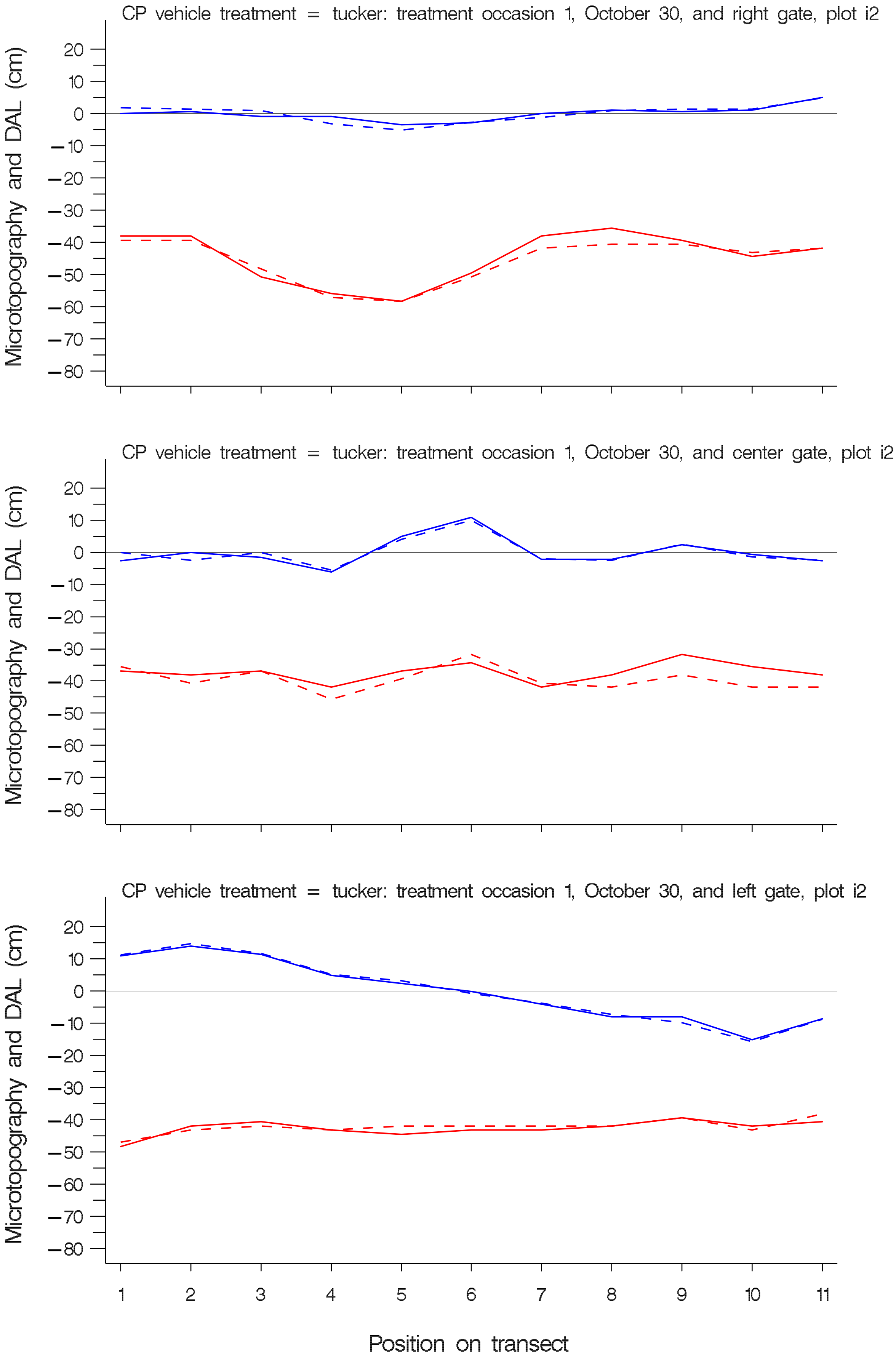
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



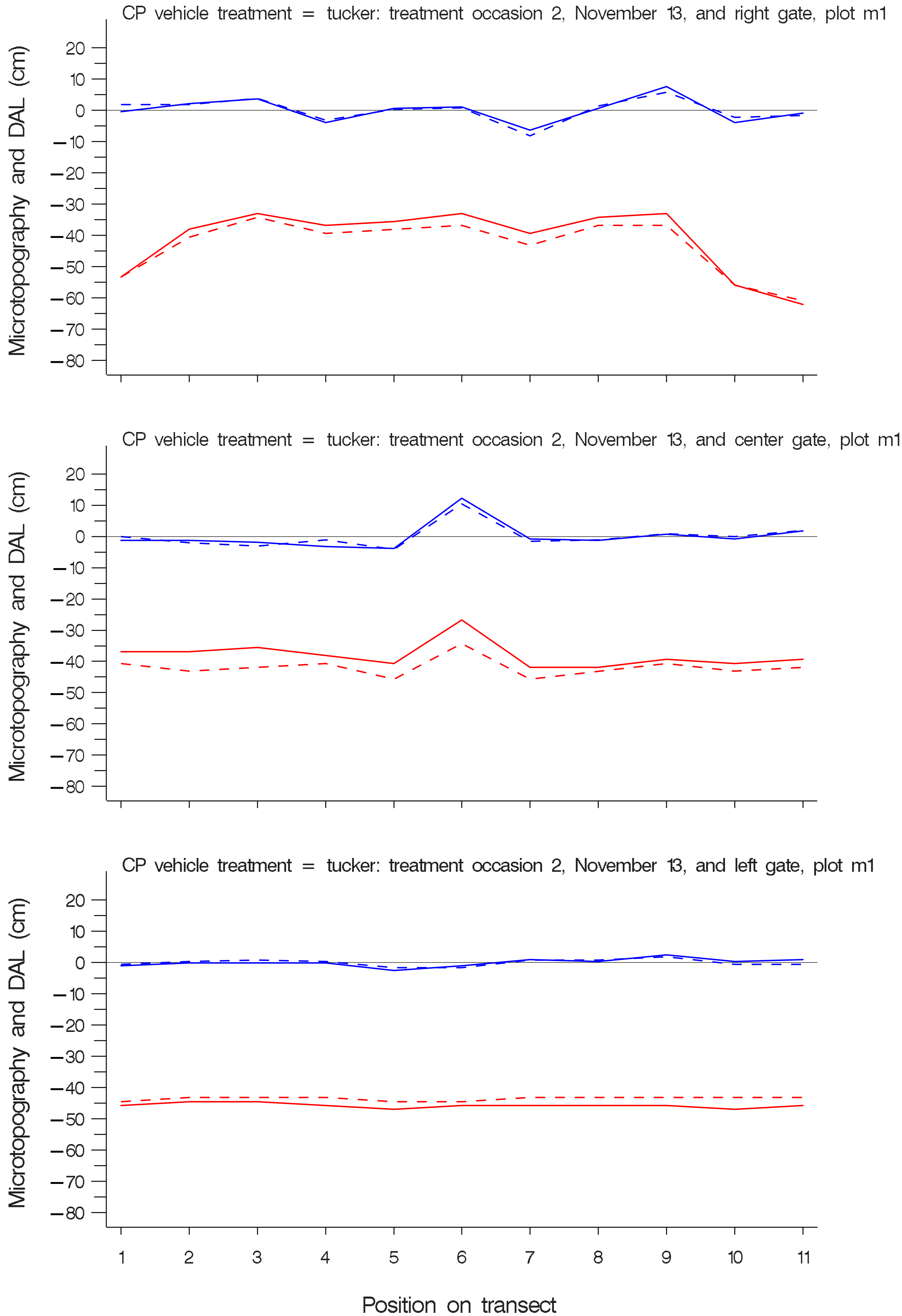
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



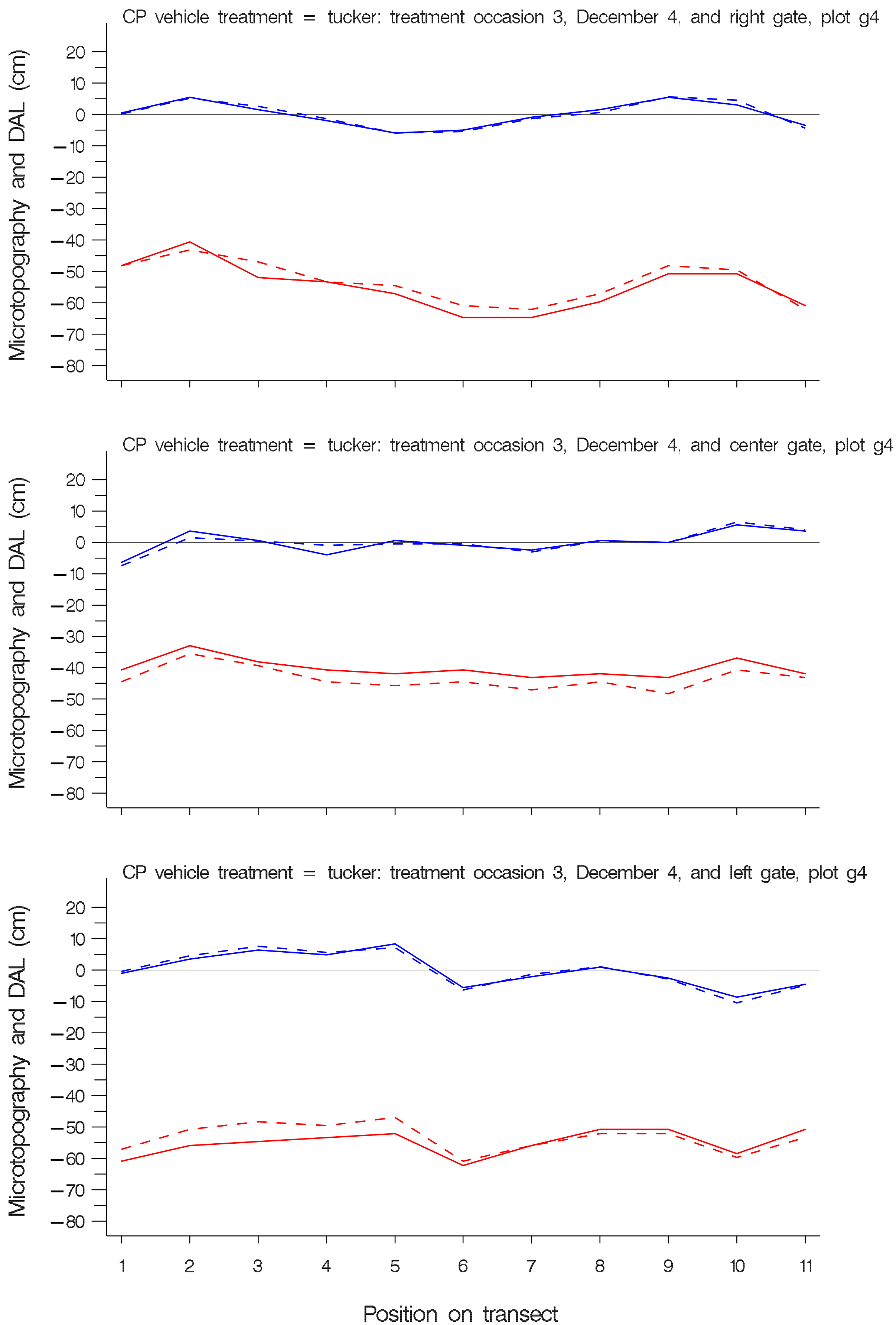
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



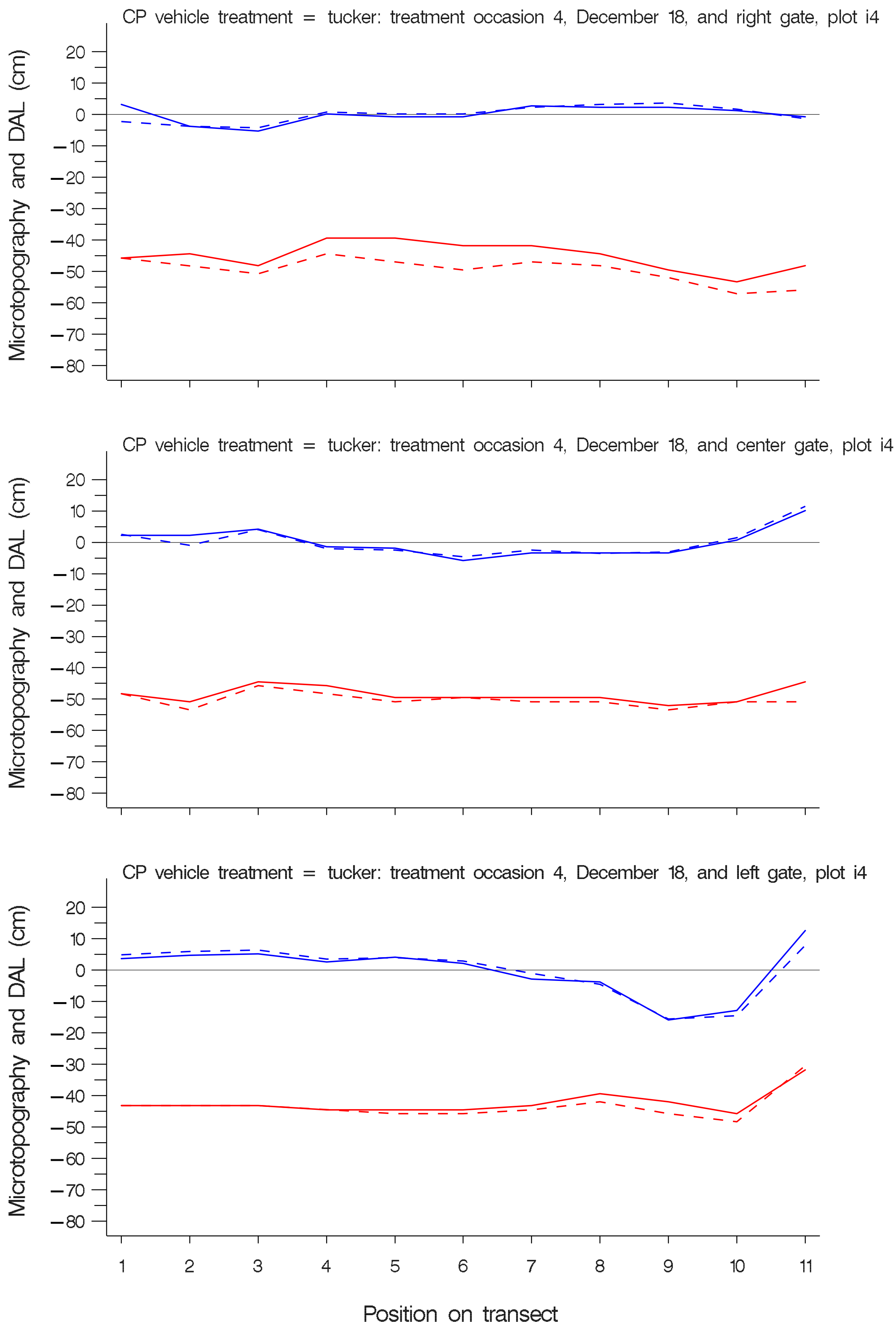
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



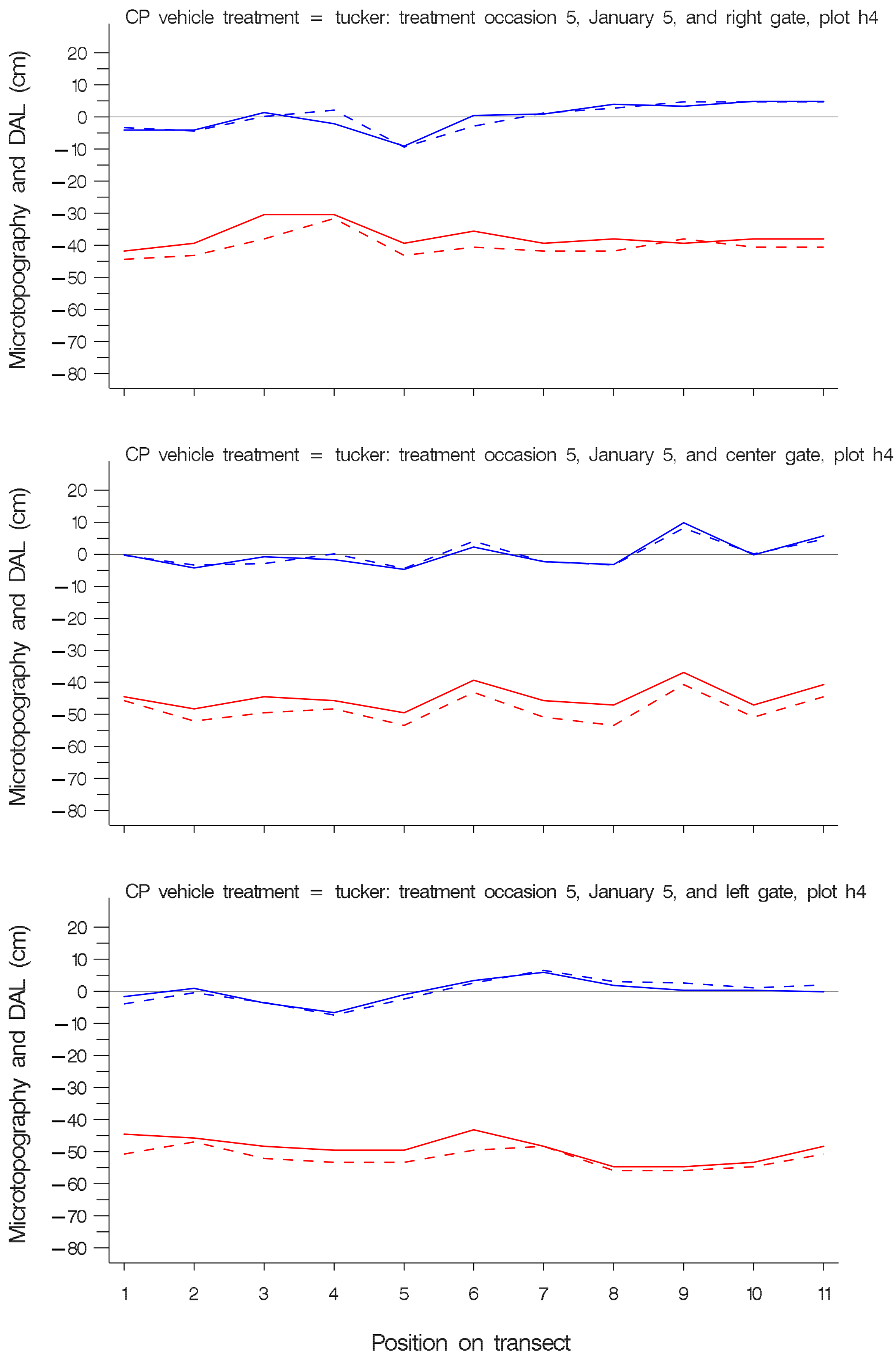
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



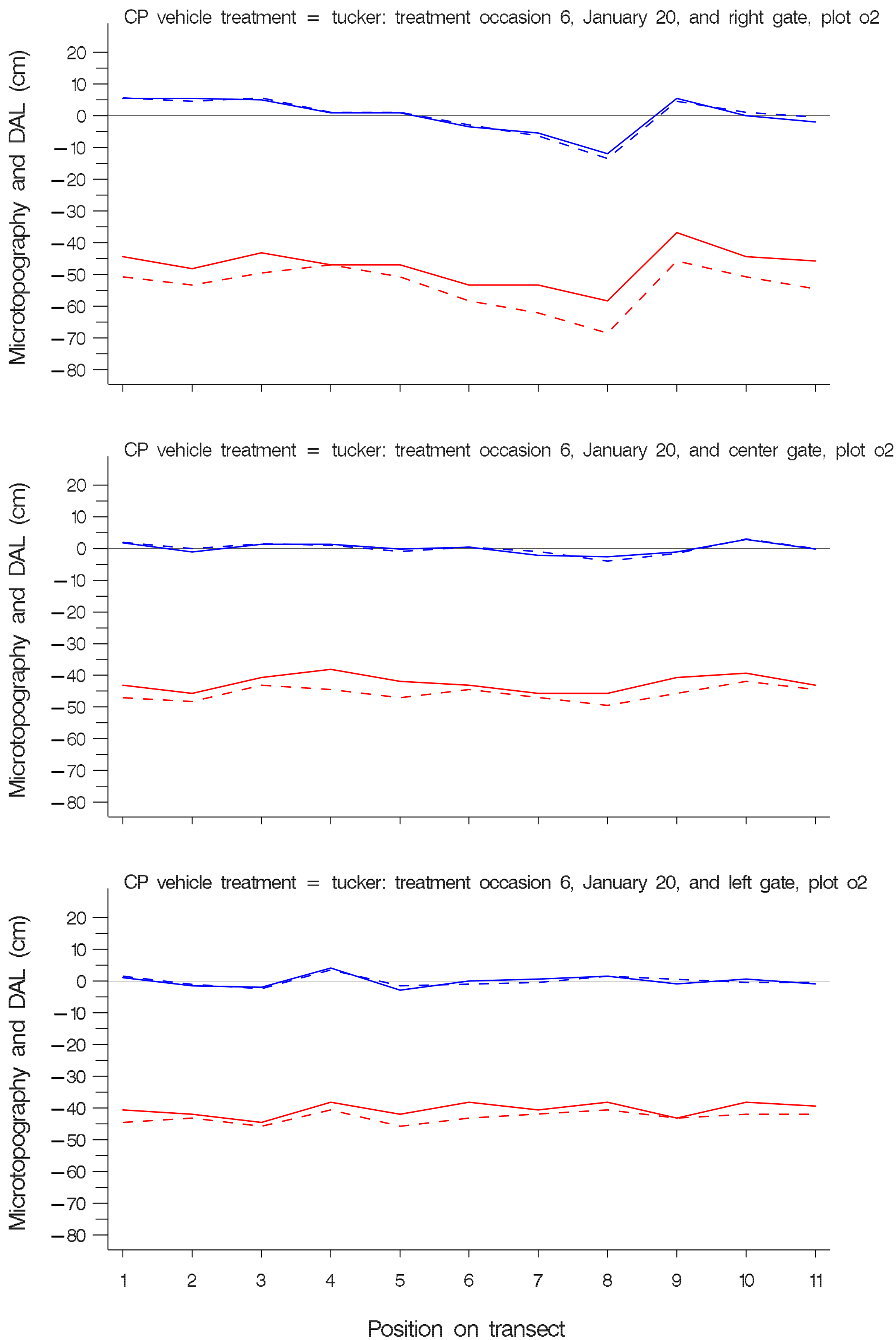
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



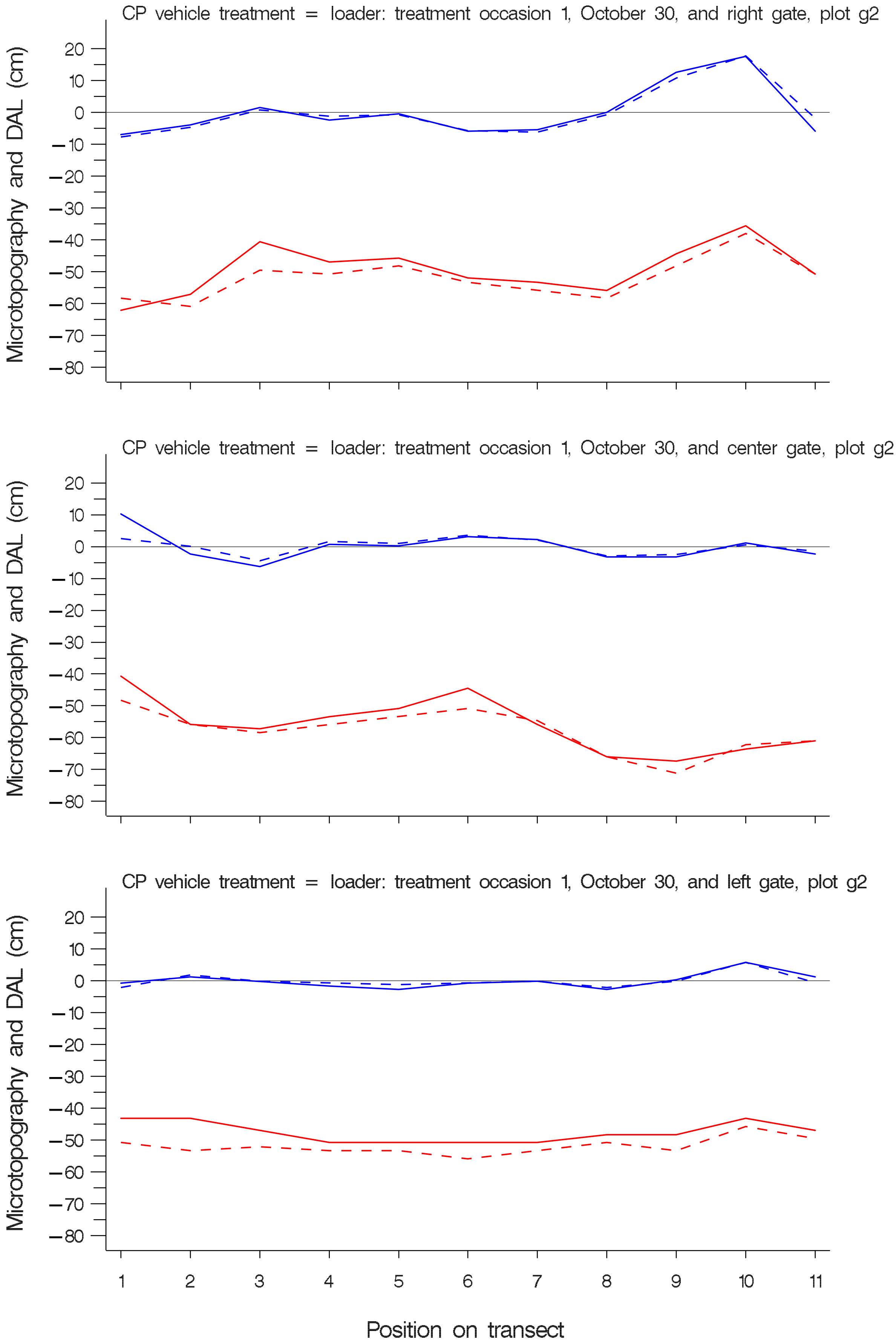
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



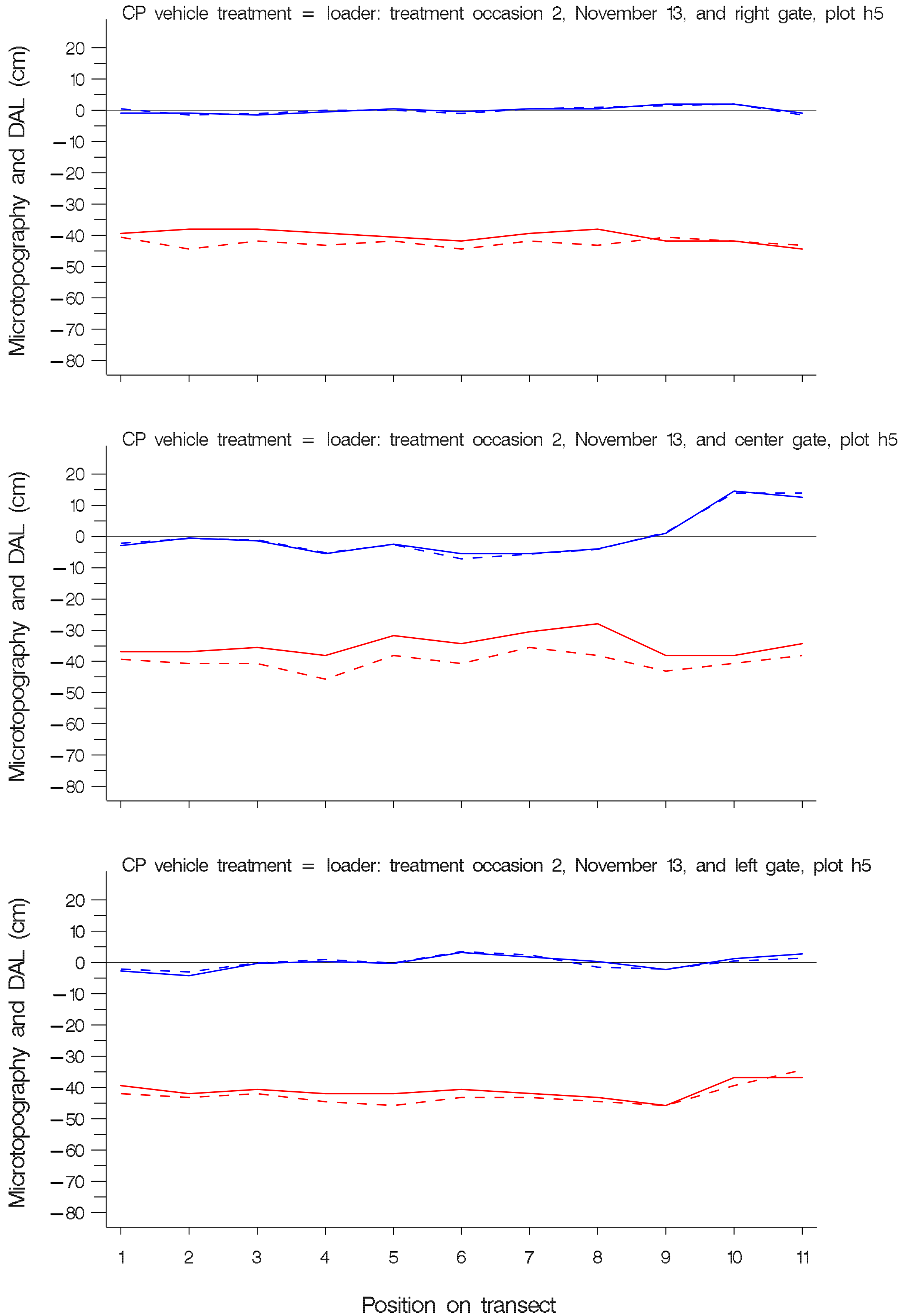
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



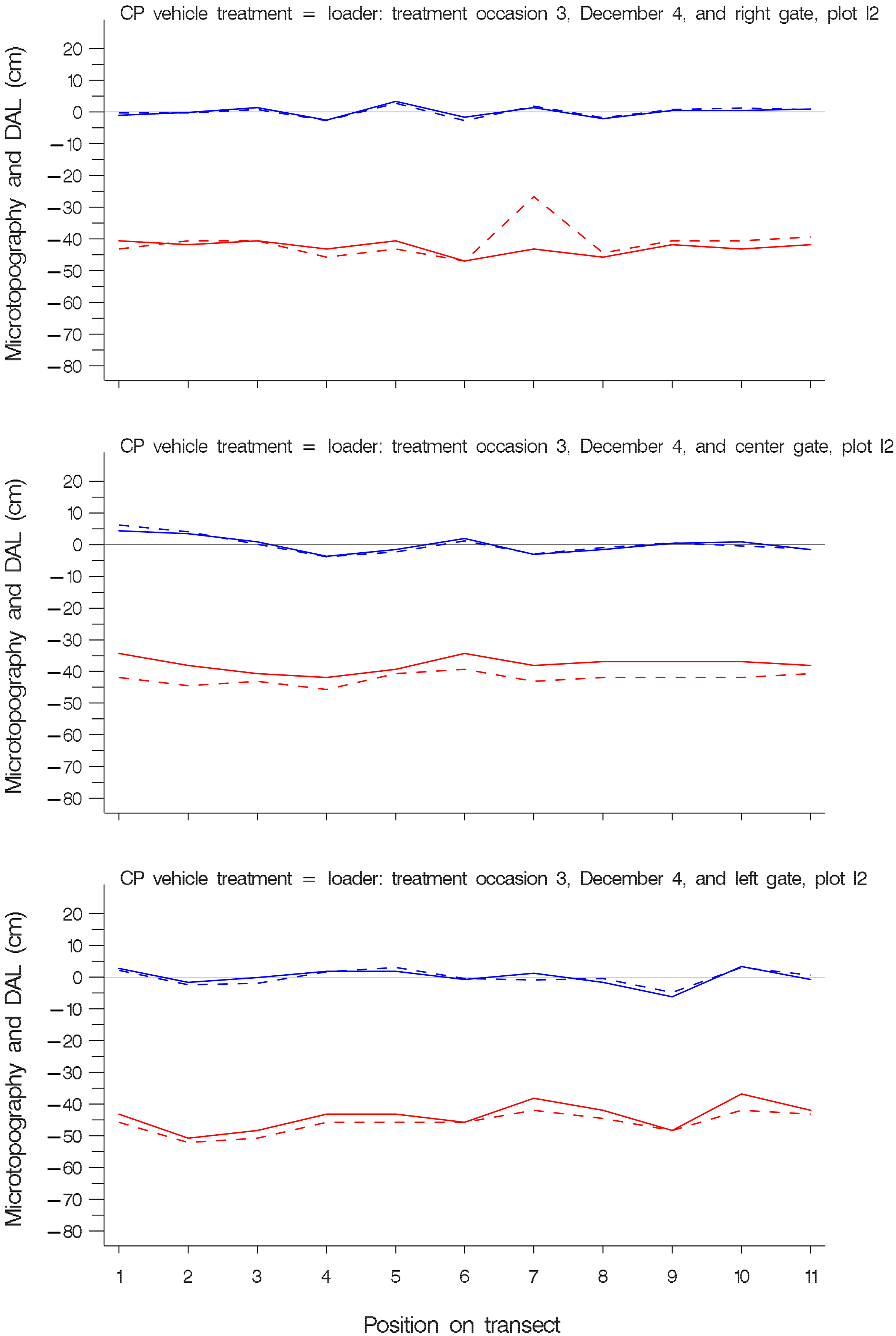
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



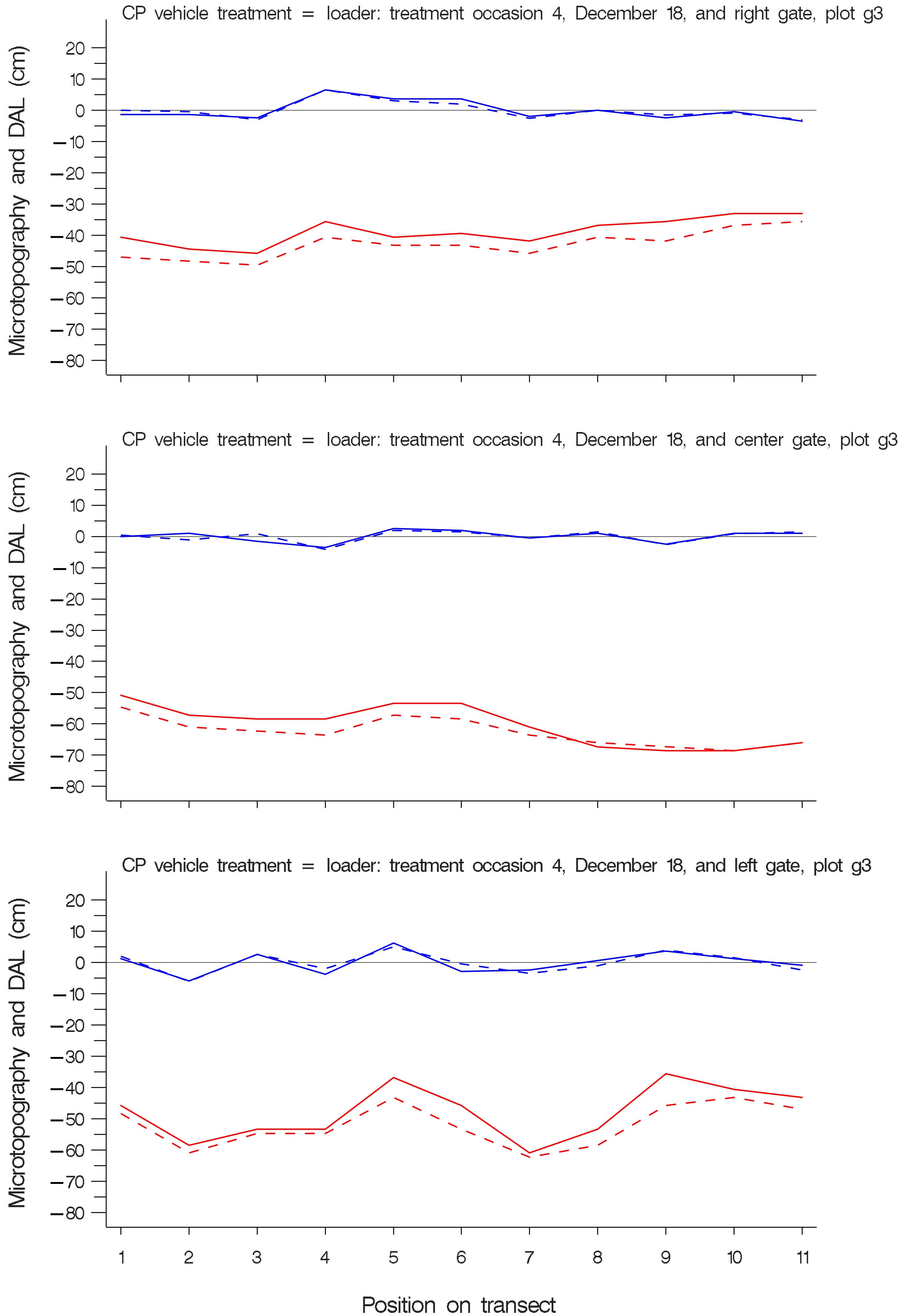
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



Solid line displays 2003, dashed line displays 2004

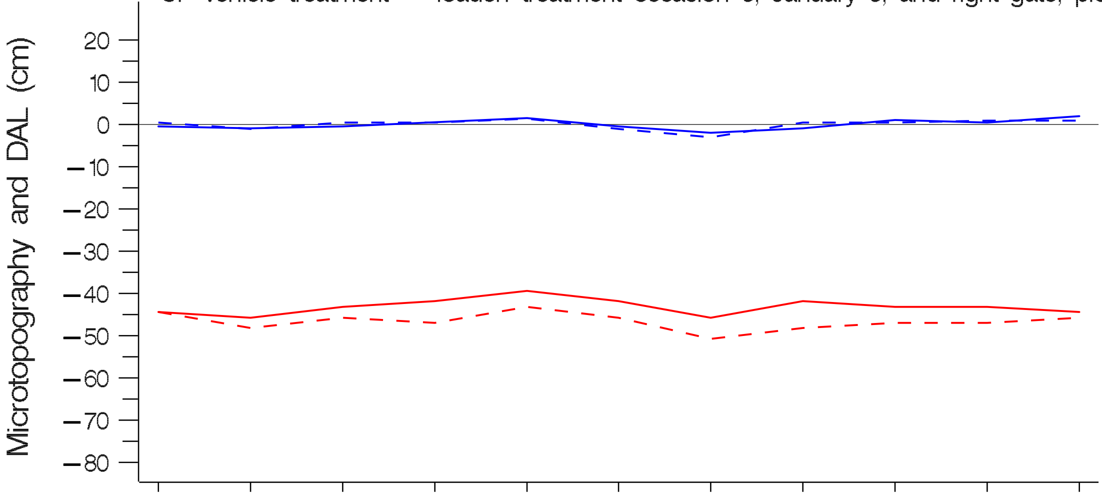
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



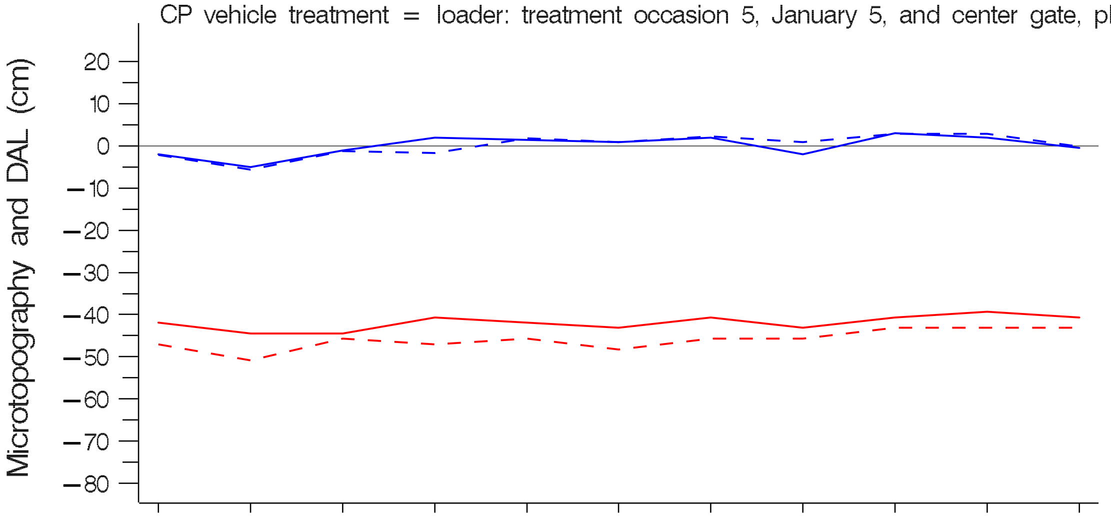
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

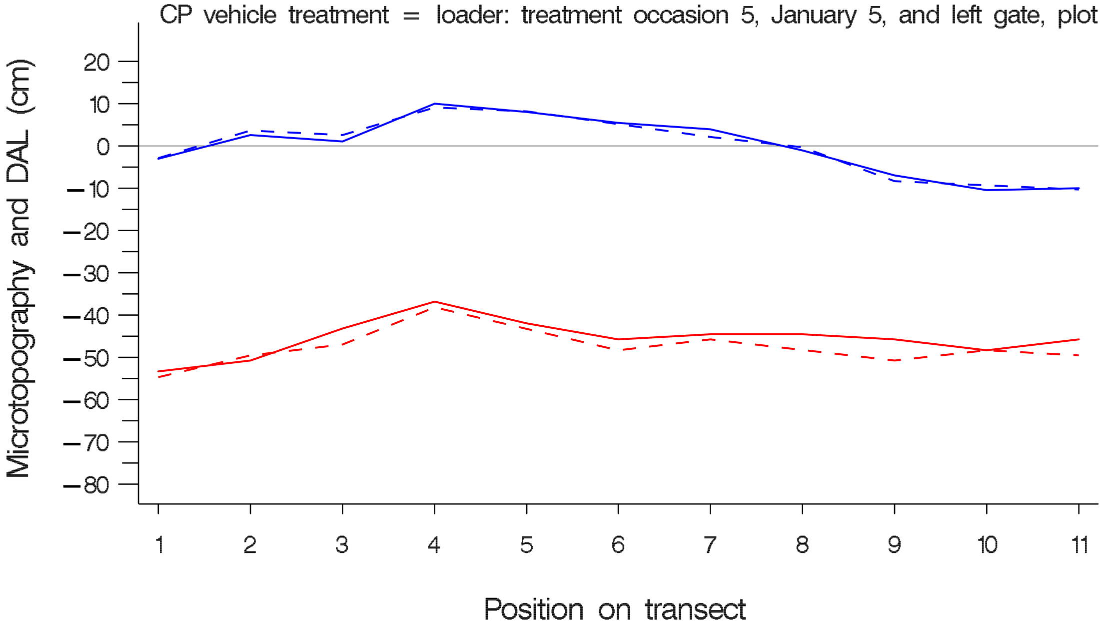
CP vehicle treatment = loader: treatment occasion 5, January 5, and right gate, plot k1



CP vehicle treatment = loader: treatment occasion 5, January 5, and center gate, plot k1

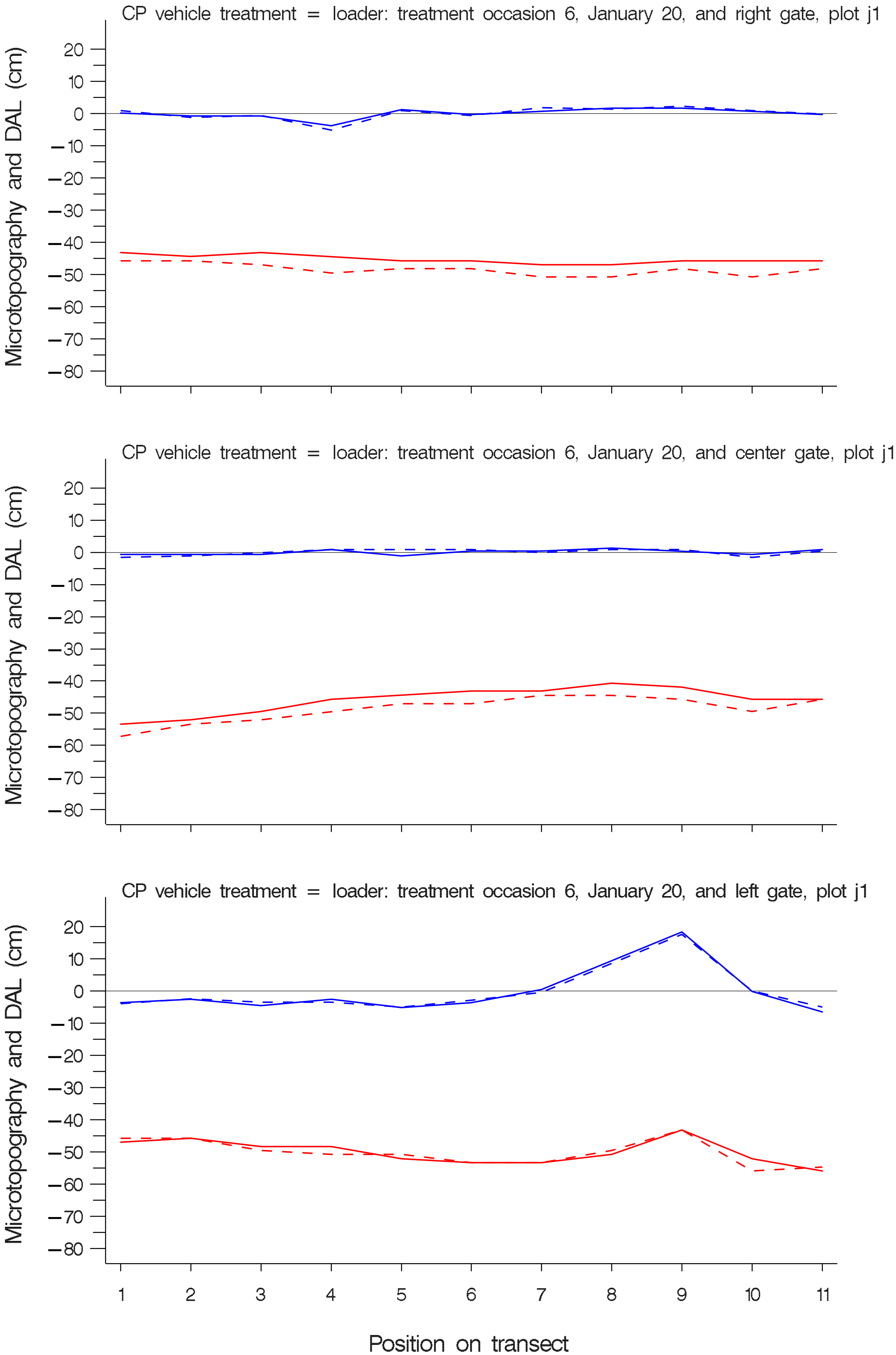


CP vehicle treatment = loader: treatment occasion 5, January 5, and left gate, plot k1



Solid line displays 2003, dashed line displays 2004

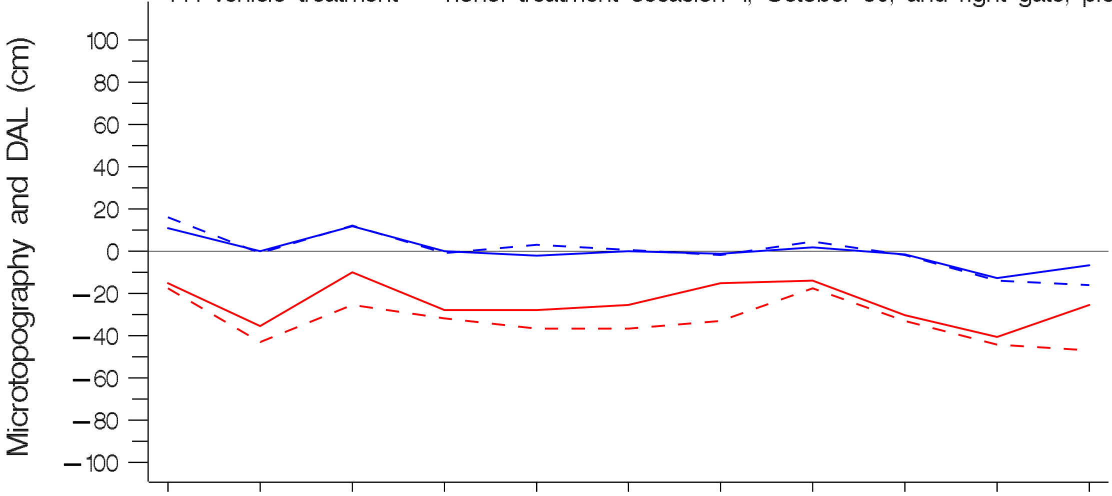
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



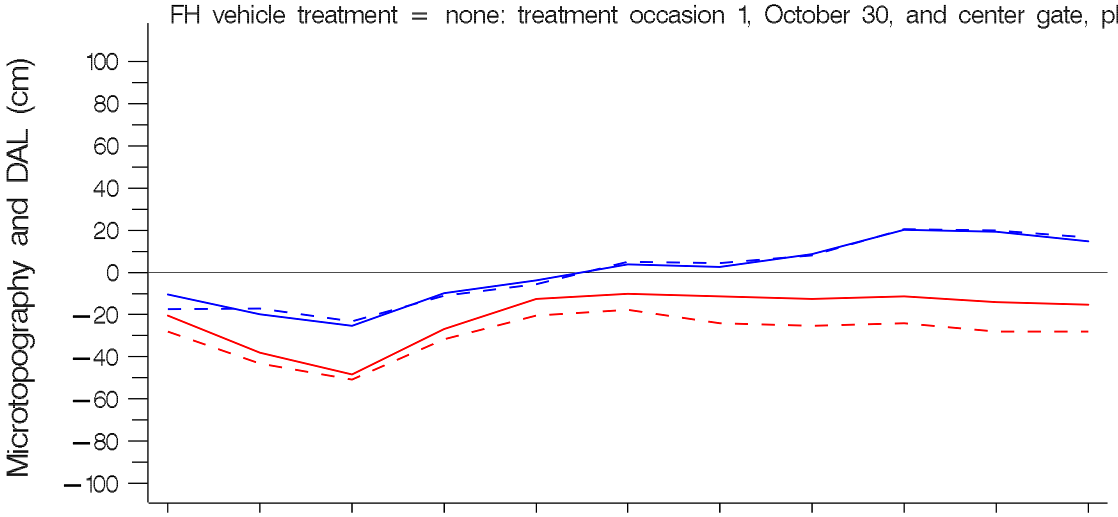
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

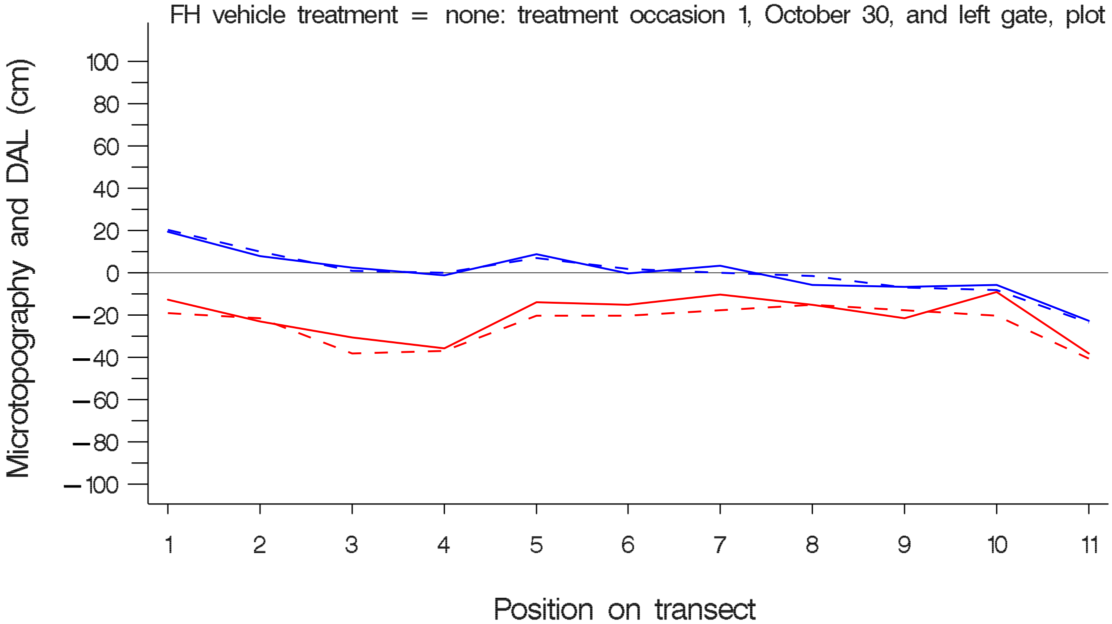
FH vehicle treatment = none: treatment occasion 1, October 30, and right gate, plot c3



FH vehicle treatment = none: treatment occasion 1, October 30, and center gate, plot c3



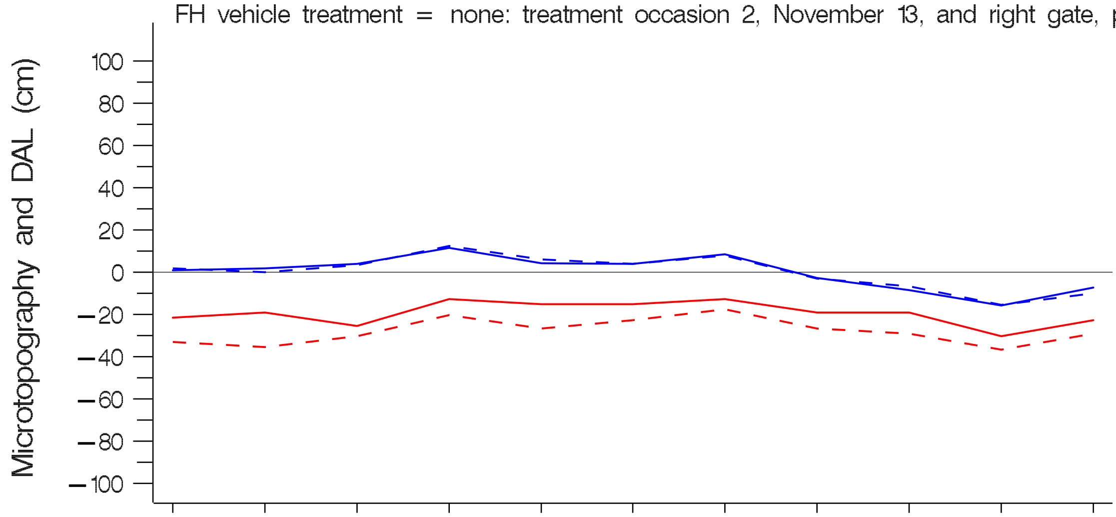
FH vehicle treatment = none: treatment occasion 1, October 30, and left gate, plot c3



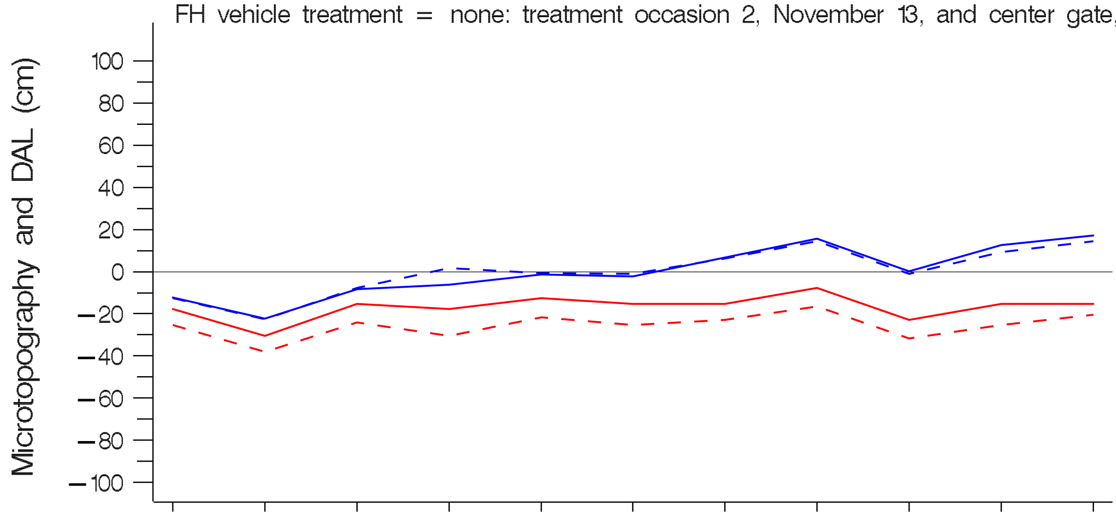
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

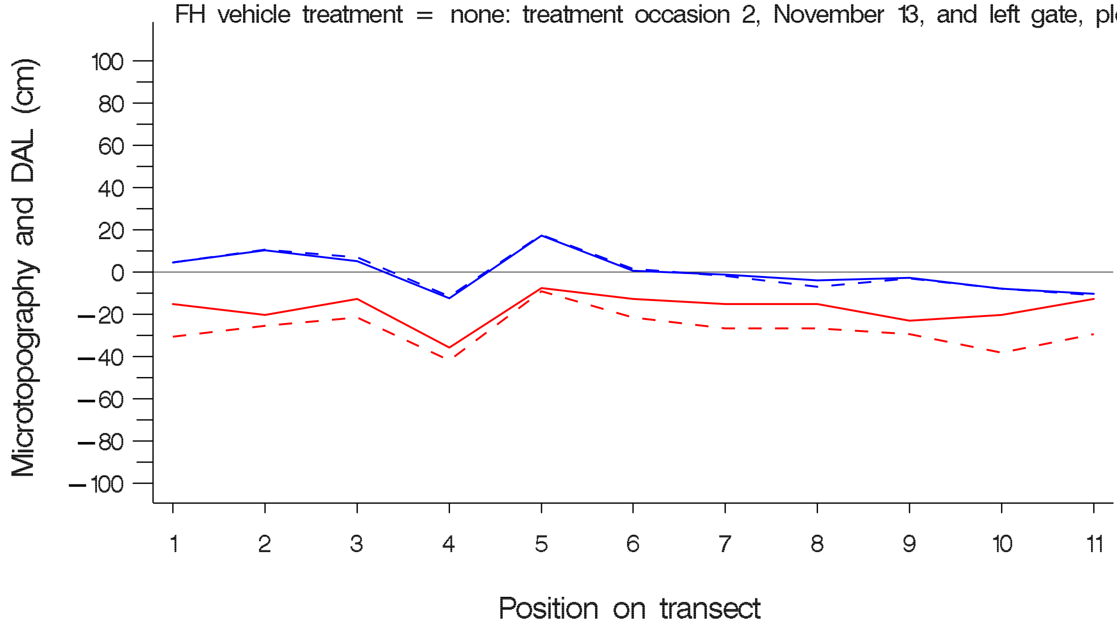
FH vehicle treatment = none: treatment occasion 2, November 13, and right gate, plot c1



FH vehicle treatment = none: treatment occasion 2, November 13, and center gate, plot c1

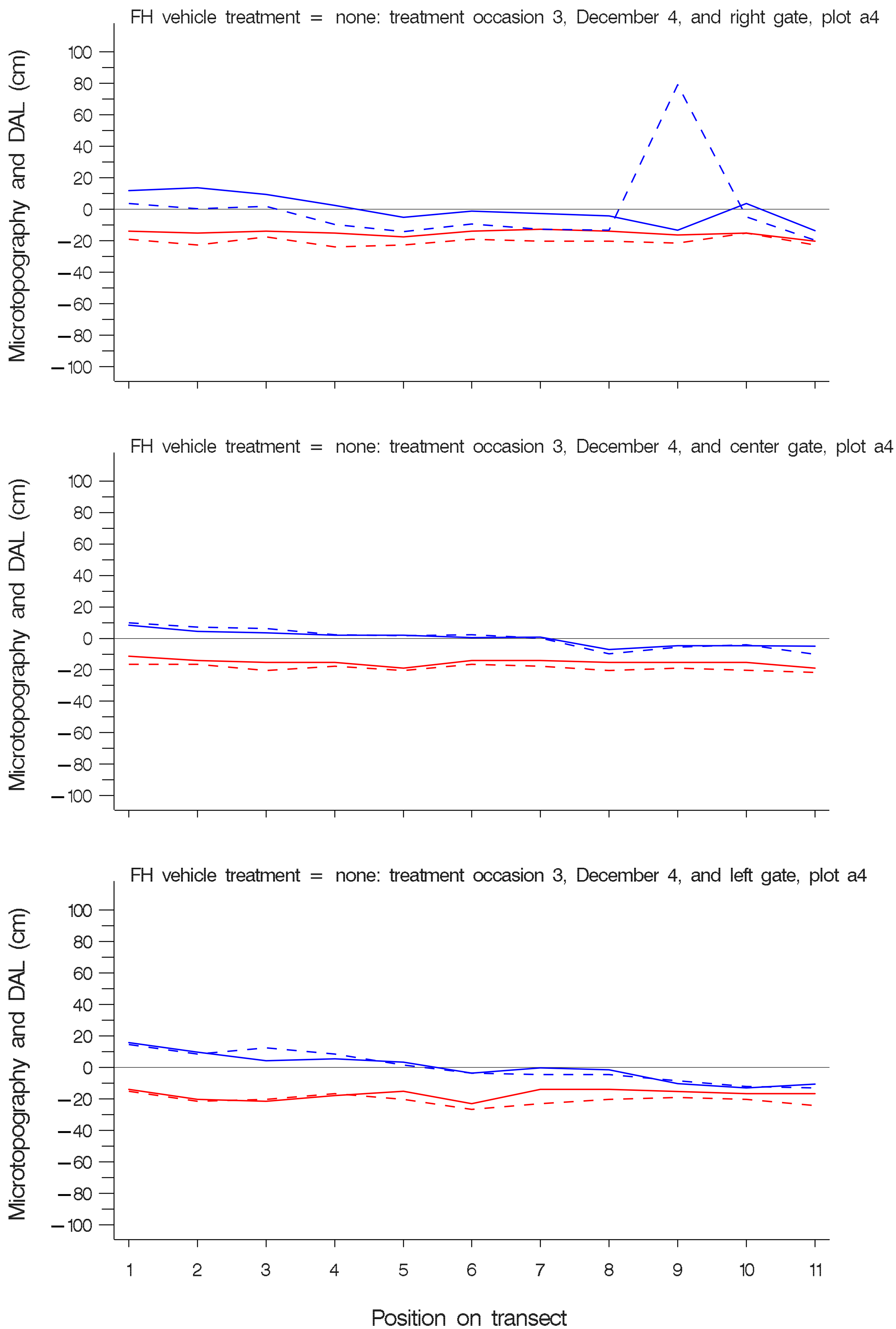


FH vehicle treatment = none: treatment occasion 2, November 13, and left gate, plot c1



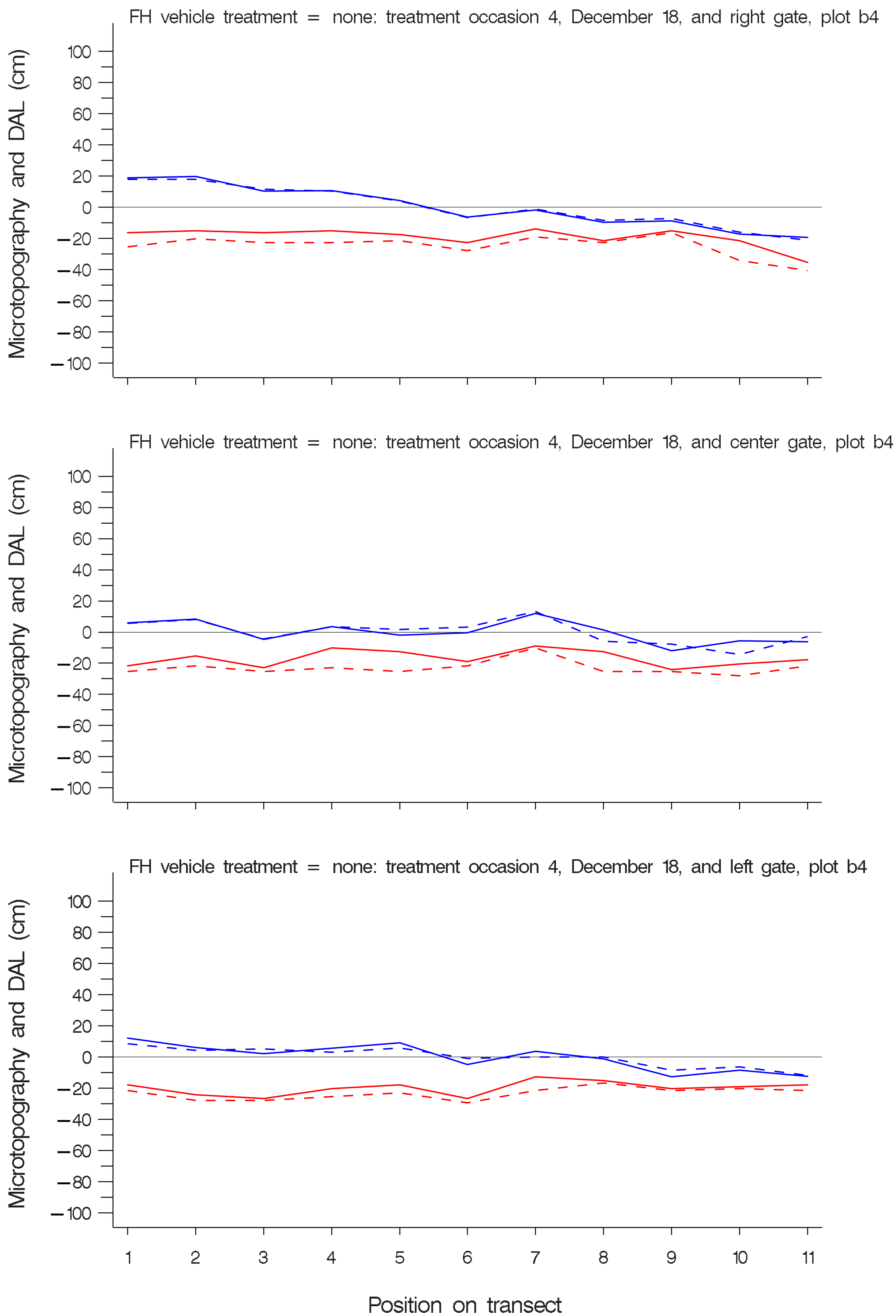
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

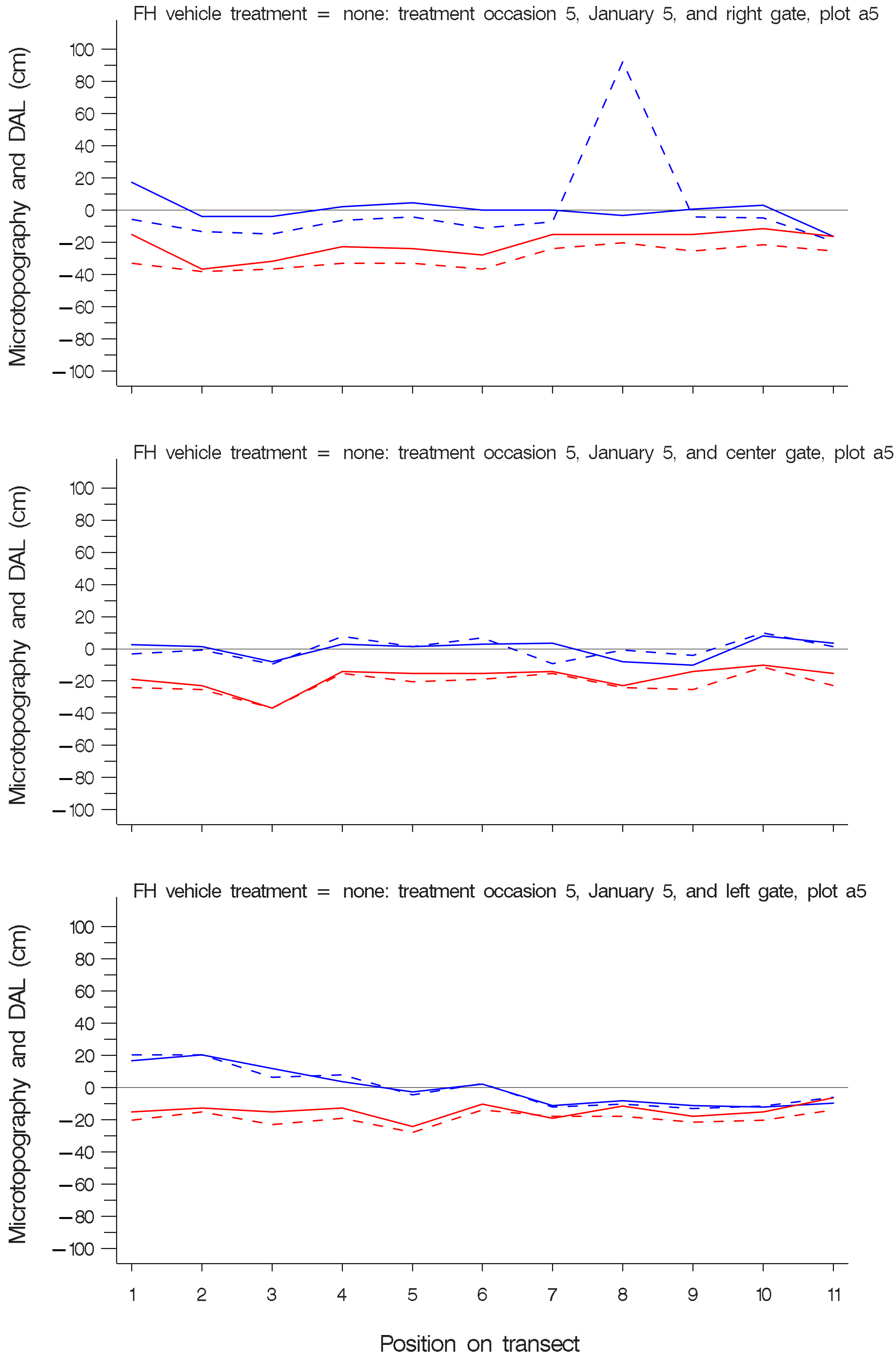


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

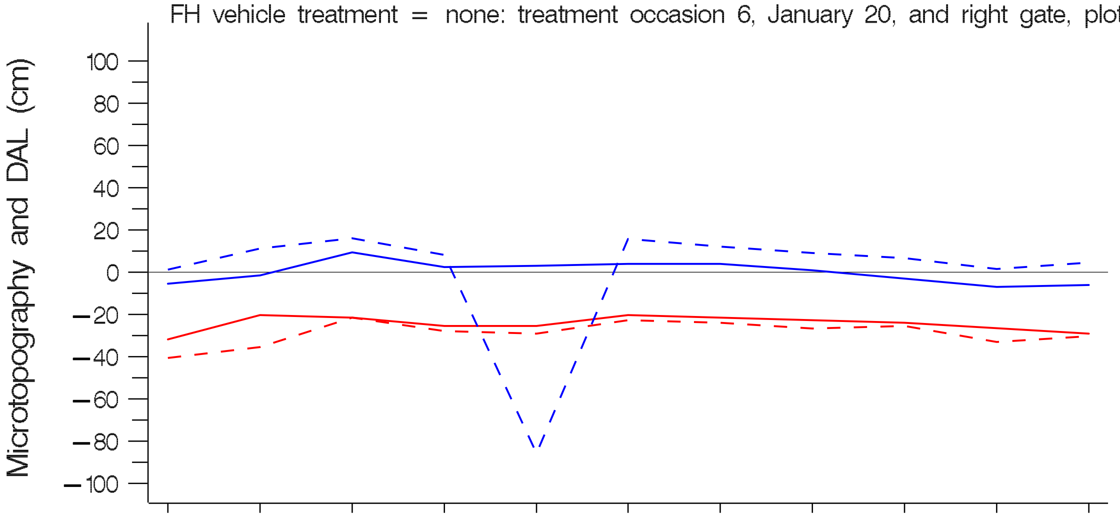


Solid line displays 2003, dashed line displays 2004

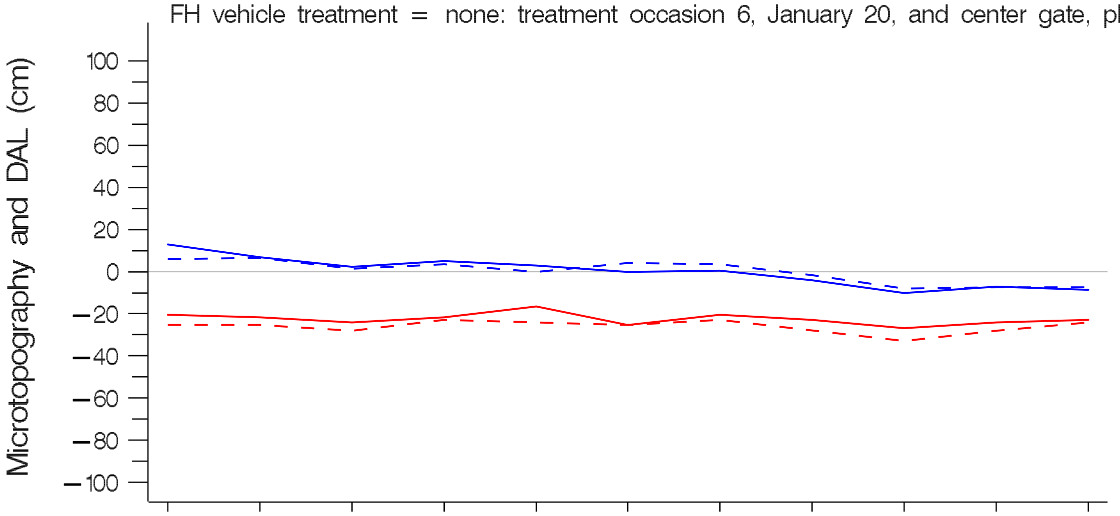


Solid line displays 2003, dashed line displays 2004

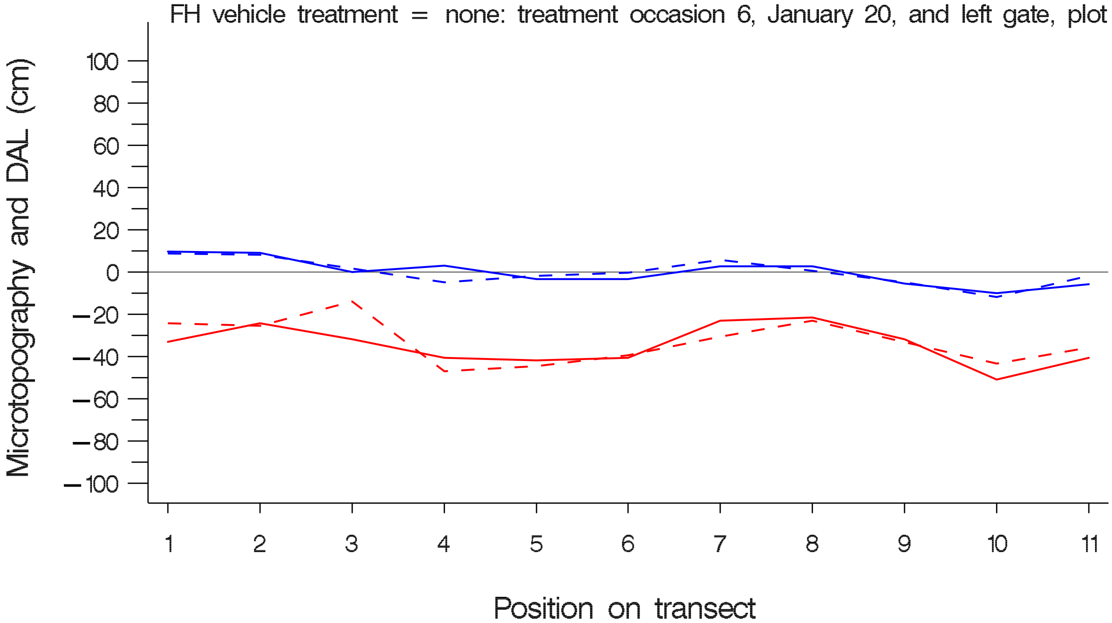
FH vehicle treatment = none: treatment occasion 6, January 20, and right gate, plot f5



FH vehicle treatment = none: treatment occasion 6, January 20, and center gate, plot f5



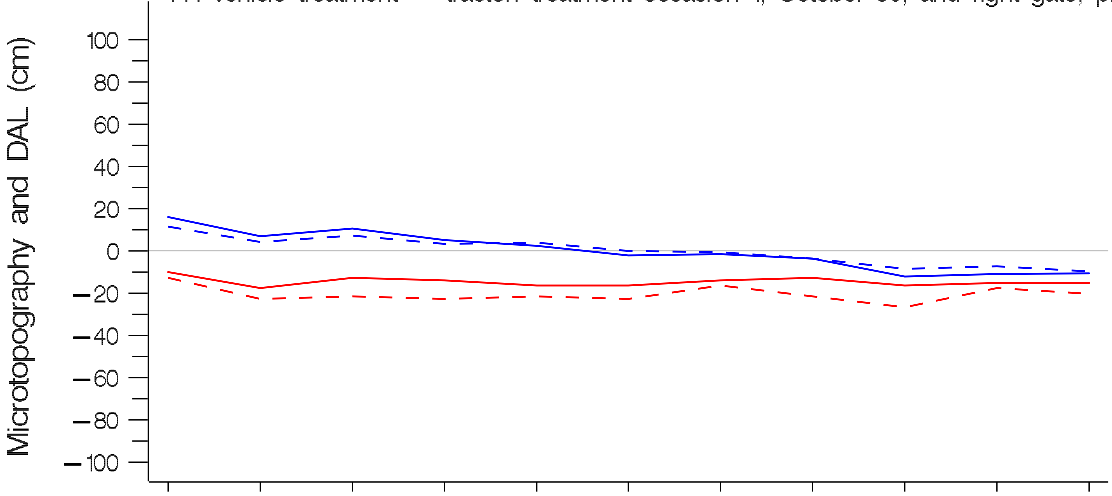
FH vehicle treatment = none: treatment occasion 6, January 20, and left gate, plot f5



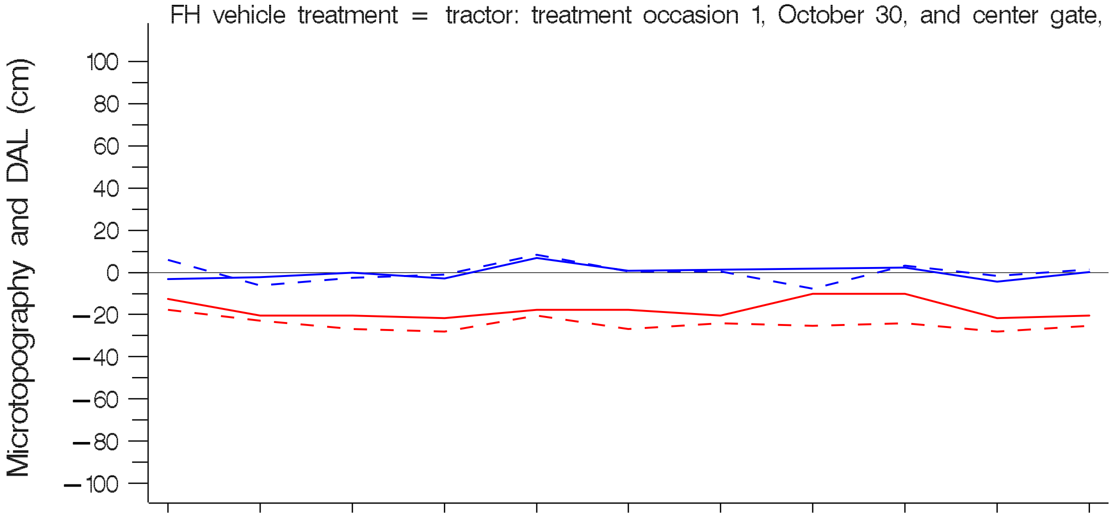
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

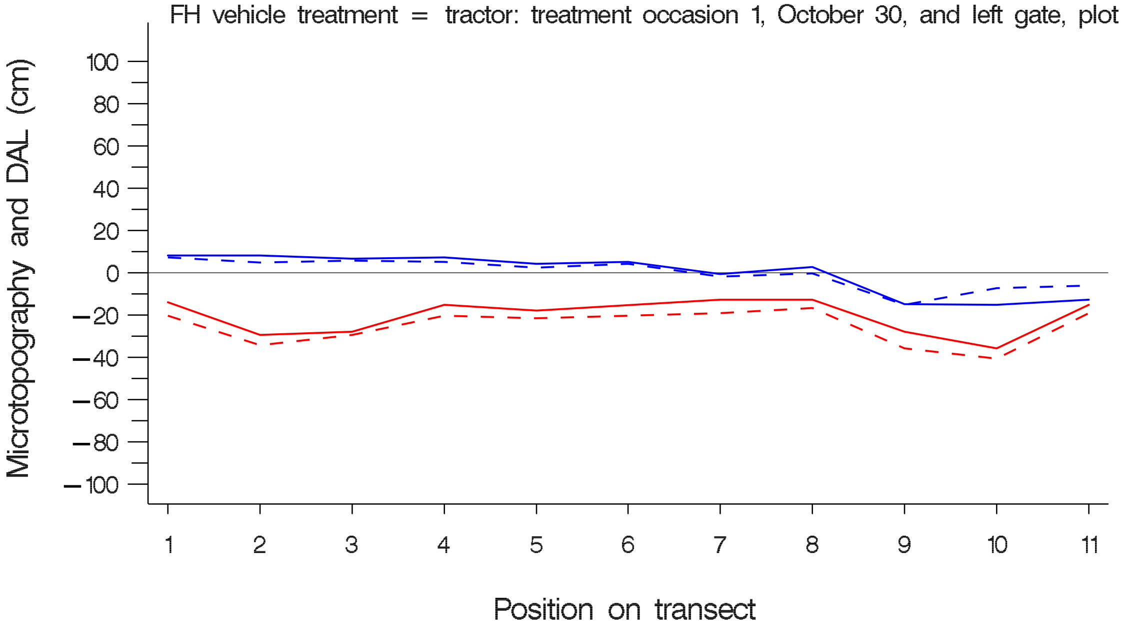
FH vehicle treatment = tractor: treatment occasion 1, October 30, and right gate, plot a2



FH vehicle treatment = tractor: treatment occasion 1, October 30, and center gate, plot a2



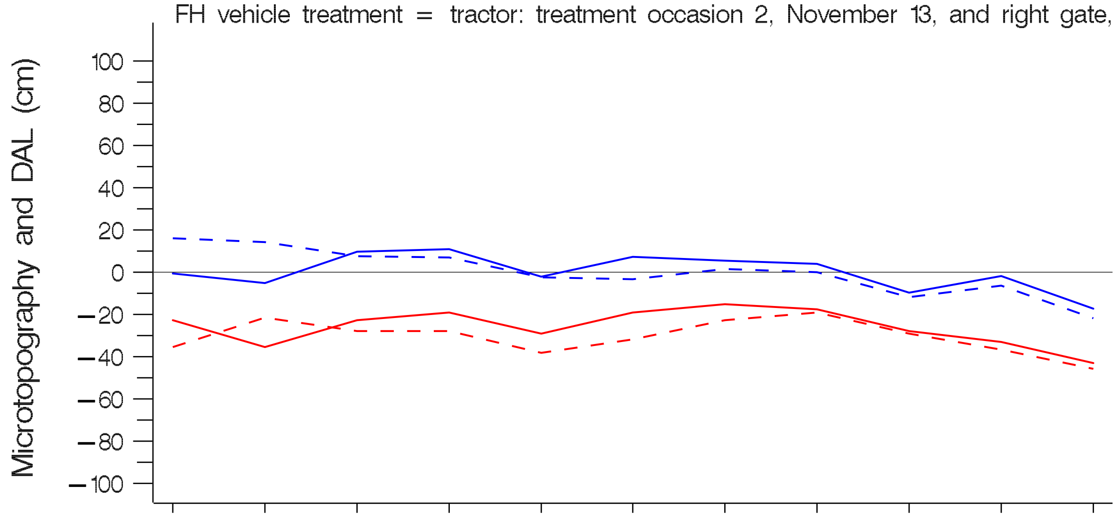
FH vehicle treatment = tractor: treatment occasion 1, October 30, and left gate, plot a2



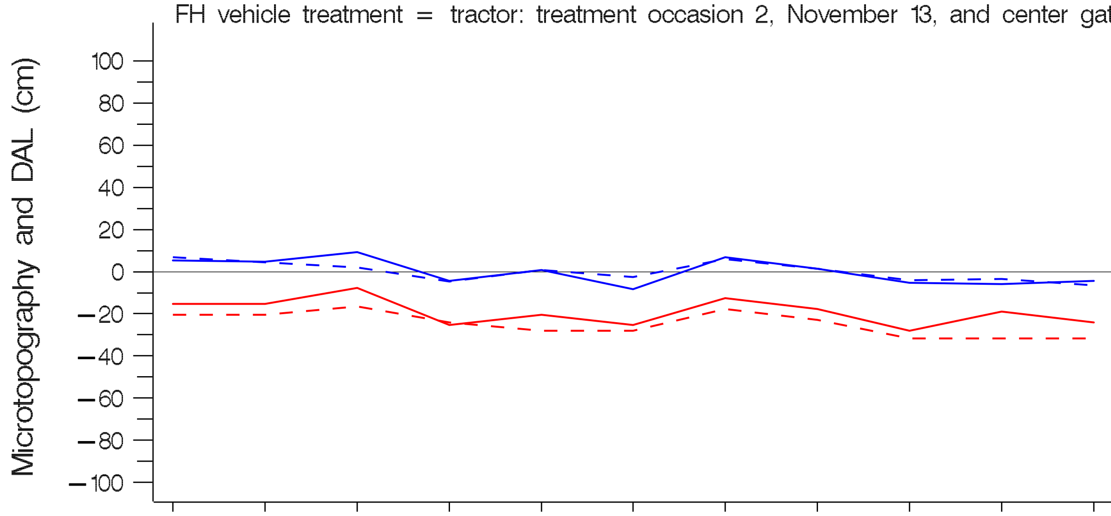
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

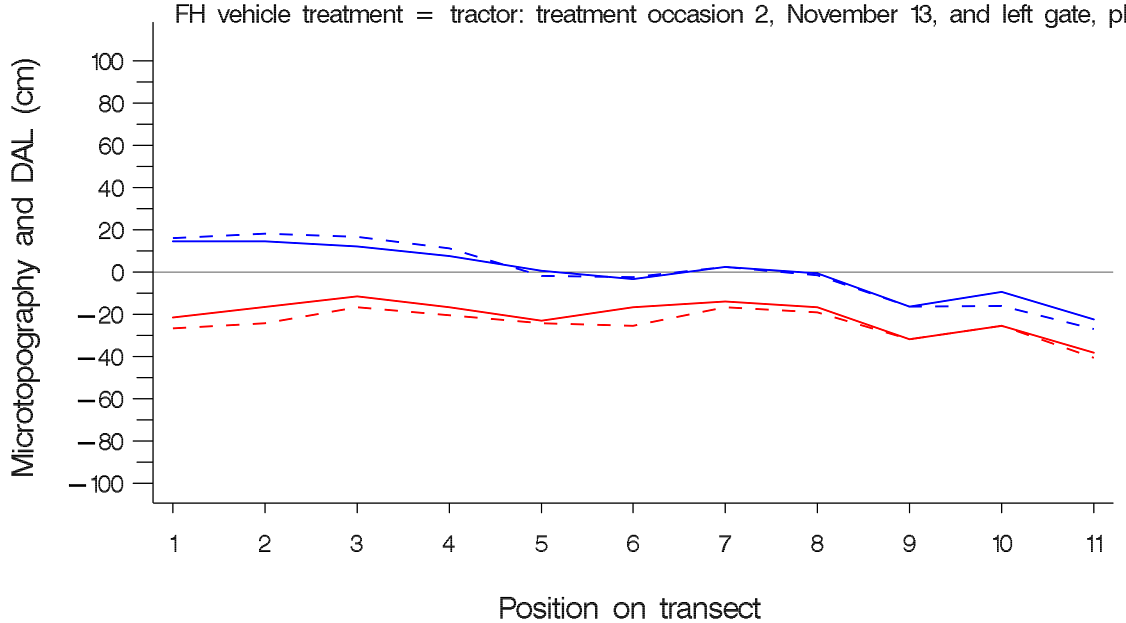
FH vehicle treatment = tractor: treatment occasion 2, November 13, and right gate, plot c5



FH vehicle treatment = tractor: treatment occasion 2, November 13, and center gate, plot c5

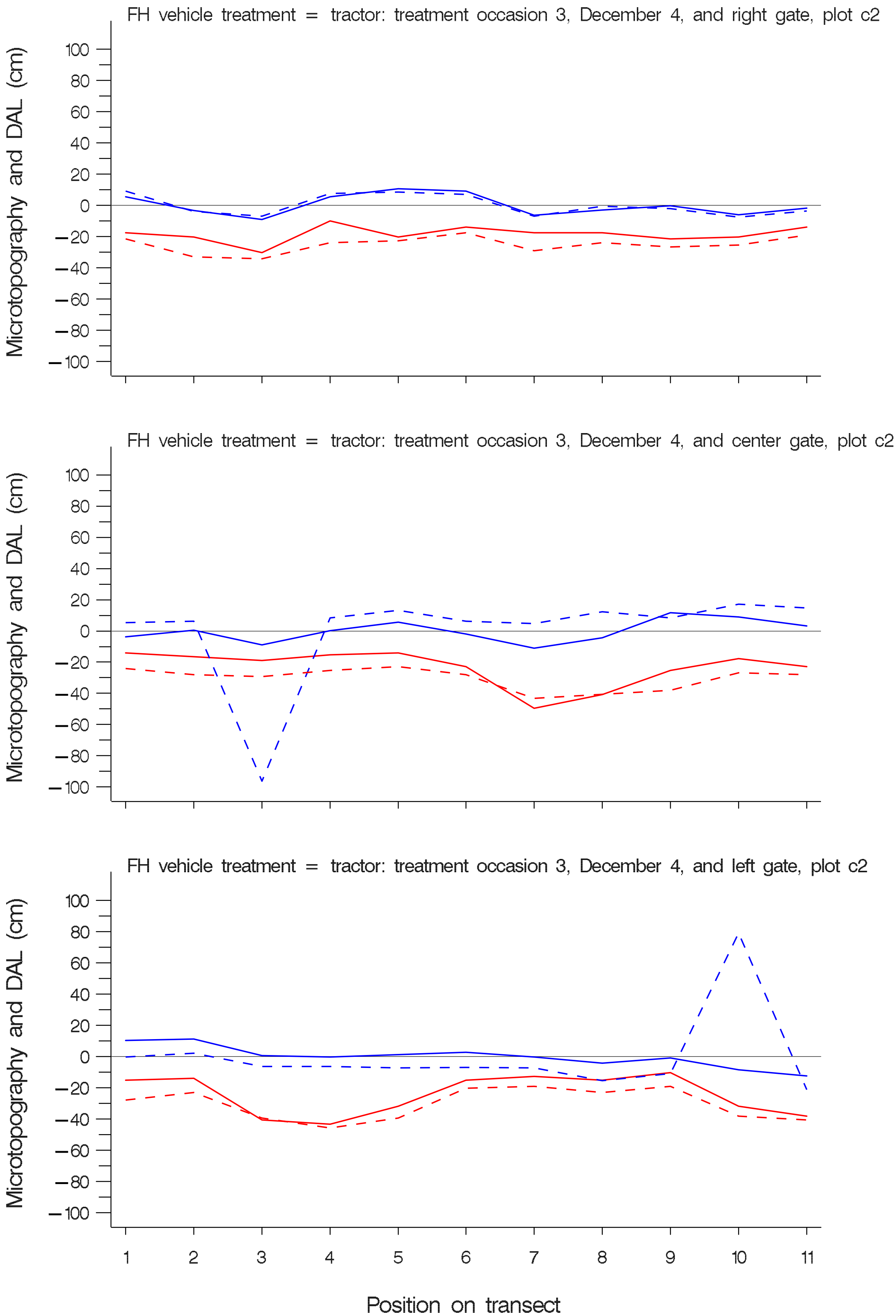


FH vehicle treatment = tractor: treatment occasion 2, November 13, and left gate, plot c5



Solid line displays 2003, dashed line displays 2004

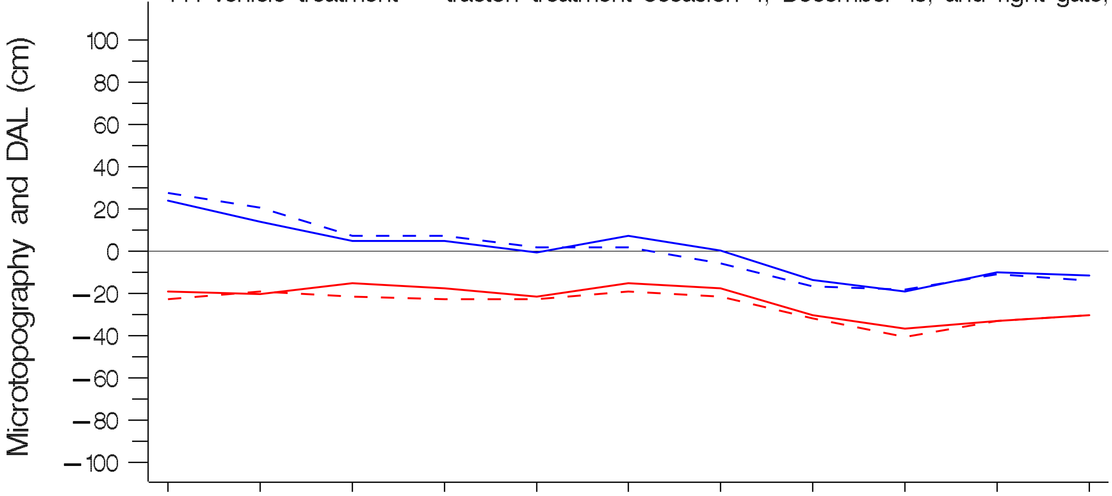
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



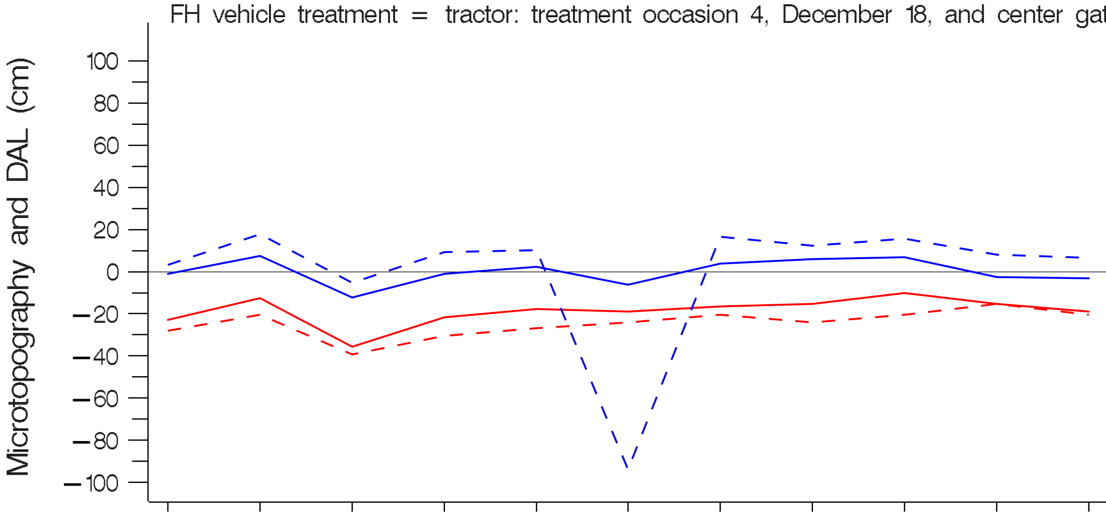
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

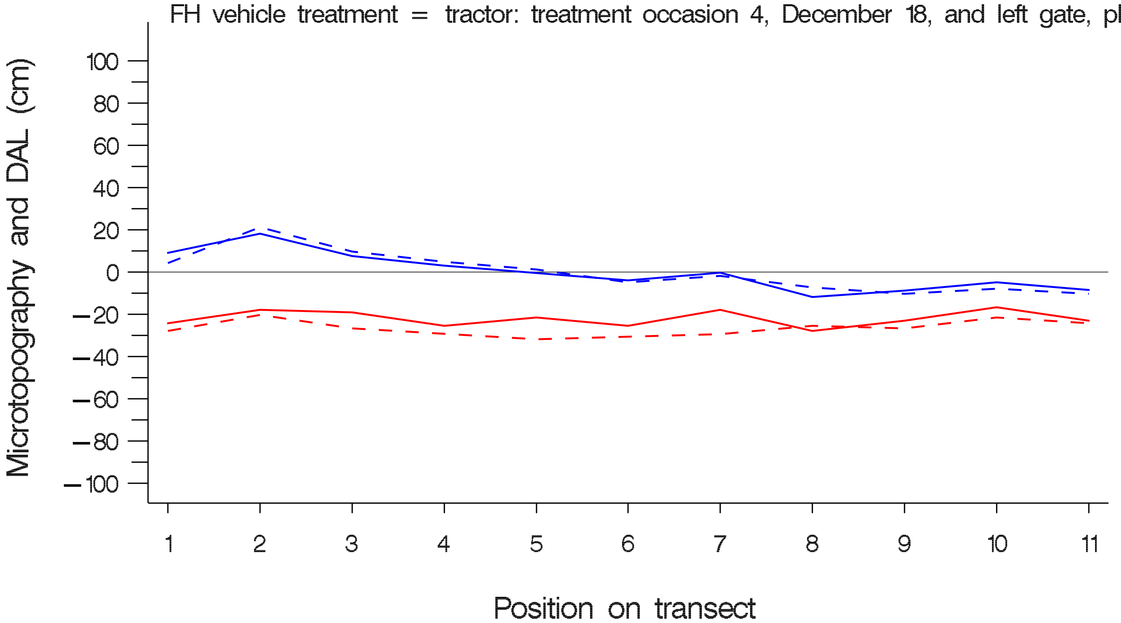
FH vehicle treatment = tractor: treatment occasion 4, December 18, and right gate, plot b5



FH vehicle treatment = tractor: treatment occasion 4, December 18, and center gate, plot b5

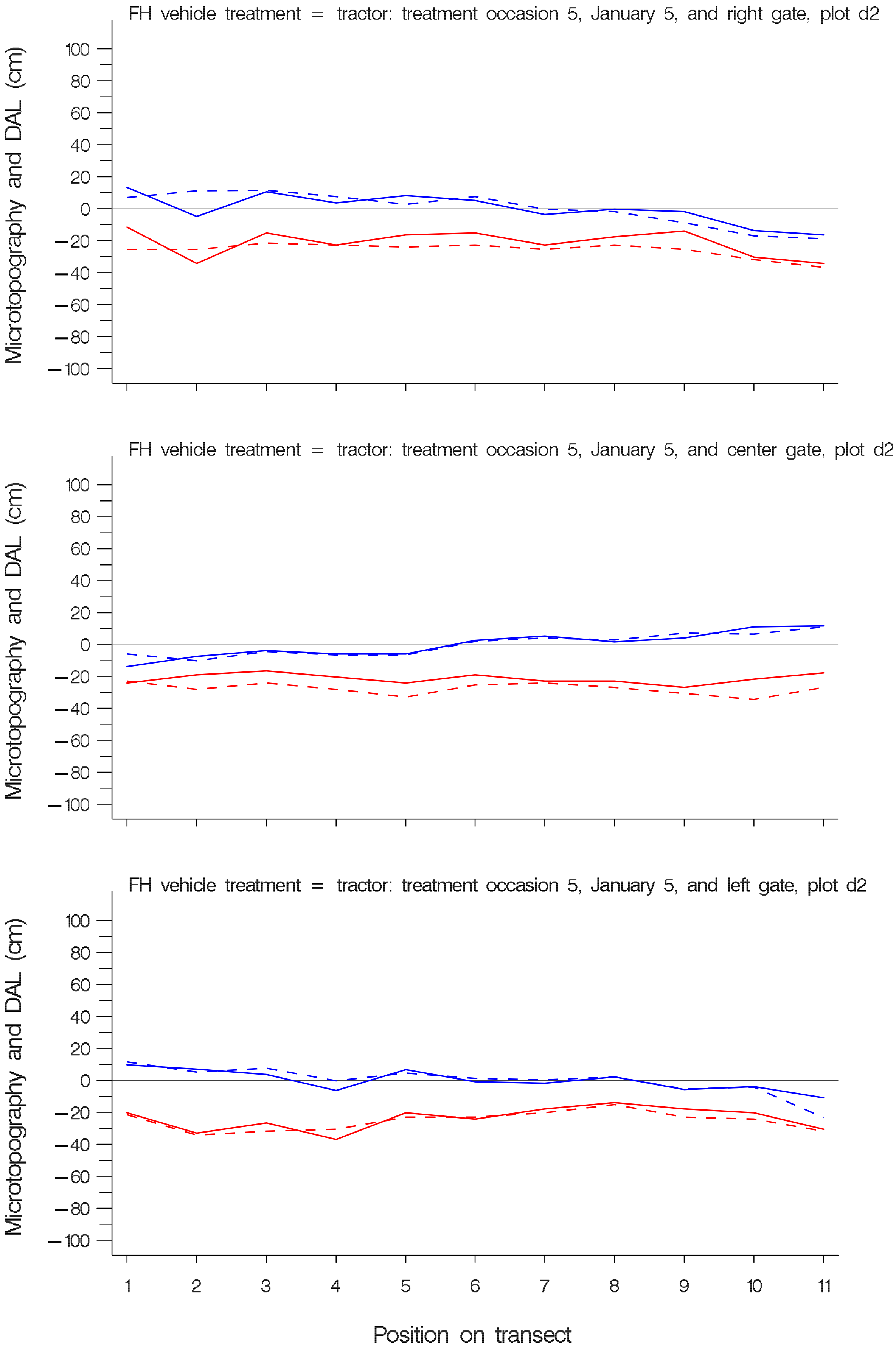


FH vehicle treatment = tractor: treatment occasion 4, December 18, and left gate, plot b5



Solid line displays 2003, dashed line displays 2004

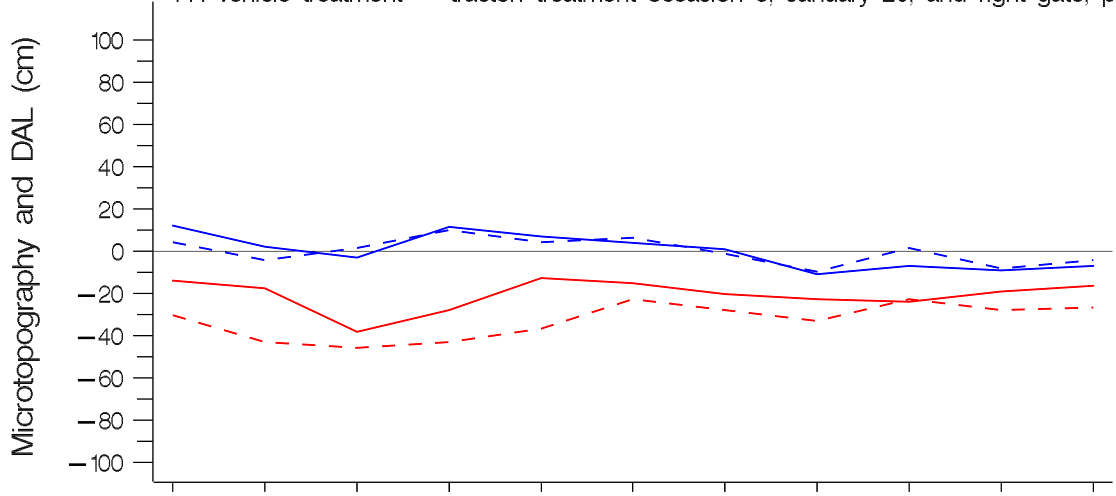
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



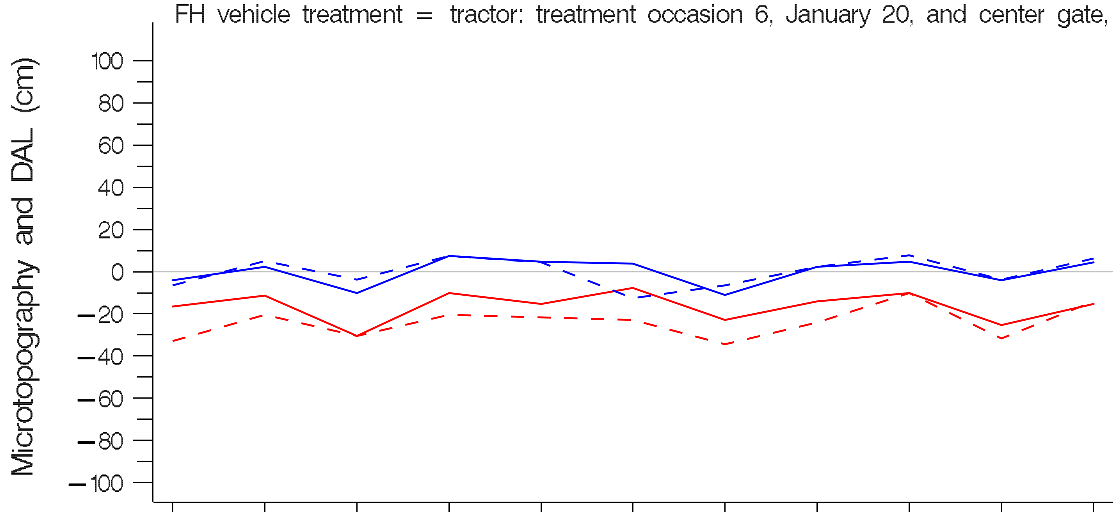
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

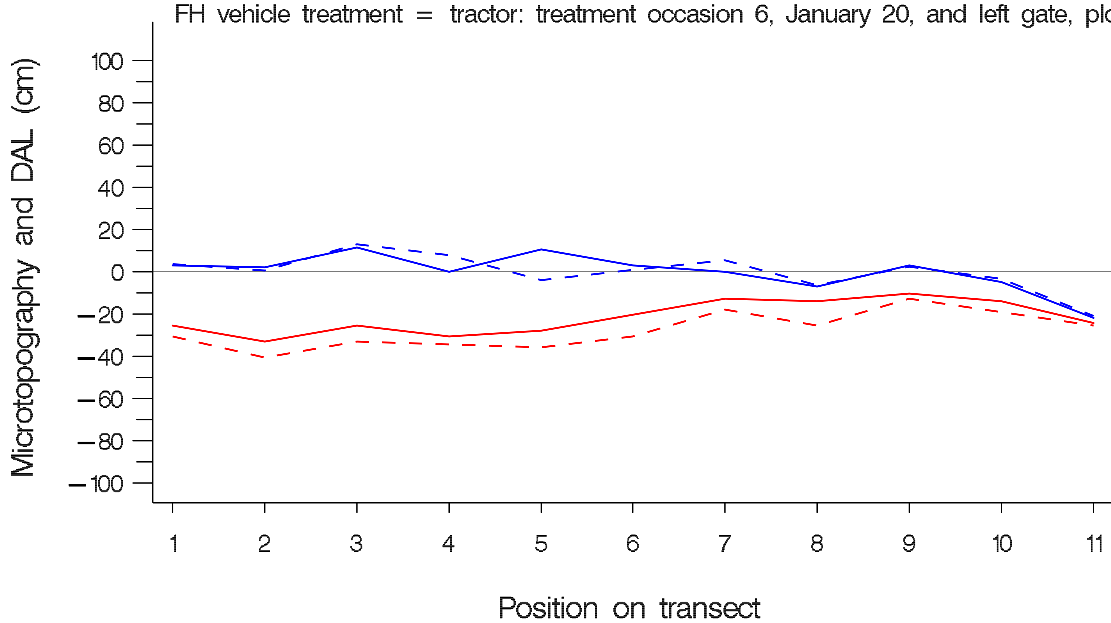
FH vehicle treatment = tractor: treatment occasion 6, January 20, and right gate, plot c4



FH vehicle treatment = tractor: treatment occasion 6, January 20, and center gate, plot c4

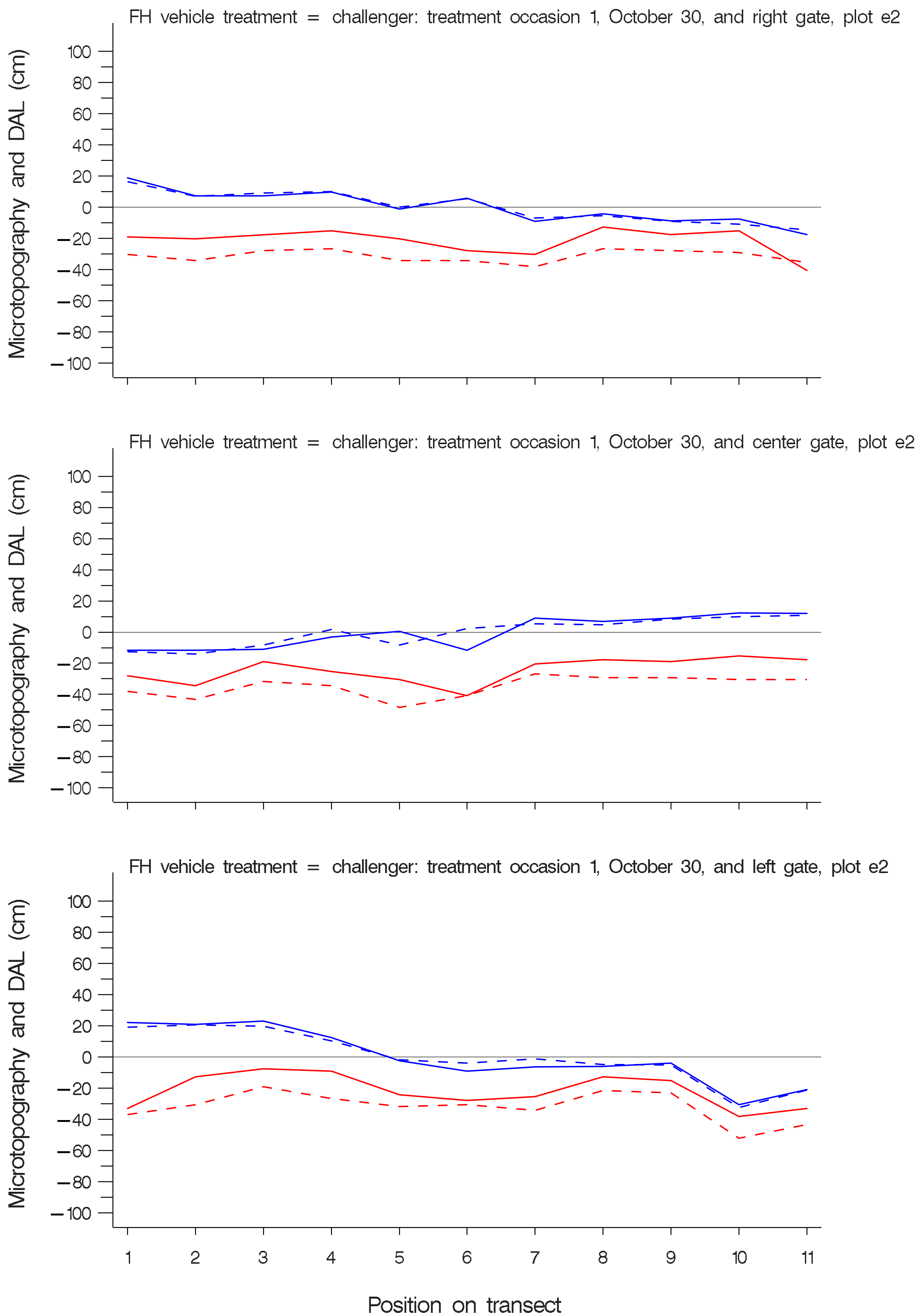


FH vehicle treatment = tractor: treatment occasion 6, January 20, and left gate, plot c4



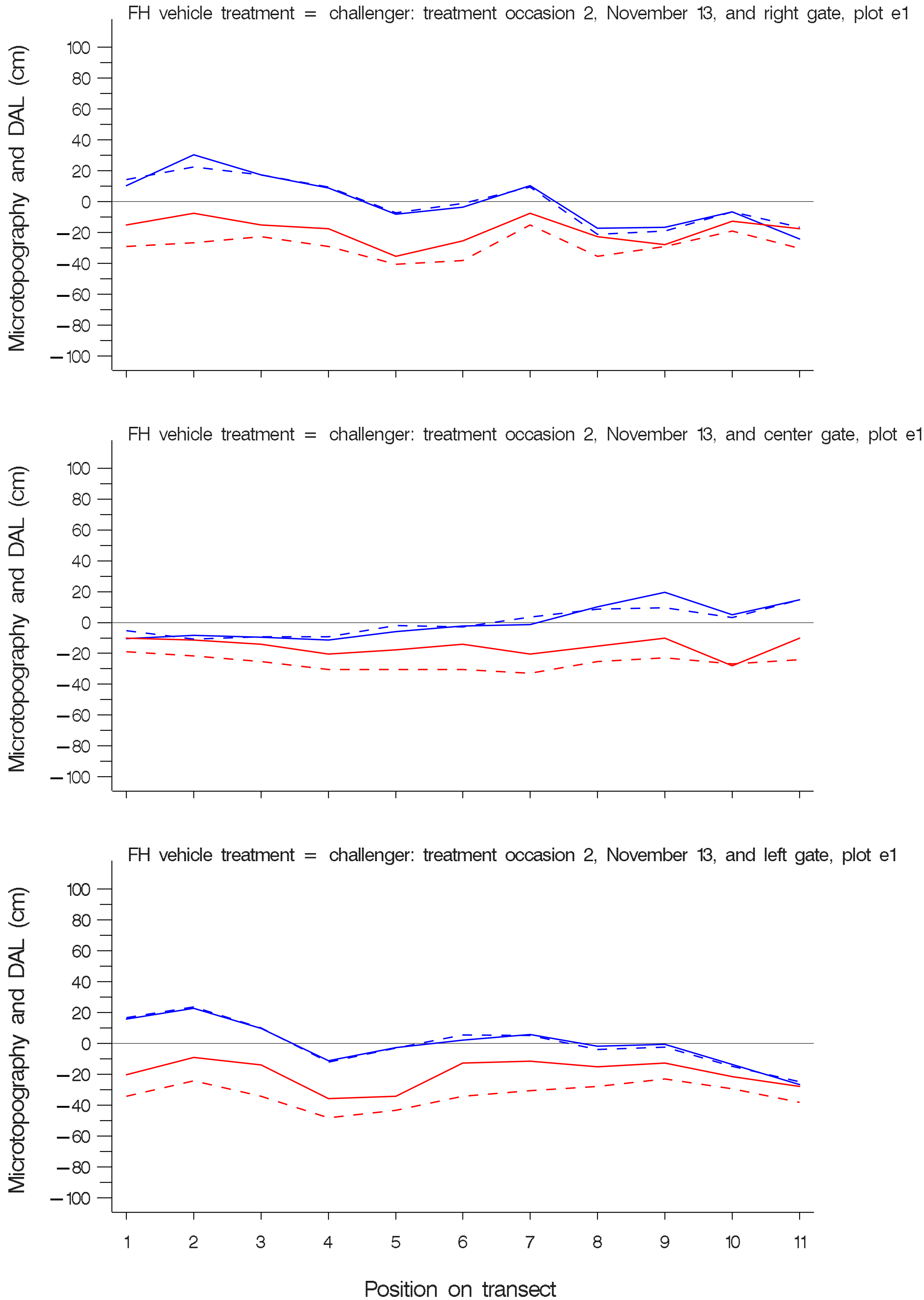
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



Solid line displays 2003, dashed line displays 2004

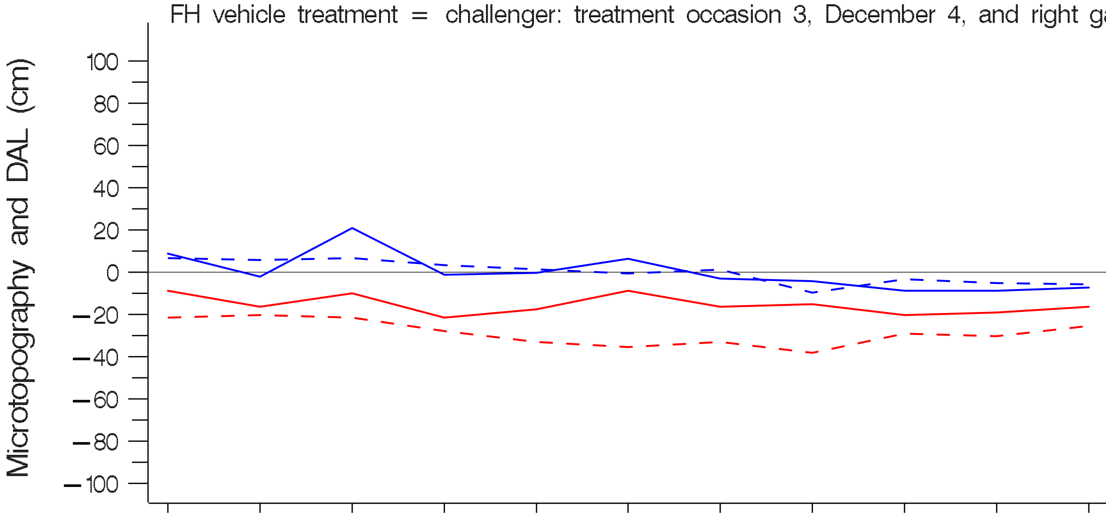
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



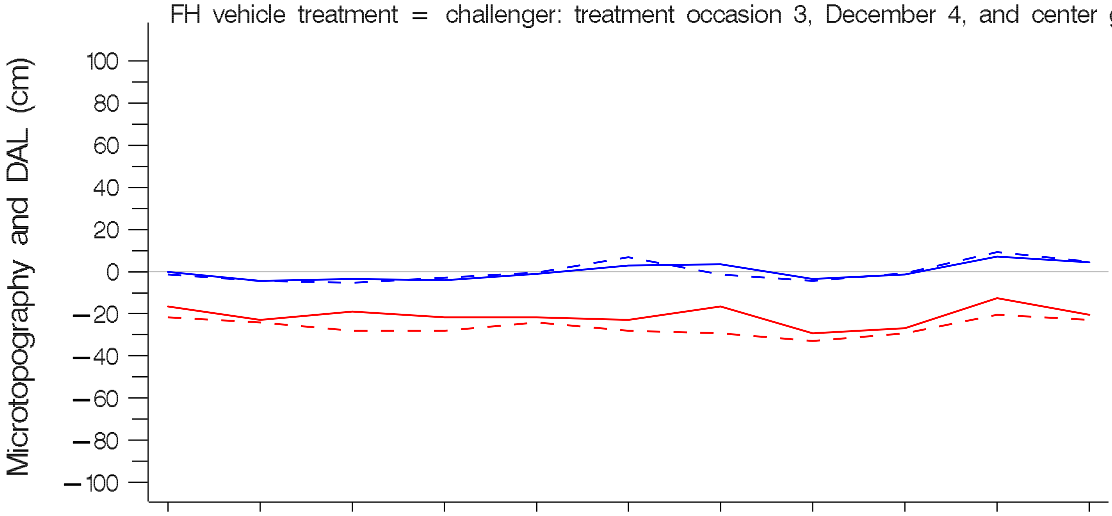
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

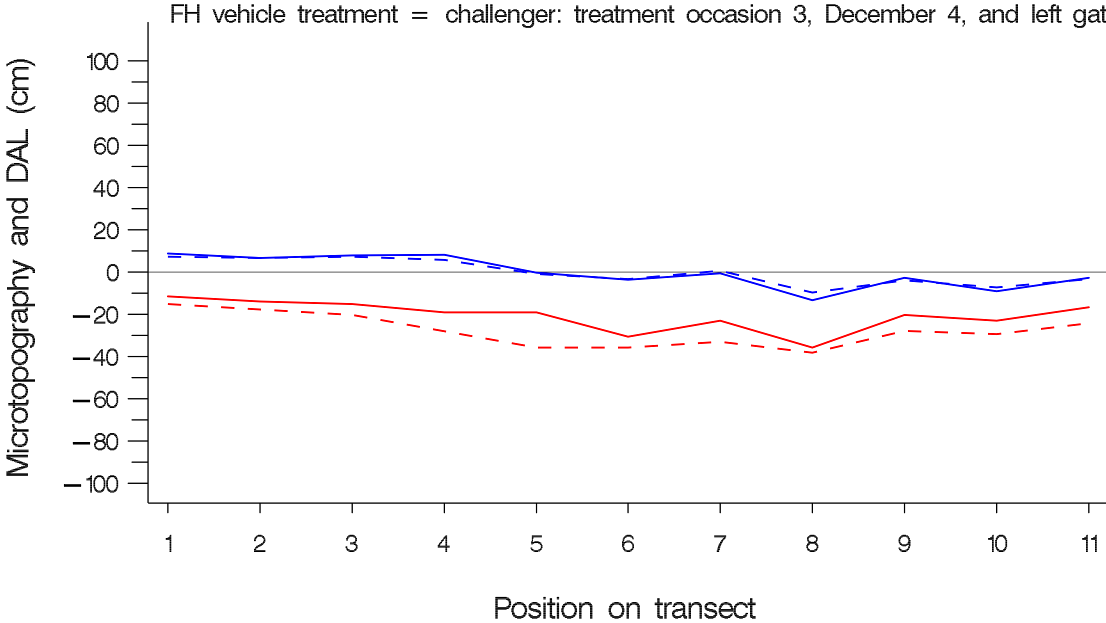
FH vehicle treatment = challenger: treatment occasion 3, December 4, and right gate, plot b2



FH vehicle treatment = challenger: treatment occasion 3, December 4, and center gate, plot b2

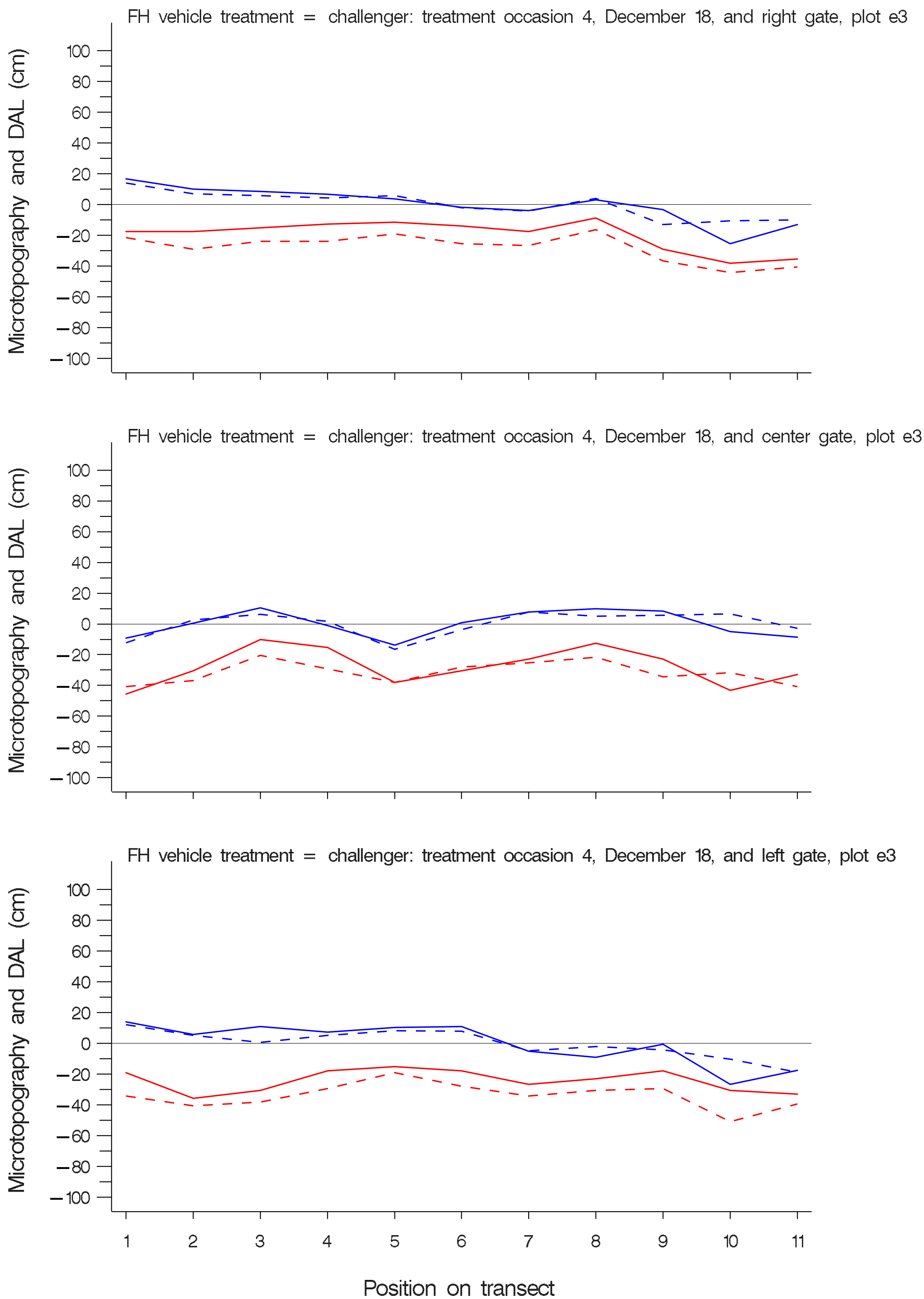


FH vehicle treatment = challenger: treatment occasion 3, December 4, and left gate, plot b2



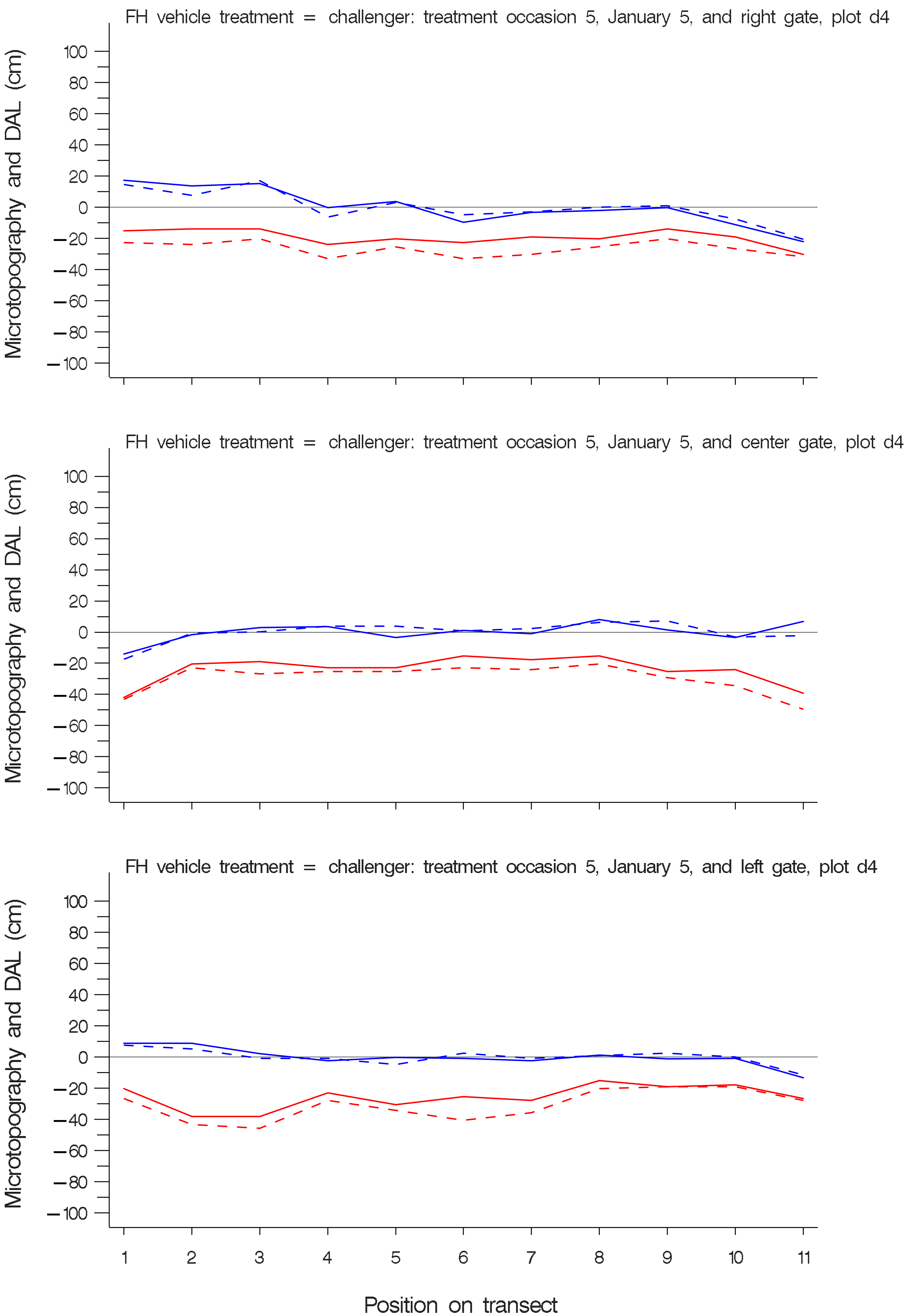
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



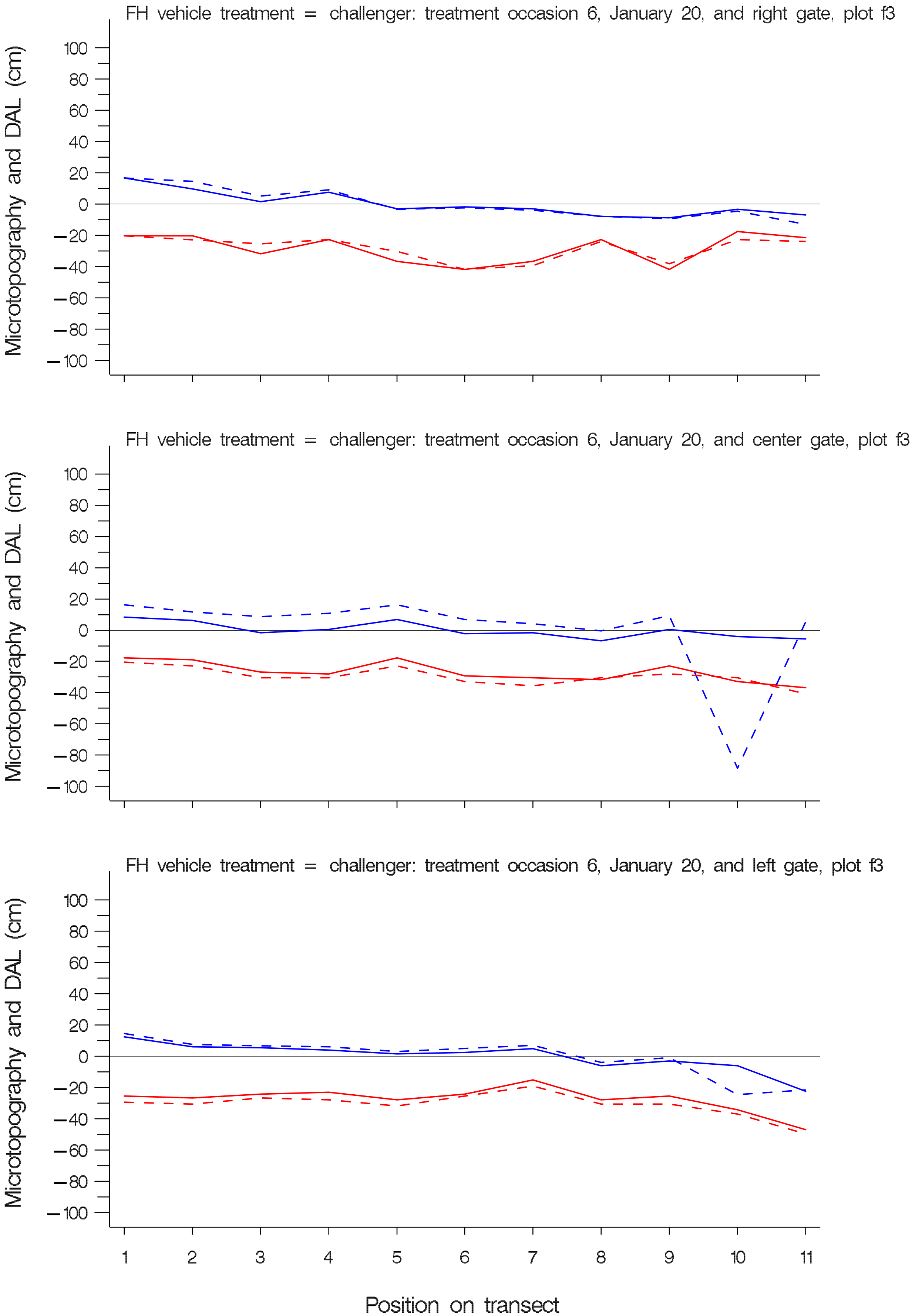
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



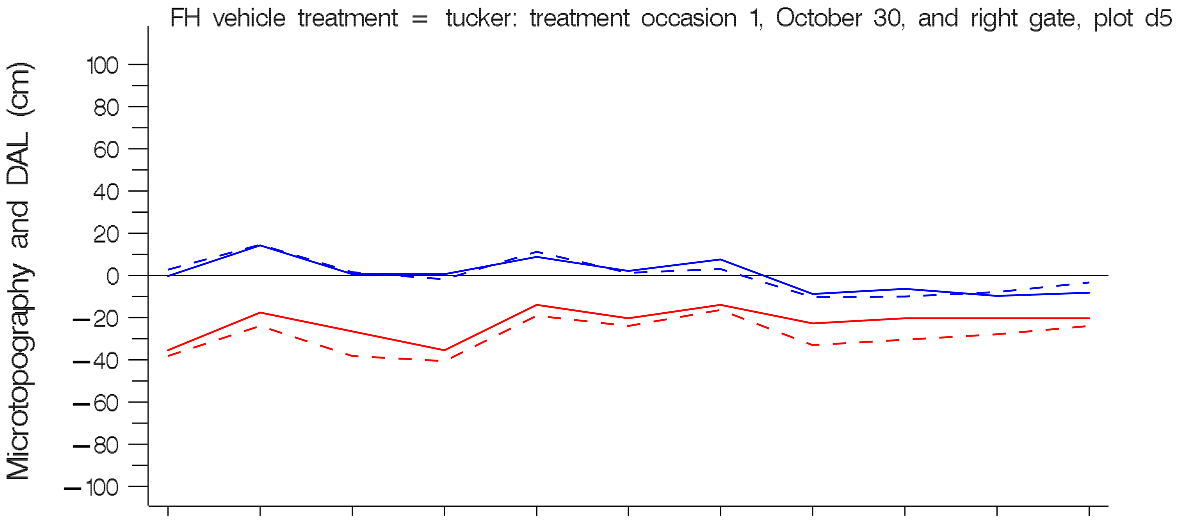
Solid line displays 2003, dashed line displays 2004

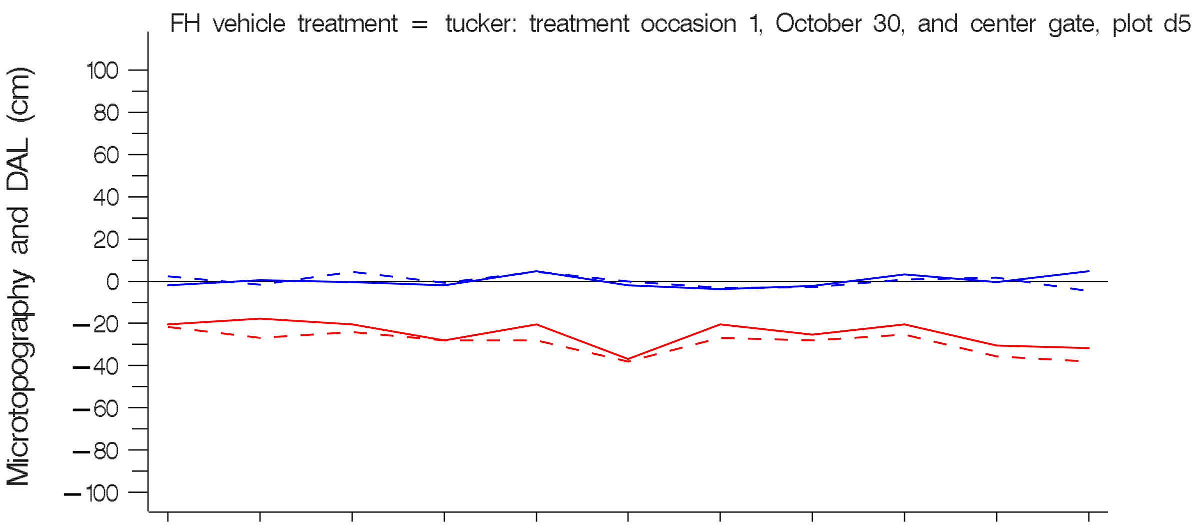
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

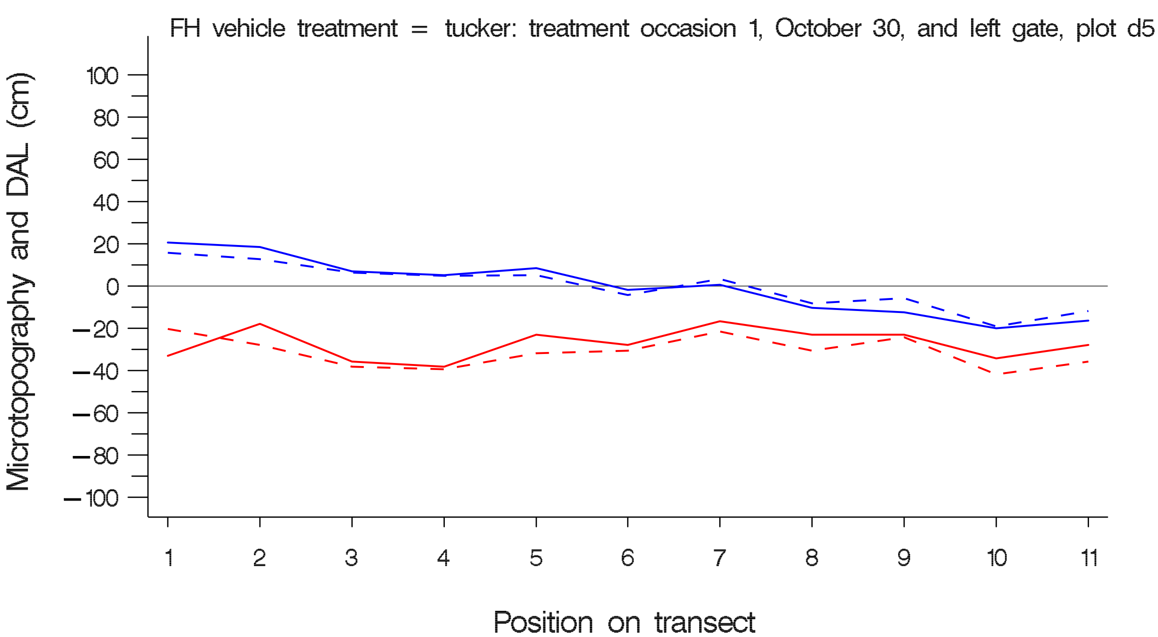


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

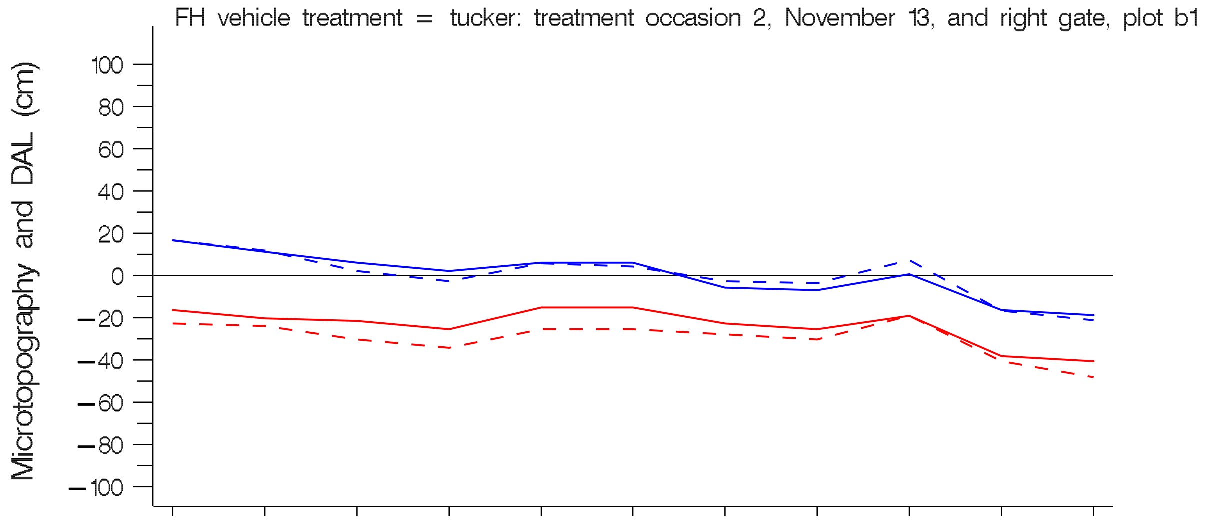


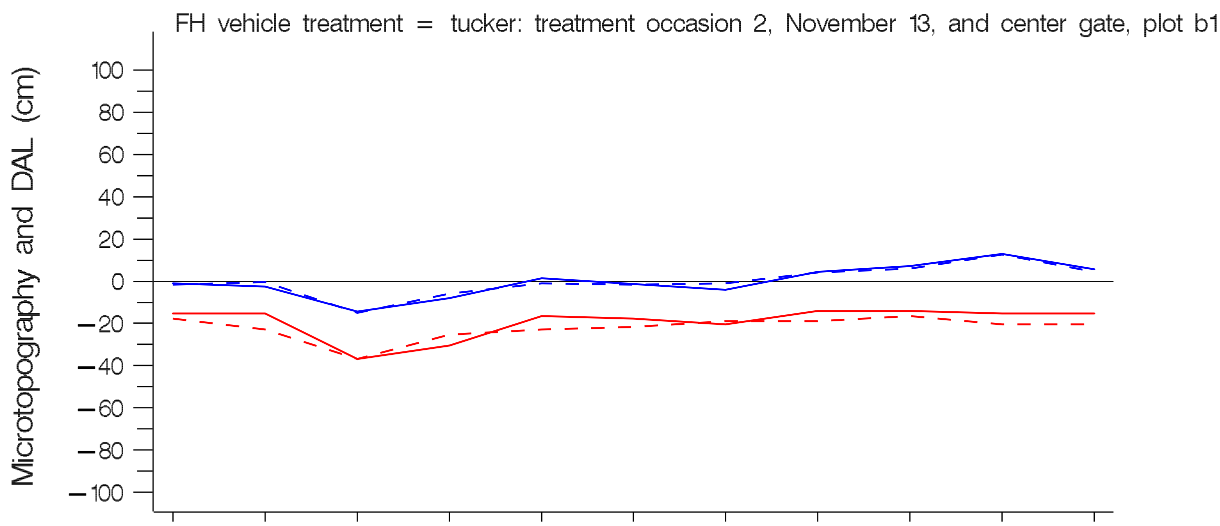


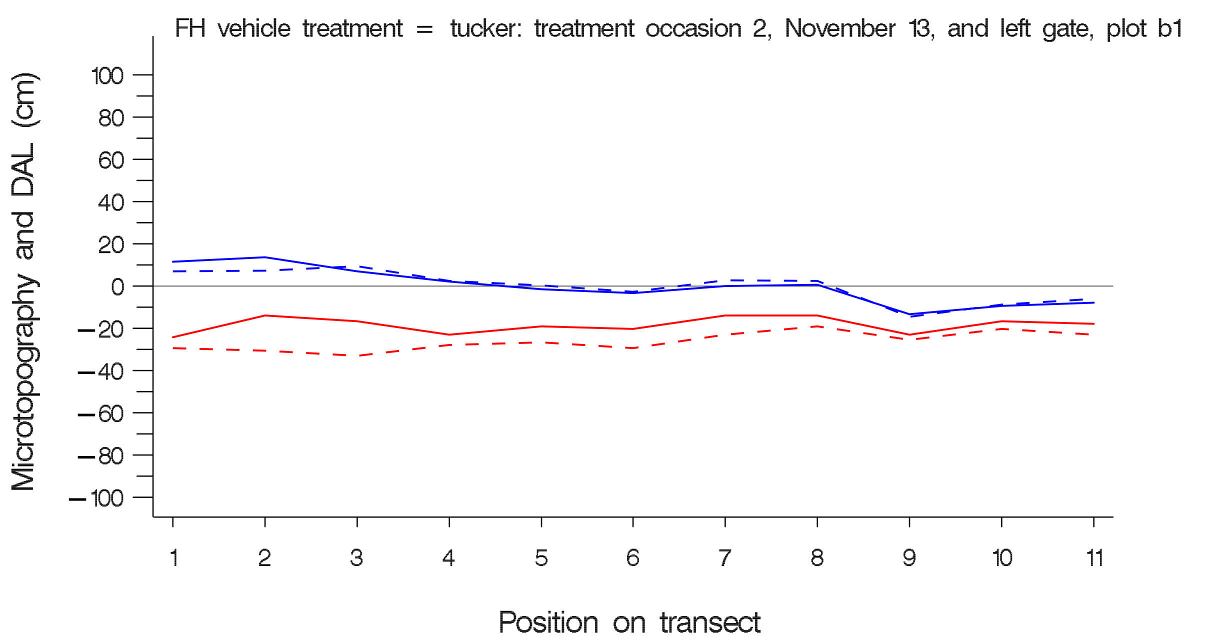


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



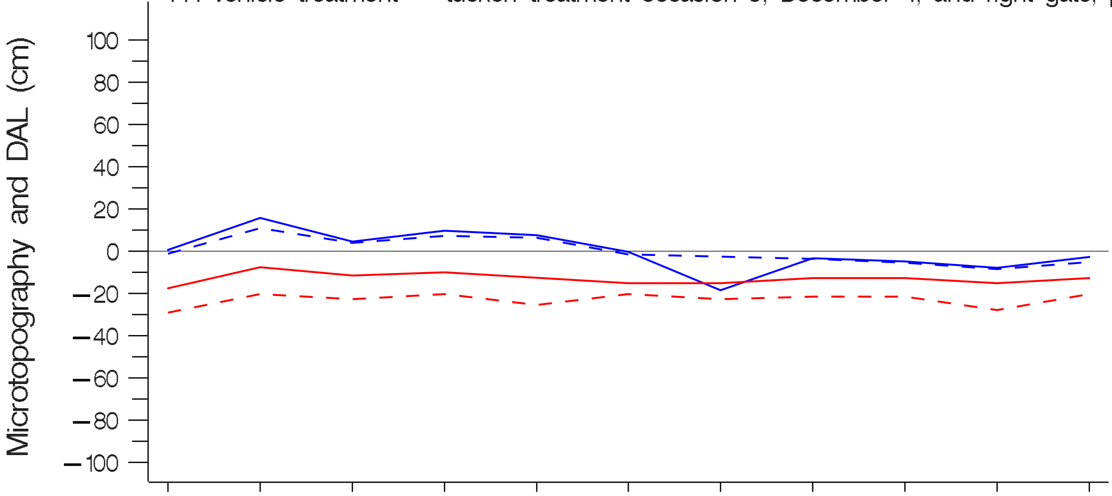




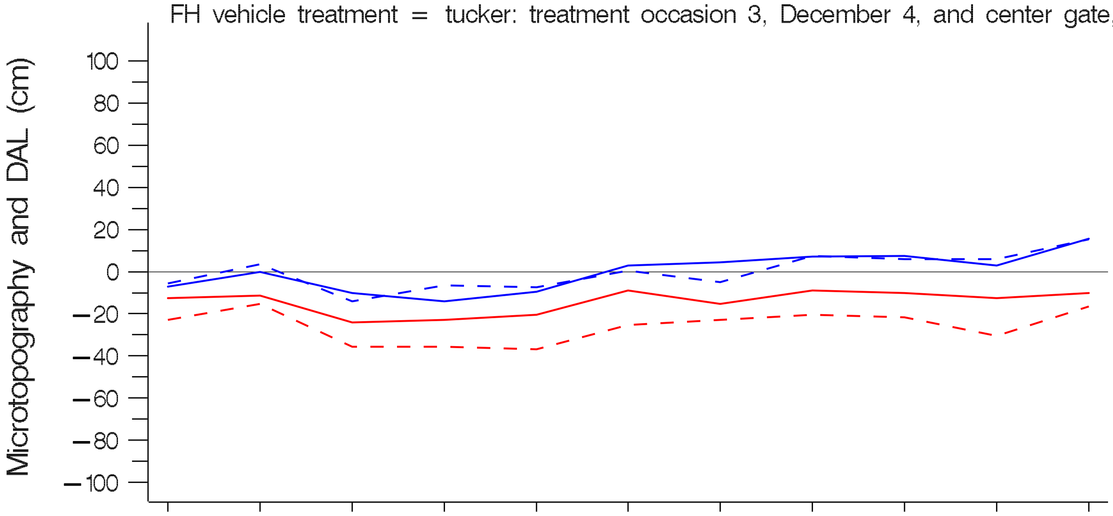
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

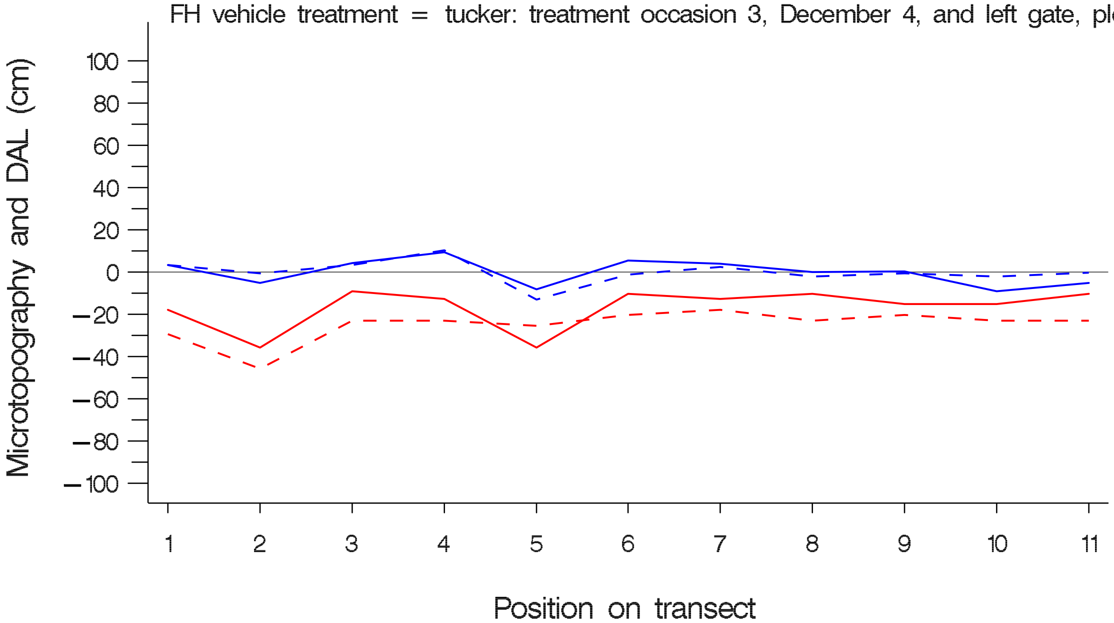
FH vehicle treatment = tucker: treatment occasion 3, December 4, and right gate, plot a1



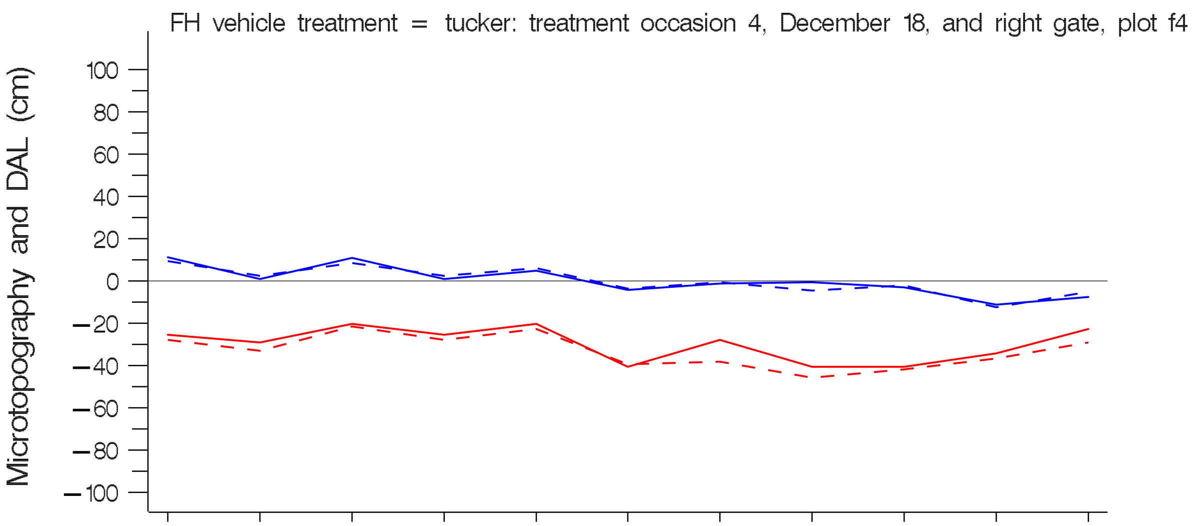
FH vehicle treatment = tucker: treatment occasion 3, December 4, and center gate, plot a1

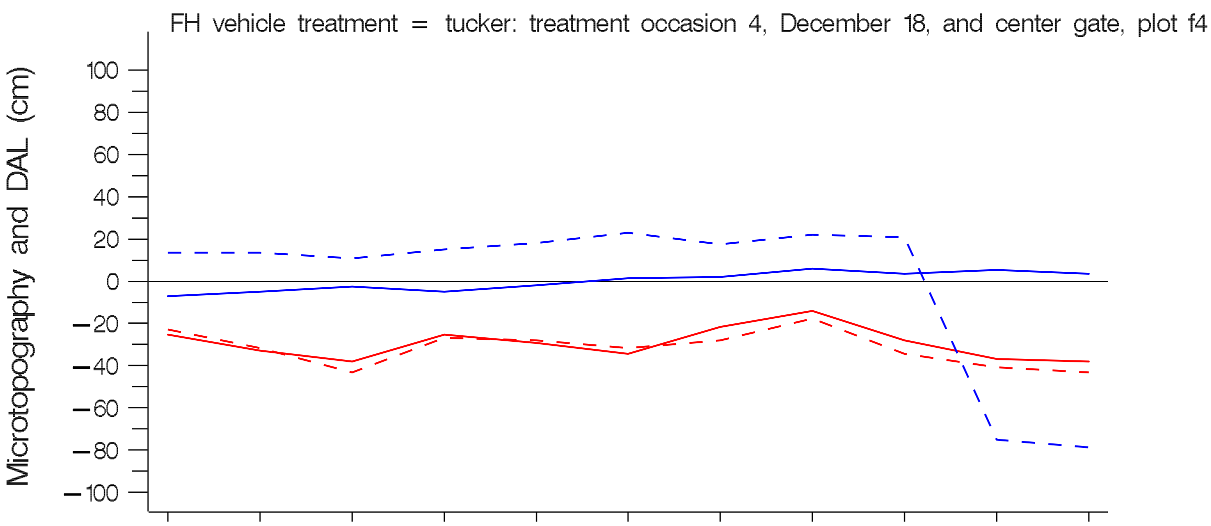


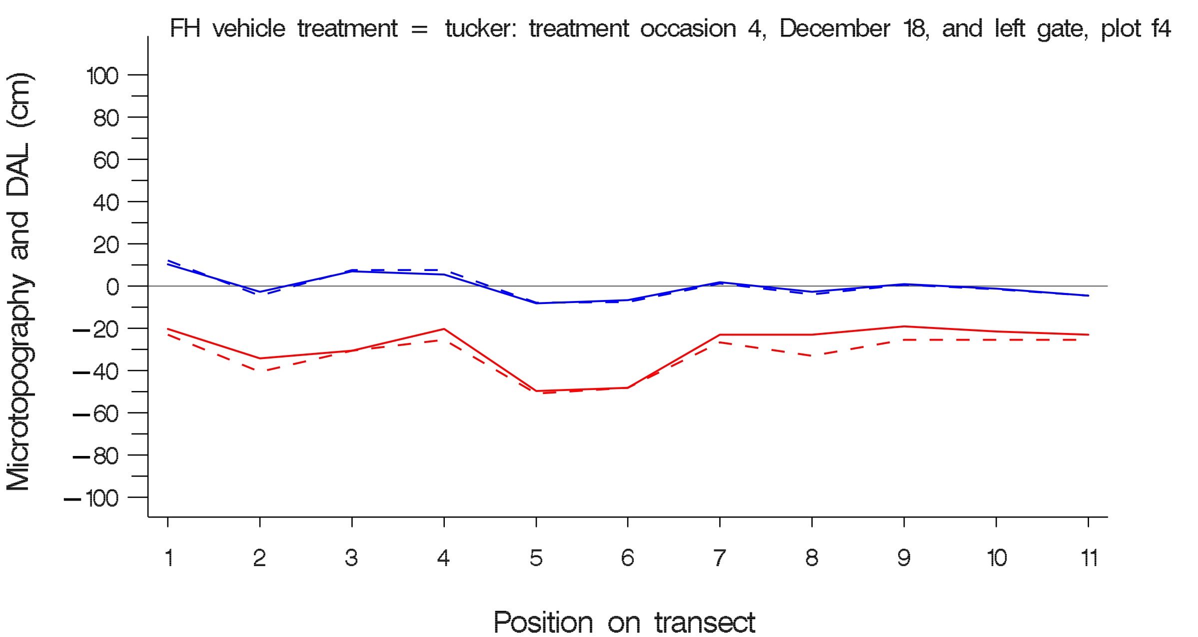
FH vehicle treatment = tucker: treatment occasion 3, December 4, and left gate, plot a1



Solid line displays 2003, dashed line displays 2004



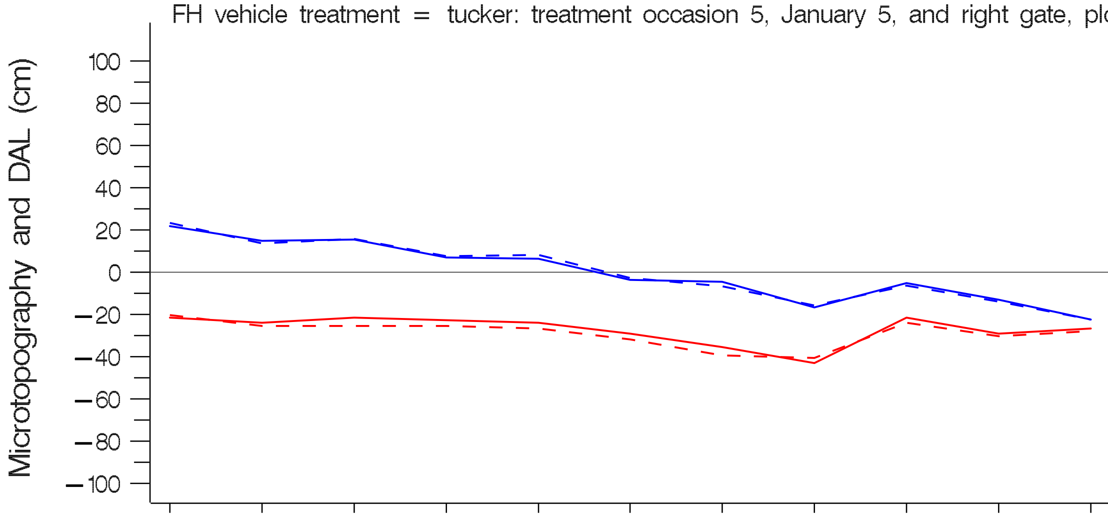




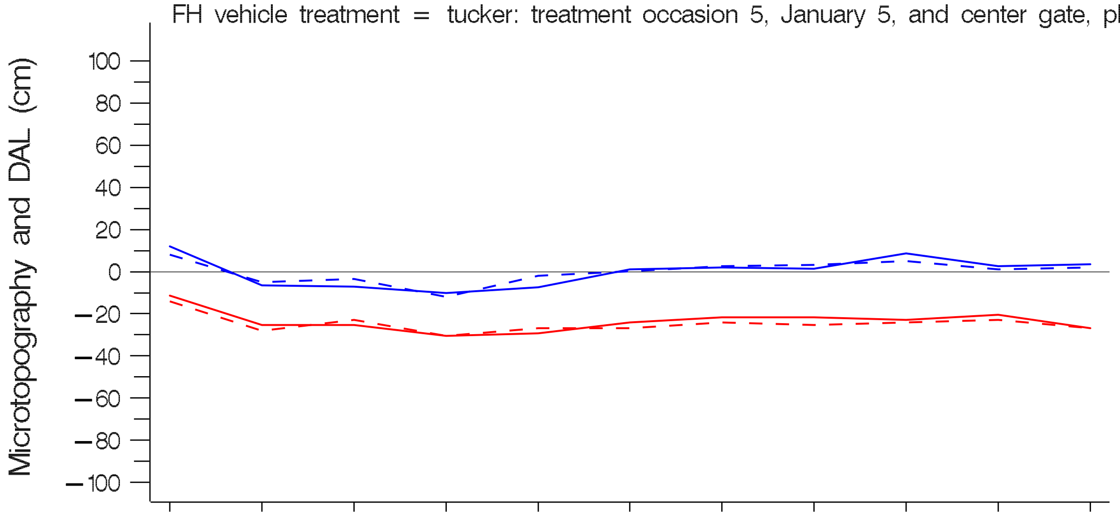
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

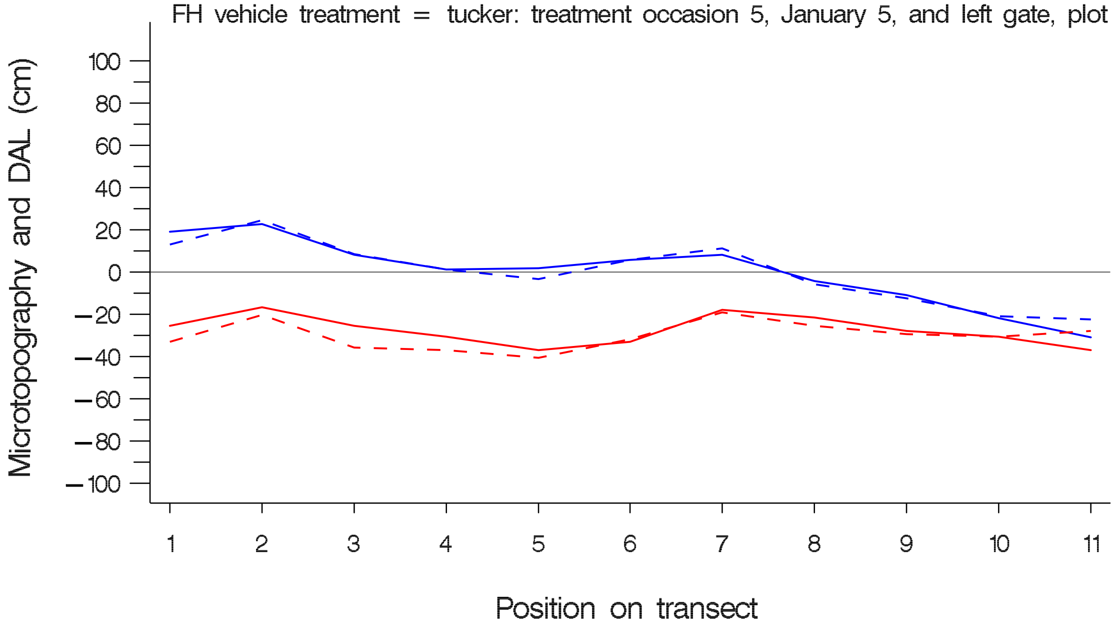
FH vehicle treatment = tucker: treatment occasion 5, January 5, and right gate, plot f1



FH vehicle treatment = tucker: treatment occasion 5, January 5, and center gate, plot f1

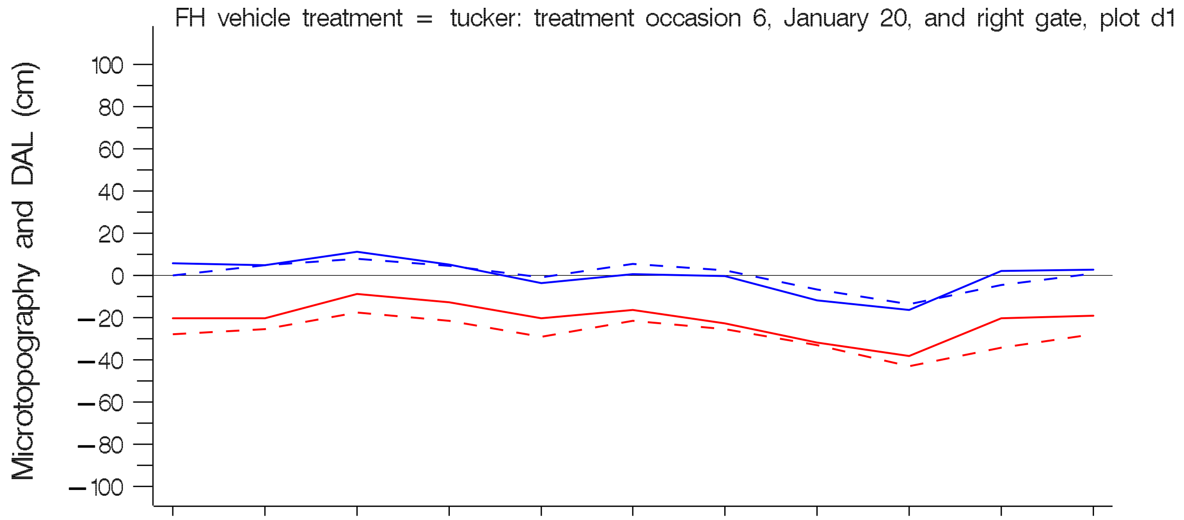


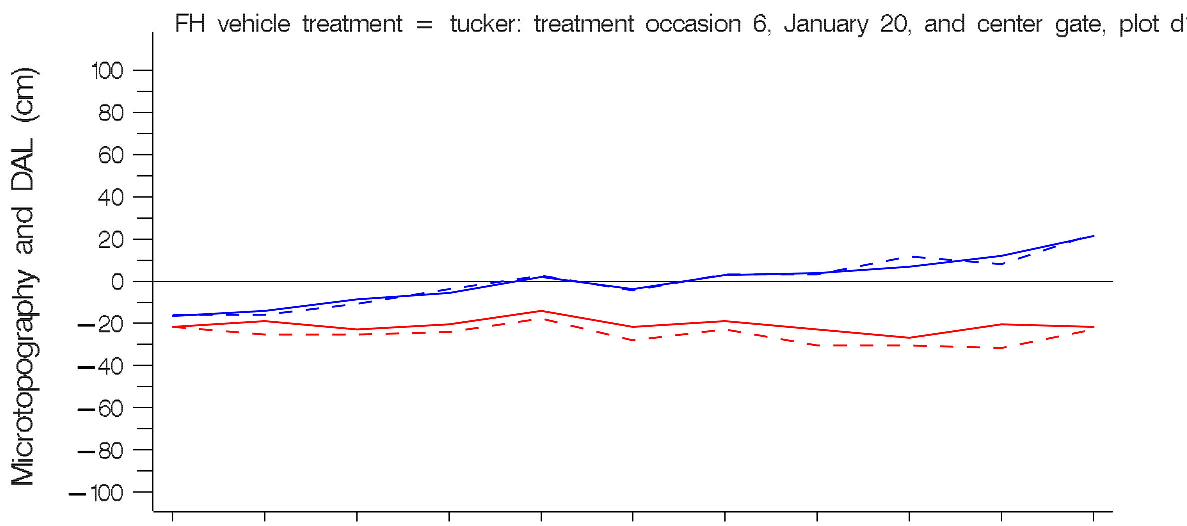
FH vehicle treatment = tucker: treatment occasion 5, January 5, and left gate, plot f1

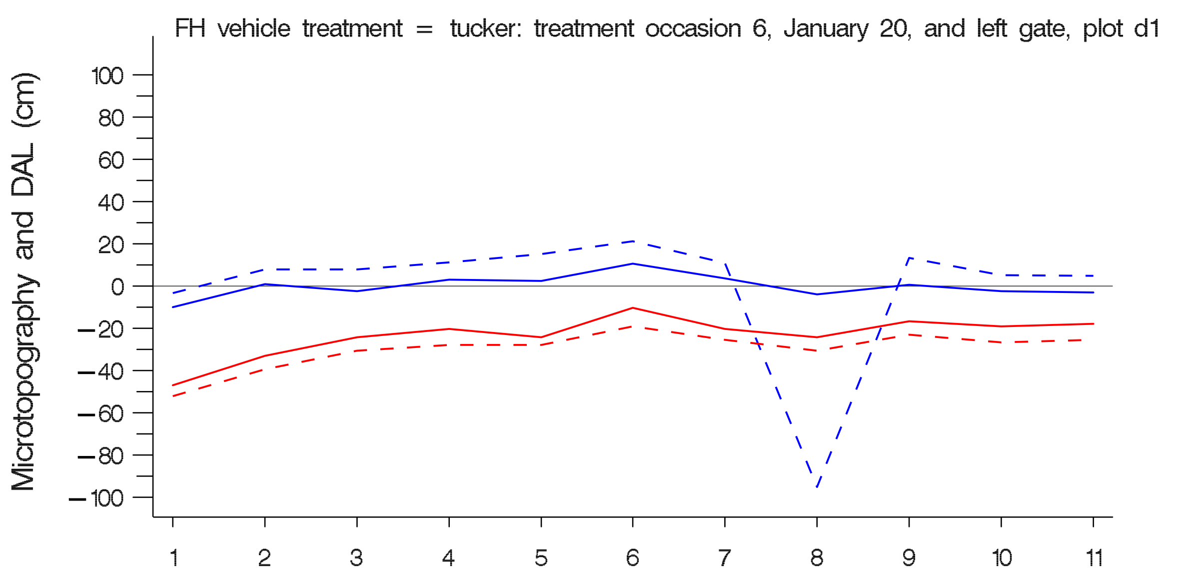


Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



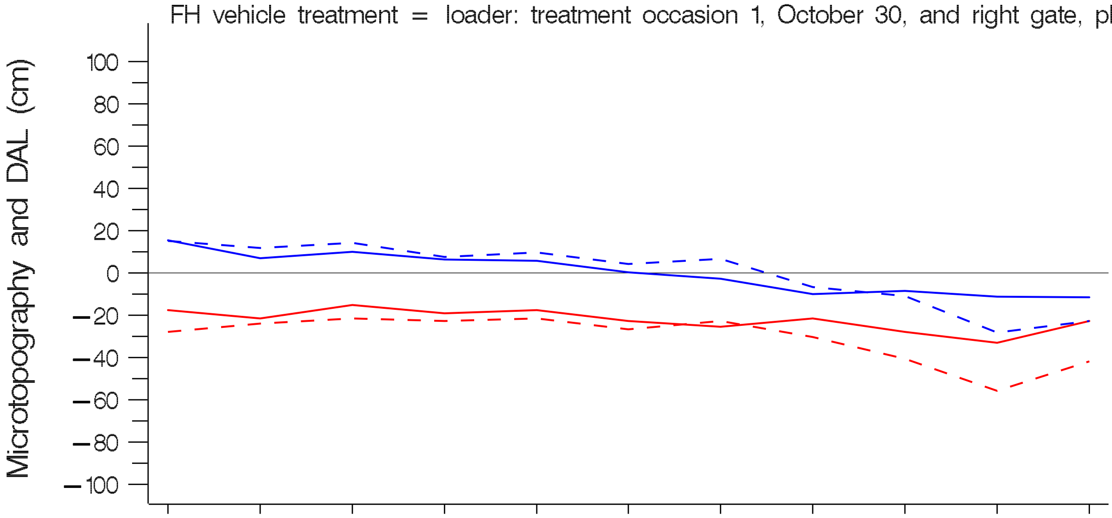




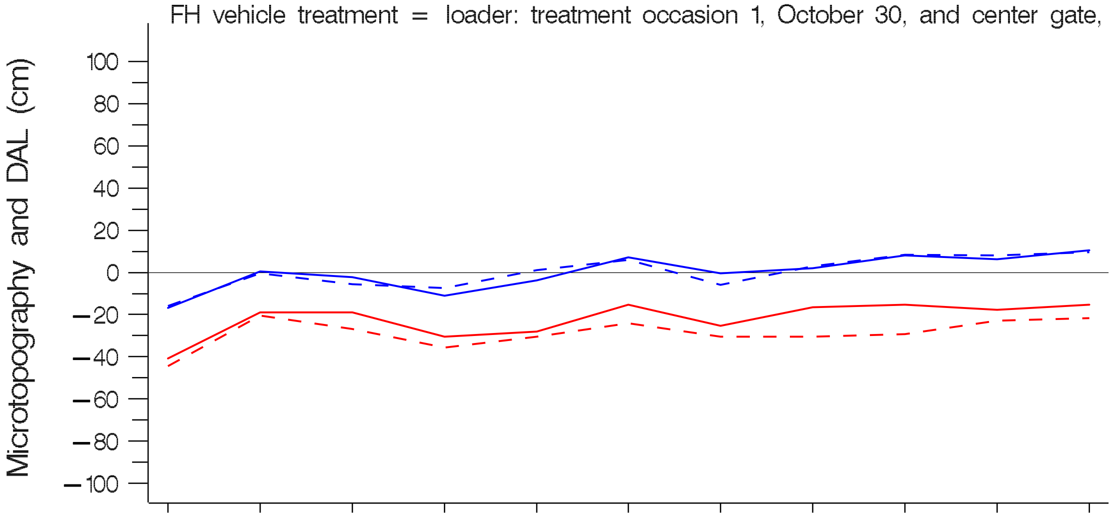
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

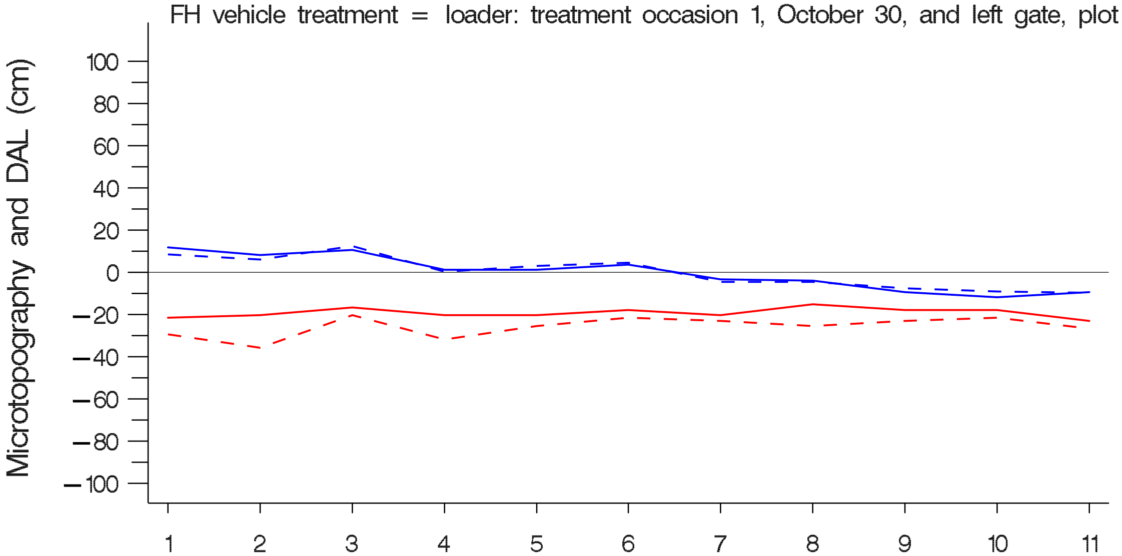
FH vehicle treatment = loader: treatment occasion 1, October 30, and right gate, plot d3



FH vehicle treatment = loader: treatment occasion 1, October 30, and center gate, plot d3



FH vehicle treatment = loader: treatment occasion 1, October 30, and left gate, plot d3

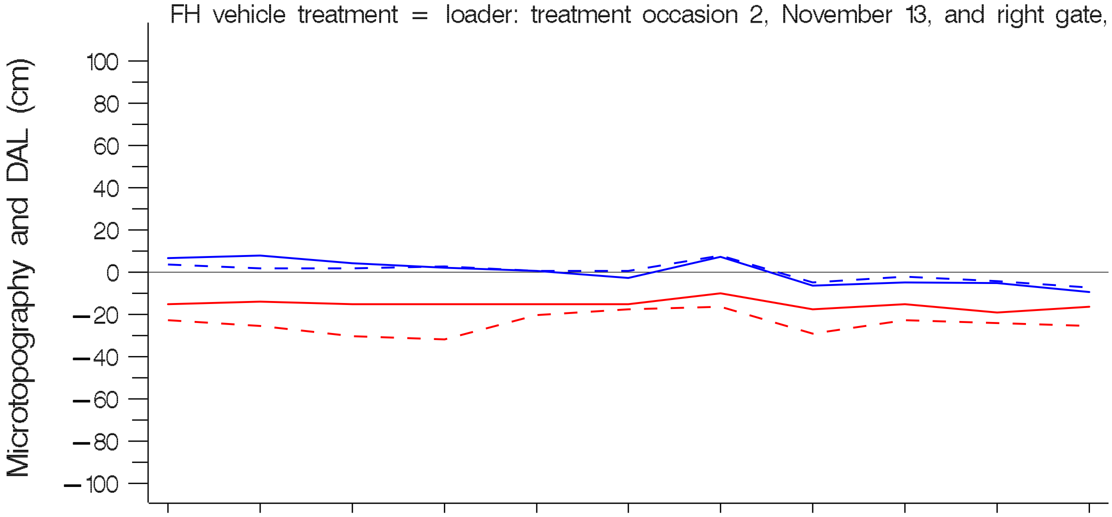


Position on transect

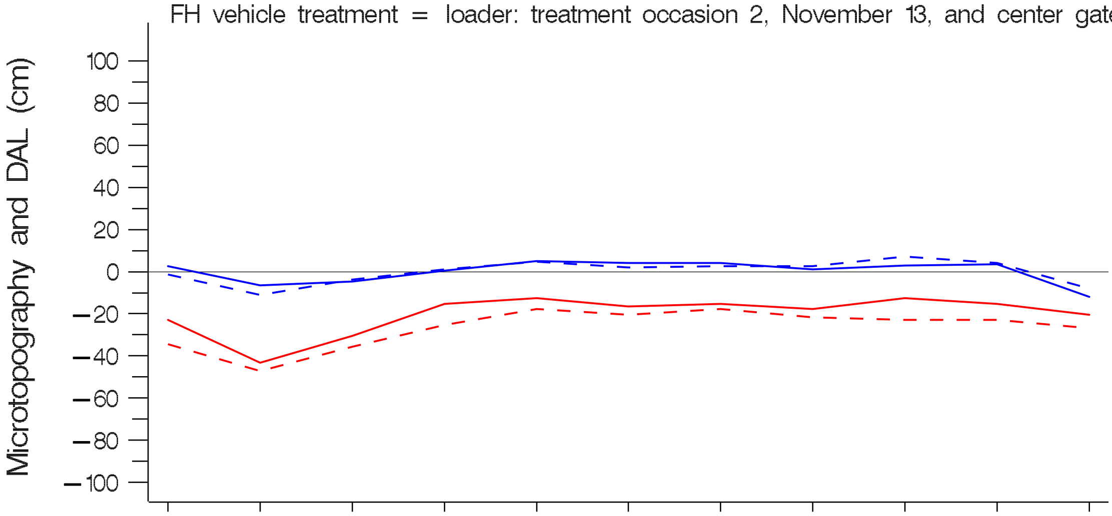
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

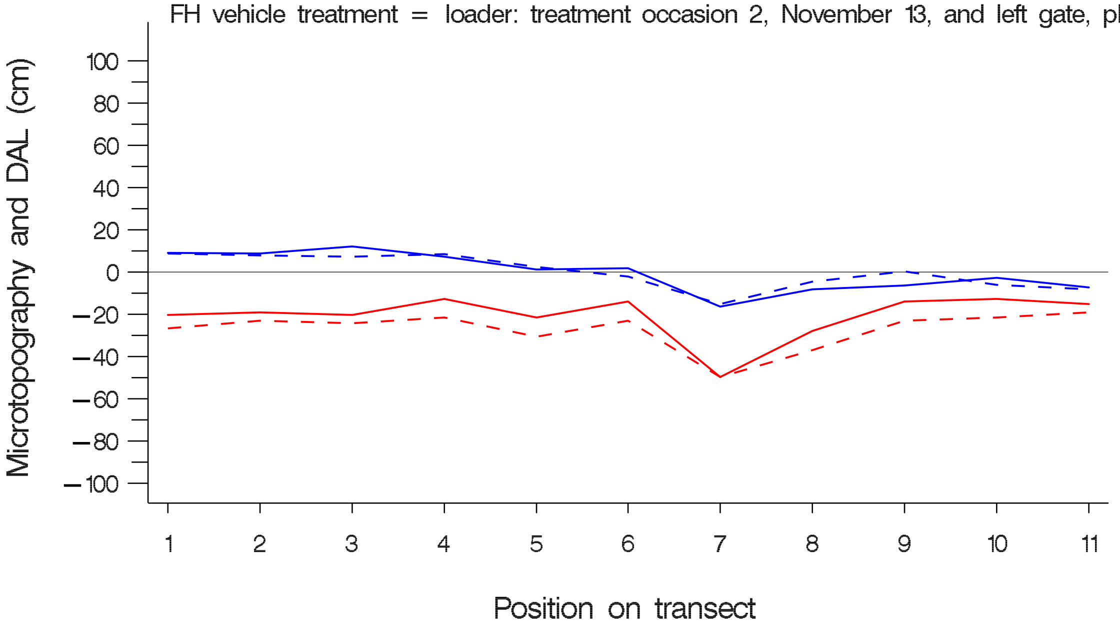
FH vehicle treatment = loader: treatment occasion 2, November 13, and right gate, plot a3



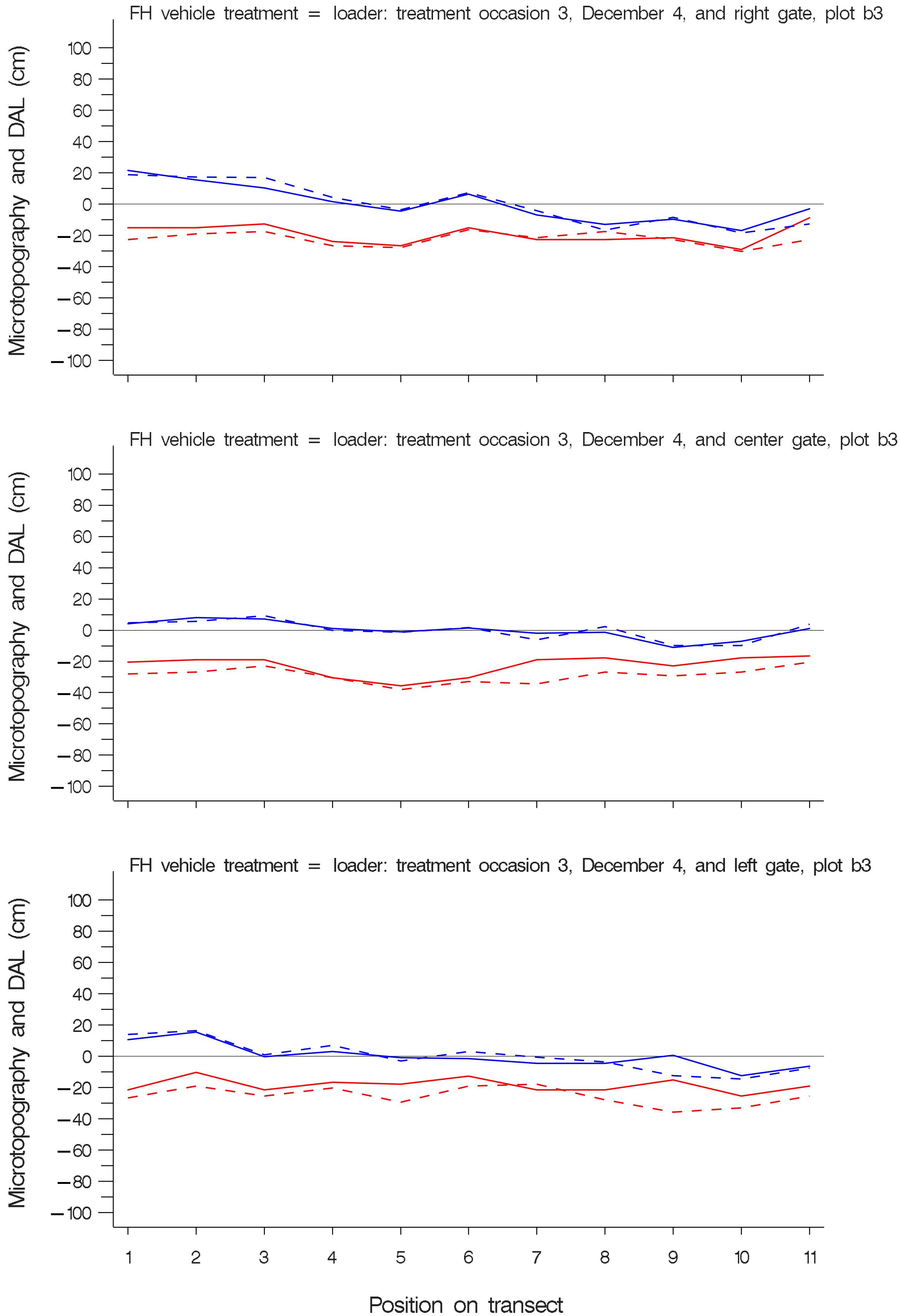
FH vehicle treatment = loader: treatment occasion 2, November 13, and center gate, plot a3



FH vehicle treatment = loader: treatment occasion 2, November 13, and left gate, plot a3

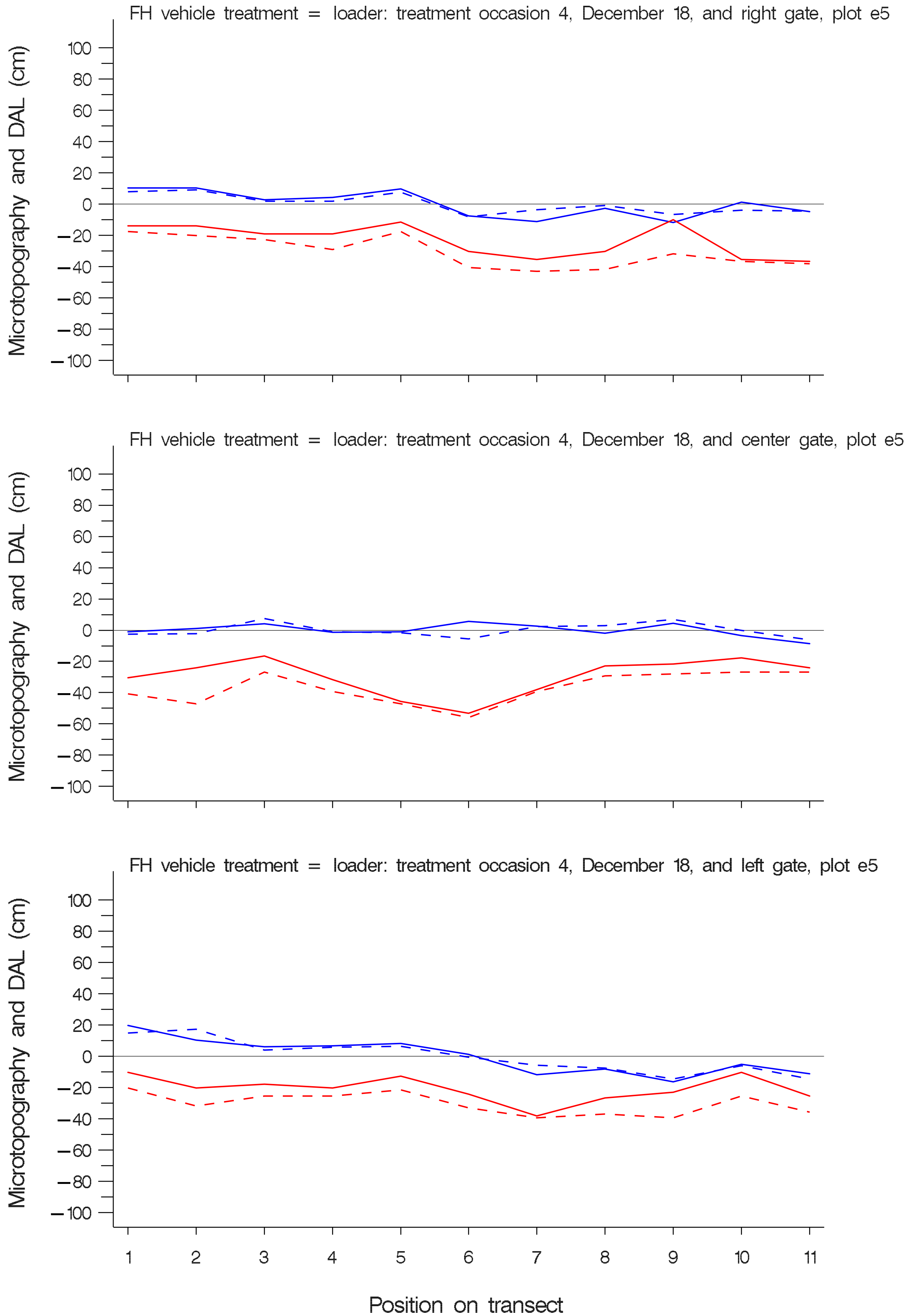


Solid line displays 2003, dashed line displays 2004



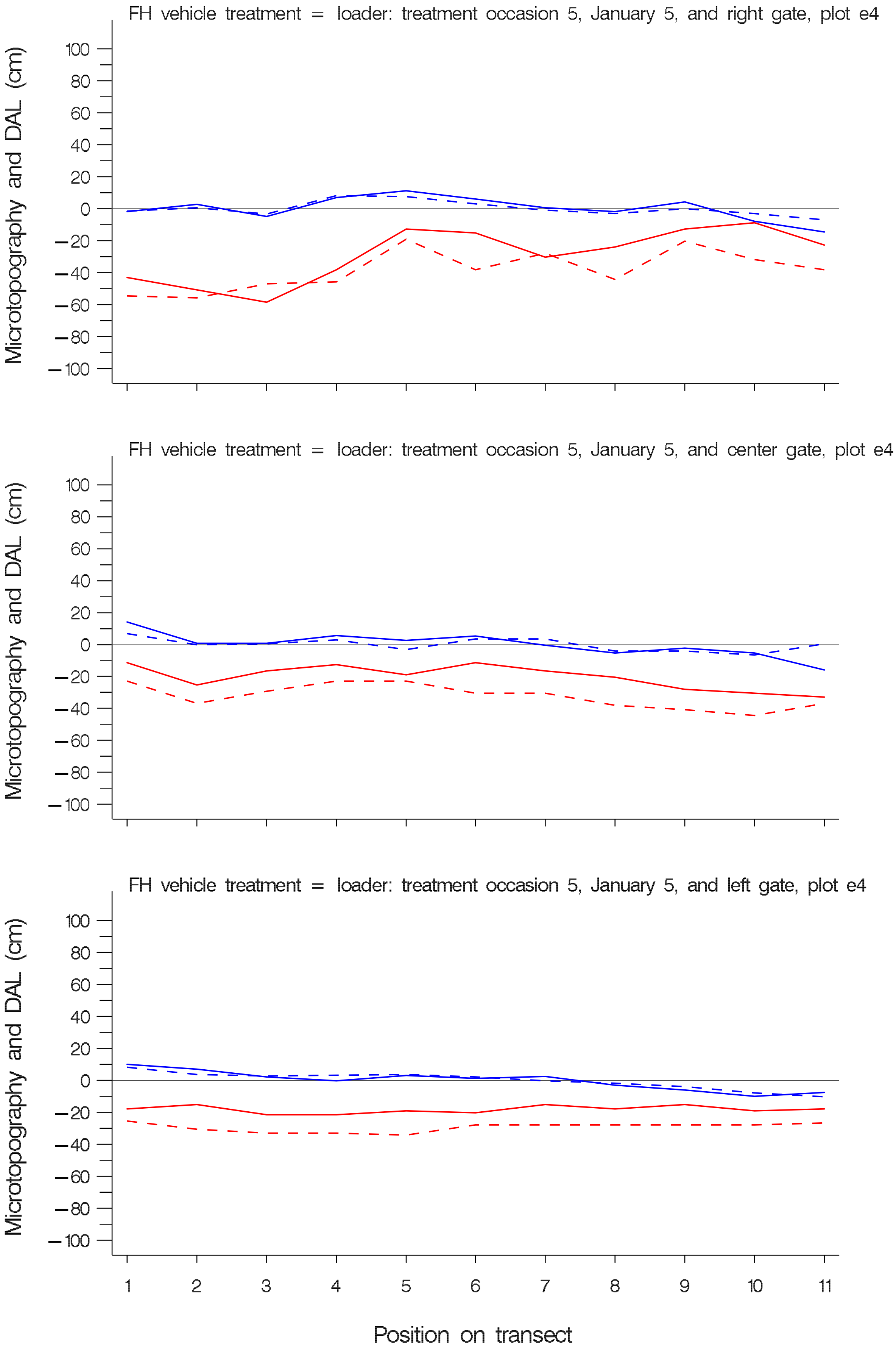
Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

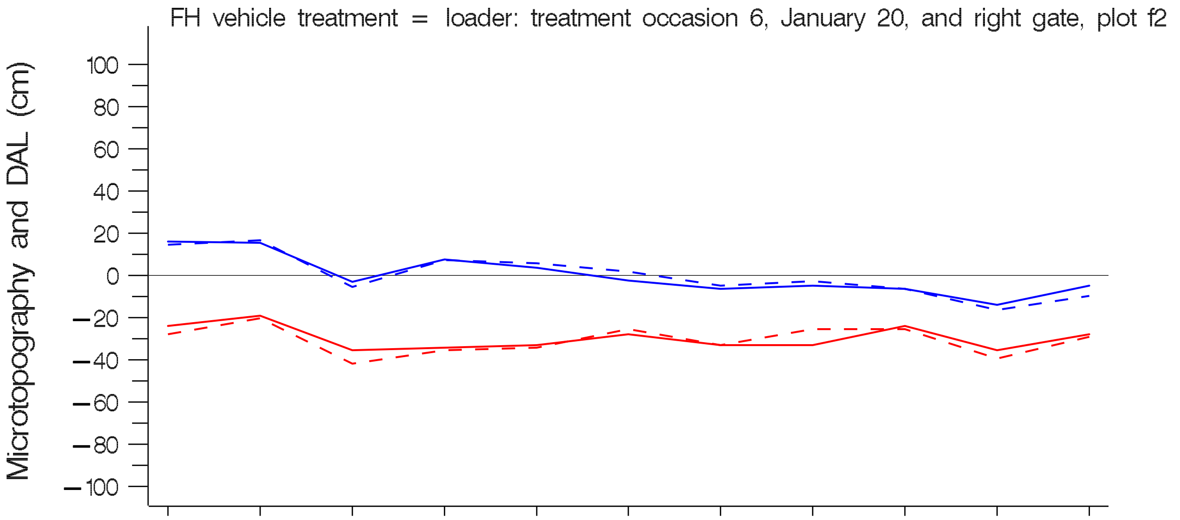


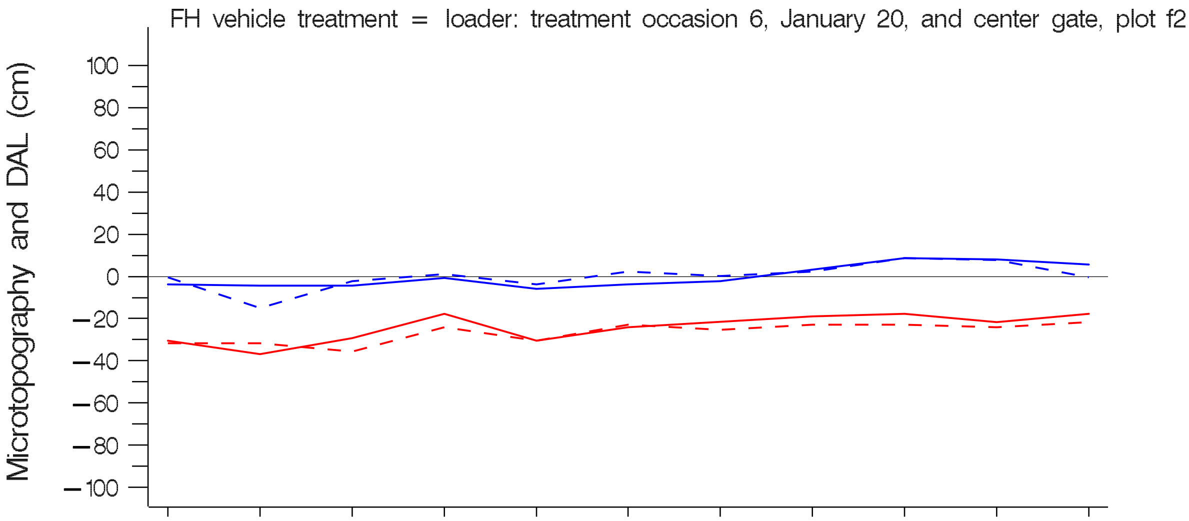
Solid line displays 2003, dashed line displays 2004

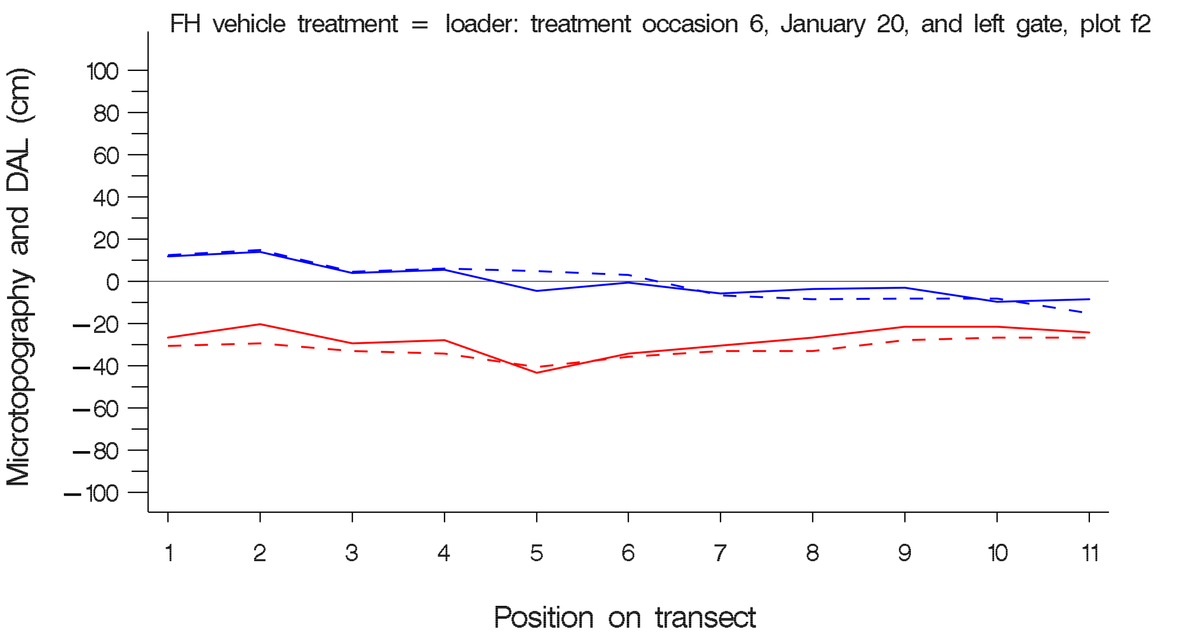
February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas



Solid line displays 2003, dashed line displays 2004







Solid line displays 2003, dashed line displays 2004

February 1, 2005 : output from program TTM_microtop_DAL_graphs . sas

Model
Wet Sedge-Coastal Plain
Change Depth of Active Layer

	DF	SS	MS	F Value	Pr>F
Model	17	2218.9215	130.5247	21.38	<.0001
Error	972	5933.1328	6.1040		

R-Square	0.2721
Coeff Var	-102.6068
Root MSE	2.4706
Dal_diff Mean	-2.4078

Source	DF	Type III SS	MS	F Value	Pr>F
Groundhardness_gate_	1	89.7959	89.7959	14.71	0.0001
Logslab	1	23.7486	23.7486	3.89	0.0488
Inside	1	49.2776	49.2776	8.07	0.0046
Treatment	4	648.7794	162.1948	26.57	<.0001
Direction	1	126.4720	126.4720	20.72	<.0001
Dal_03	1	1315.4382	1315.4382	215.50	<.0001
Groundhard*Treatment	4	455.2550	113.8137	18.65	<.0001
Logslab*Treatment	4	91.6782	22.9195	3.75	0.0049

Parameter	Standard Est.	Error	t Value	Pr>t
Intercept	-10.5842	0.6729	-15.73	<.0001
Groundhardness_gate_	0.0049	0.0046	1.06	0.2900
Logslab	-0.7321	0.3438	-2.13	0.0335
Inside (Inside)	-0.4638	0.1632	-2.84	0.0046
Inside (Outside)	0.0000			
Treatment (Challenger)	3.2870	0.5573	5.90	<.0001
Treatment (Loader)	0.1673	0.5553	0.30	0.7632
Treatment (Tractor)	-1.1345	0.5798	-1.96	0.0507
Treatment (Tucker)	2.9938	0.5602	5.34	<.0001
Treatment (ZNone)	0.0000			
Direction (Curve)	0.7608	0.1671	4.55	<.0001
Direction (Straight)	0.0000			
Dal_03	0.1667	0.0113	14.68	<.0001
Groundhard*Treatment (Challenger)	-0.0375	0.0066	-5.65	<.0001
Groundhard*Treatment (Loader)	-0.0038	0.0067	-0.58	0.5648
Groundhard*Treatment (Tractor)	0.0092	0.0072	1.28	0.2005
Groundhard*Treatment (Tucker)	-0.0348	0.0067	-5.16	<.0001
Groundhard*Treatment (Znone)	0.0000			
Logslab*Treatment (Challenger)	0.9582	0.3873	2.47	0.0135
Logslab*Treatment (Loader)	1.4202	0.3995	3.55	0.0004
Logslab*Treatment (Tractor)	1.3715	0.4108	3.34	0.0009
Logslab*Treatment (Tucker)	0.9375	0.3917	2.39	0.0169
Logslab*Treatment (Znone)	0.0000			

Model
Wet Sedge-Coastal Plain
Change in Soil Moisture

	DF	SS	MS	F Value	Pr>F
Model	12	4783.8834	398.6569	21.34	<.0001
Error	527	9847.0499	18.6851		

R-Square	0.3269
Coeff Var	63.1552
Root MSE	4.3226
Soilmoist_diff Mean	6.8444

Source	DF	Type III SS	MS	F Value	Pr>F
Groundhardness_gate_	1	495.7707	495.7707	26.53	<.0001
Logslab	1	31.1203	31.1203	1.67	0.1974
Treatment	4	1411.6474	352.9118	18.89	<.0001
Soilmoist_03	1	2789.8509	2789.8509	149.31	<.0001
Logslab*Treatment	4	404.4648	101.1162	5.41	0.0003
Loader2	1	375.5503	375.5503	20.10	<.0001

Parameter	Standard Est.	Error	t Value	Pr>t
Intercept	-13.4823	1.9642	-6.86	<.0001
Groundhardness_gate_	-0.0280	0.0054	-5.15	<.0001
Logslab	0.9326	0.8071	1.16	0.2485
Treatment (Challenger)	-3.6308	0.7134	-5.09	<.0001
Treatment (Loader)	-2.9975	0.7425	-4.04	<.0001
Treatment (Tractor)	1.0283	0.7050	1.46	0.1452
Treatment (Tucker)	-1.3319	0.7147	-1.86	0.0629
Treatment (ZNone)	0.0000			
Soilmoist_03	0.2808	0.0229	12.22	<.0001
Logslab*Treatment (Challenger)	-0.6797	0.9046	-0.75	0.4527
Logslab*Treatment (Loader)	-1.3909	0.9363	-1.49	0.1380
Logslab*Treatment (Tractor)	-3.2892	0.9414	-3.49	0.0005
Logslab*Treatment (Tucker)	-0.9441	0.9156	-1.03	0.3030
Logslab*Treatment (Znone)	0.0000			
Loader2	5.4355	1.2124	4.48	<.0001

Model
Tussock Tundra-Foothills
Change Depth of Active Layer

	DF	SS	MS	F Value	Pr>F
Model	27	10114.6576	374.6169	21.41	<.0001
Error	962	16832.5742	17.4974		

R-Square	0.3753
Coeff Var	-67.7350
Root MSE	4.1829
Dal_diff Mean	-6.1755

Source	DF	Type III SS	MS	F Value	Pr>F
Operator	1	67.6761	67.6761	3.87	0.0495
Gateelevation	5	1992.8865	398.5773	22.78	<.0001
Snowdepth_gate_mean	1	193.5453	193.5453	11.06	0.0009
Treatment	4	388.8709	97.2177	5.56	0.0002
Dal_03	1	3330.7446	3330.7446	190.36	<.0001
Snowdepth*Treatment	4	372.4199	93.1049	5.32	0.0003
Treatment*Gateelevation	11	786.9841	71.5440	4.09	<.0001

Model
Tussock Tundra-Foothills
Change Depth of Active Layer

Parameter	Standard Est.	Error	t Value	Pr>t
Intercept	-3.1264	1.8023	-1.73	0.0831
Operator (Set One)	1.4538	0.7392	1.97	0.0495
Operator (Set Two)	0.0000			
Gateelevation (322.4784)	-1.3036	1.1864	-1.10	0.2721
Gateelevation (328.2696)	-2.6039	1.2828	-2.03	0.0427
Gateelevation (335.8896)	-5.4757	1.1743	-4.66	<.0001
Gateelevation (340.7664)	-1.2205	0.8395	-1.45	0.1463
Gateelevation (351.1296)	-7.6292	1.1632	-6.56	<.0001
Gateelevation (364.236)	0.0000			
Snowdepth_gate_mean	-0.2076	0.0592	-3.50	0.0005
Treatment (Challenger)	3.7521	2.9535	1.27	0.2043
Treatment (Loader)	-7.9120	2.8371	-2.79	0.0054
Treatment (Tractor)	-6.4394	3.0015	-2.15	0.0322
Treatment (Tucker)	-6.8099	2.8219	-2.41	0.0160
Treatment (ZNone)	0.0000			
Dal_03	0.2394	0.0173	13.8	<.0001
Snowdepth*Treatment (Challenger)	-0.1724	0.1114	-1.55	0.1219
Snowdepth*Treatment (Loader)	0.2829	0.0986	2.87	0.0042
Snowdepth*Treatment (Tractor)	0.2058	0.0831	2.48	0.0134
Snowdepth*Treatment (Tucker)	0.1881	0.0838	2.24	0.0251
Snowdepth*Treatment (ZNone)	0.0000			
Treatment*Gateelevation Challenger (328.2696)	-4.7117	1.4978	-3.15	0.0017
Treatment*Gateelevation Challenger (340.7664)	-1.8072	1.7378	-1.04	0.2986
Treatment*Gateelevation Challenger (351.1296)	1.0306	1.2522	0.82	0.4107
Treatment*Gateelevation Challenger (364.236)	0.0000			
Treatment*Gateelevation Loader (322.4784)	-2.9294	1.3713	-2.14	0.0329
Treatment*Gateelevation Loader (328.2696)	0.5613	1.5724	0.36	0.7212
Treatment*Gateelevation Loader (340.7664)	-3.3101	1.7186	-1.93	0.0544
Treatment*Gateelevation Loader (351.1296)	0.0000			
Treatment*Gateelevation Loader (364.236)	0.0000			
Treatment*Gateelevation Tractor (322.4784)	-0.6702	2.0844	-0.32	0.7479
Treatment*Gateelevation Tractor (328.2696)	1.3129	1.9962	0.66	0.5109
Treatment*Gateelevation Tractor (335.8896)	2.4383	2.0318	1.2	0.2304
Treatment*Gateelevation Tractor (340.7664)	0.0000			
Treatment*Gateelevation Tucker (322.4784)	-3.1684	1.7048	-1.86	0.0634
Treatment*Gateelevation Tucker (328.2696)	1.0781	1.624	0.66	0.5069
Treatment*Gateelevation Tucker (340.7664)	0.0000			
Treatment*Gateelevation Tucker (364.236)	0.0000			
Treatment*Gateelevation Znone (322.4784)	0.0000			
Treatment*Gateelevation Znone (328.2696)	0.0000			
Treatment*Gateelevation Znone (335.8896)	0.0000			
Treatment*Gateelevation Znone (364.236)	0.0000			

Model
Tussock Tundra-Foothills
Change in Soil Moisture

	DF	SS	MS	F Value	Pr>F
Model	24	39113.8523	1629.7438	8.33	<.0001
Error	515	100806.8348	195.7414		

R-Square	0.2795
Coeff Var	-196.3871
Root MSE	13.9907
Soilmoist_diff Mean	-7.1240

Source	DF	Type III SS	MS	F Value	Pr>F
Gateelevation	5	7651.4166	1530.2833	7.82	<.0001
Slopecat	2	1663.6406	831.8203	4.25	0.0148
Treatment	4	625.3798	156.3449	0.80	0.5263
Direction	1	1019.4182	1019.4182	5.21	0.0229
Soilmoist_03	1	22588.9852	22588.9852	115.40	<.0001
Treatment*Gateelevation	11	7000.6943	636.4267	3.25	0.0003

Model
Tussock Tundra-Foothills
Change in Soil Moisture

Parameter	Standard Est.	Error	t Value	Pr>t
Intercept	-27.6273	4.2121	-6.56	<.0001
Gateelevation (322.4784)	3.9543	4.1848	0.94	0.3451
Gateelevation (328.2696)	-1.1774	4.7018	-0.25	0.8024
Gateelevation (335.8896)	7.1828	4.1032	1.75	0.0806
Gateelevation (340.7664)	-4.2648	3.3279	-1.28	0.2006
Gateelevation (351.1296)	-2.3876	4.1469	-0.58	0.5650
Gateelevation (364.236)	0.0000			
Slopecat (1)	5.5107	2.3001	2.40	0.0169
Slopecat (2)	-0.8115	1.4804	-0.55	0.5838
Slopecat (3)	0.0000			
Treatment (Challenger)	10.0547	4.6939	2.14	0.0327
Treatment (Loader)	4.8043	4.7362	1.01	0.3109
Treatment (Tractor)	8.7735	5.7529	1.53	0.1279
Treatment (Tucker)	7.6972	4.0623	1.89	0.0587
Treatment (ZNone)	0.0000			
Direction (Curve)	3.1272	1.3703	2.28	0.0229
Direction (Straight)	0.0000			
Soilmoist_03	0.4007	0.0373	10.74	<.0001
Treatment*Gateelevation Challenger (328.2696)	-18.3887	6.6645	-2.76	0.0060
Treatment*Gateelevation Challenger (340.7664)	-1.2390	5.7910	-0.21	0.8307
Treatment*Gateelevation Challenger (351.1296)	-8.9362	5.6428	-1.58	0.1139
Treatment*Gateelevation Challenger (364.236)	0.0000			
Treatment*Gateelevation Loader (322.4784)	-7.5204	6.4318	-1.17	0.2428
Treatment*Gateelevation Loader (328.2696)	-5.9243	6.7154	-0.88	0.3781
Treatment*Gateelevation Loader (340.7664)	-4.6775	5.8489	-0.80	0.4242
Treatment*Gateelevation Loader (351.1296)	0.0000			
Treatment*Gateelevation Loader (364.236)	0.0000			
Treatment*Gateelevation Tractor (322.4784)	-26.0101	7.0741	-3.68	0.0003
Treatment*Gateelevation Tractor (328.2696)	-10.7639	7.4316	-1.45	0.1481
Treatment*Gateelevation Tractor (335.8896)	-11.7486	6.5460	-1.79	0.0733
Treatment*Gateelevation Tractor (340.7664)	0.0000			
Treatment*Gateelevation Tucker (322.4784)	-21.6095	5.7524	-3.76	0.0002
Treatment*Gateelevation Tucker (328.2696)	-8.6529	6.2611	-1.38	0.1676
Treatment*Gateelevation Tucker (340.7664)	0.0000			
Treatment*Gateelevation Tucker (364.236)	0.0000			
Treatment*Gateelevation Znone (322.4784)	0.0000			
Treatment*Gateelevation Znone (328.2696)	0.0000			
Treatment*Gateelevation Znone (335.8896)	0.0000			
Treatment*Gateelevation Znone (364.236)	0.0000			

APPENDIX I:
Treatment Vehicle Specifications

Type	Gross Wt. (Lbs.)	Lbs/sq. in. (PSI)	Track Mechanism
Tucker 1600	15,000	1.25	Rubber Cleat
Challenger 65	33,500	4	Rubber Cleat
Loader 966	40,000	40	Rubber Wheel
D7 Tractor	50,500	9	Steel Cleat