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Indian Head Long Term Crop Rotations: Indian Head Saskatchewan

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Summary
The Indian Head Long-Term Crop Rotations, established in 1957, consisted of nine different spring wheat based rotations. The rotations studied the effects of nitrogen and phosphorus fertilizer application, legume green manure crops, forage crops, different frequencies of fallow and straw removal. The study was converted from conventional-tillage to no-till in 1990. Applying fertilizers based on soil test recommendations, extending crop rotations and including green manure or hay crops and using no-till all increased grain yield, N and P uptake, soil organic matter content and soil quality, and enhanced nutrient cycling. The accumulation of nitrates in the soil can be greatly minimized when recommended rates of nitrogen are used in combination with continuous cropping. Annual straw removal during the wheat phase did not reduce soil organic matter or grain yields relative to a comparable rotation with straw retained. This suggests that some crop residues may be used for industrial purposes without detrimental effects on soil quality.

Introduction
The Indian Head Long-Term Rotations were started in 1957 by Dr. Ed Spratt and Mr. Ted McCurdy. A close examination of cropping issues in the 40's, 50's and early 60's reveals great challenges for farmers wanting to reduce tillage, reduce summer fallowing and increase cropping frequency. The difficulty was due almost exclusively to weed control. Whenever stubble cropping practices were attempted for any length of time, problems with Canada thistle (*Circum arvense*) and quackgrass (*Agropyron repens*) would emerge. The control of these weeds was only possible with extensive tillage during the summer fallow period, which exposed the soil to erosion and degradation. Wild oat (*Avena fatua*) was also problematic in stubble cropping resulting in substantial grain yield losses in some years. Control was possible with delayed seeding and additional pre-seeding tillage but not without some yield penalties and soil moisture loss. With the greater availability of nitrogen and phosphorus fertilizers, but more so the availability of new herbicides, cropping practices slowly shifted away from summer fallow cropping to stubble cropping combined with conservation tillage. Today we observe continual increases in the adoption of no-till production practices combined with continuous cropping, reduction in summer fallow area and greater crop diversity. The goals of this study were to improve our understanding of continuous cropping and assess different summer fallow frequencies along with the roles of nitrogen and phosphorus fertilizers, legume green manure crops and forage crops for sustaining crop production and maintaining soil quality. Spring wheat, which was the dominant Canadian Prairie crop for the first eight decades of the 20th century, was used as the indicator crop.

The choice of the nine crop rotations reflected the need to understand the implications of lengthening crop rotations in order to reduce fallow (Table 1). The rotations varied from two years (F-W), three years (F-W-W), three years with the fallow replaced with a green manure crop (Gm-W-W), six years with forage included (F-W-W-H-H-H) and finally continuous cropping (ContW). As well, fertilizer nitrogen (N) and phosphorus (P) or no fertilizer were added as an additional factor in certain rotations. The inclusion of three years of forage as part of a six-year rotation allowed for more cropping and a reduction in the frequency of fallow to one year in six. The three years of hay (usually brome-alfalfa) allowed for the control of wild oat and the one year of fallow allowed for the control of quackgrass and Canada thistle. Another aspect of the study was the inclusion of a legume green manure crop to reduce the fallow period and allowing for the buildup of nitrogen in the soil. The latter two rotations were never fertilized. Other aspects were to determine if green manure crops could replace nitrogen fertilizer while allowing for some weed control. The inclusion of nitrogen and phosphorus fertilizer to wheat was to gain a better understanding of their effects on yield, grain protein, economics and soil fertility as a function of cropping frequency, and the influence of fertilizer and fallow frequency on soil degradation. Over the years, the study has permitted in-depth investigations of the long term impacts of different spring wheat based rotations on a number of agronomic and soils related issues. It is the only study its kind in the thin-Black Chernozemic Soil Zone of the Canadian Prairies.

Major Findings

Given the large numbers of papers published from this study, the results will be discussed by answering a number of questions deemed by the authors to best represent the overall findings to date from these rotations.

How did inorganic fertilizers, green manure crops, forage crops and frequency of fallow influence spring wheat grain yields and perennial hay production?

A summary of the spring wheat and hay yields for the period 1958 – 2007 representing the first 50 years of the study is provided in Table 2. In order to quantify the productivity and performance of these various rotations, the F-W (unfertilized) rotation will serve as the base line for comparisons unless specified otherwise[8,13].

Fertilizer N and P increased spring wheat yields on fallow by 1.32 times in F-W (fertilized) and 1.37 times in F-W-W (Table 2). With spring wheat grown on wheat stubble, fertilizer N & P increased wheat yields 2.4 times for F-W-W (fertilized) and 2.1 times for ContW (fertilized) (Table 2). Thus, the effects of fertilizer on grain yields were greater under stubble than under fallow. These findings reinforce the notion that stubble cropping cereal or oilseed crops requires the addition of fertilizer N and P, at a minimum, in order to achieve viable economic returns.

Another interesting comparison is the impact of legume green manure and forage crops on spring wheat yields. Spring wheat grown on fallow following a green manure crop (Gm-W-W) was 1.14 times higher than F-W (unfertilized) and 1.08 times higher than F-W-W (unfertilized) while spring wheat after fallow which was preceded by 3 years of hay yielded 1.26 times more than F-W (unfertilized) and 1.2 times more than F-W-W (unfertilized). Under stubble, wheat yields in GM-W-W were 1.37 times more than F-W-W (unfertilized) while stubble wheat yields in the forage rotation were 1.83 times more than F-W-W (unfertilized). The beneficial effects of green manure crops and forage crops were more noticeable under stubble than fallow cropping conditions because the extra nitrogen mineralized under the legume systems were more advantageous to stubble systems (less N mineralized than under fallow). Also, the benefits of hay in the rotation were greater than the benefits of green manure because the hay represented 50% of the rotation (three years in 6) while the green manure crop only accounted for 33% of the rotation (one year in 3). However if one compares Gm-W-W and F-W-W-H-H-H to the fertilized rotations, they yielded much less (Table 2). This is because although the green manure crop and the forage crops are providing nitrogen to the soil through nitrogen fixation, P is not being added to the soil. With time, the depletion of soil P limited grain yields under both fallow and stubble cropping conditions. The full beneficial effect of green manure and forage crops in rotations on soil quality will only be realized when P and other nutrients are not limiting, which was not the case in this study[8].

Another approach to quantifying the effects of these various rotations on wheat yields is to calculate the annualized wheat yields taking into consideration the frequency of summer fallow and whether fertilizer was used (Table 2). For example, in the F-W rotation, it takes two years to grow one crop while in the F-W-W rotation, it takes three years to grow two crops and so on. When reported as annualized yields, and comparing results to the base line rotation F-W (unfertilized), ContW (fertilized) produced the most grain (2.16 times), followed by F-W-W (fertilized) (1.64 times), F-W (fertilized) (1.31 times) and Gm-W-W (unfertilized) (1.23 times). The yields in the remaining rotations were either similar to or lower than F-W (unfertilized). What we observed was that, as the frequency of summer fallow in the rotation is reduced and when N&P fertilizer is applied, productivity increases.

Another observation was the more rapid decline in wheat grain yields for the unfertilized F-W, F-W-W and ContW rotations after 1991, which coincided with the conversion from a conventional-tillage system to no-till. These effects observed with conversion to no-till does not imply that soil degradation was accelerated but, in fact, provides evidence that the opposite was occurring. The lack of tillage slowed down the breakdown of soil organic nitrogen into mineral nitrogen because of the lack of soil disturbance resulting in overall lower grain yields for the unfertilized rotations. Larger yield differences between the fertilized and unfertilized rotations were noted after 1991[8].

Future needs for food, feed, fibre and energy will only be met providing that we apply fertilizer based on soil tests, replace, at a minimum, the N and P exported in the grain and that we adopt cropping systems that will maximize production (continuous cropping) and protect the soils against wind, water or tillage erosion (e.g. use of no-till).

What is the impact of these crop rotations on soil organic matter, nitrogen supplying power and other soil quality attributes?

Soil organic matter is the main indicator of soil health and productivity. It is responsible for soil aggregation which gives the soil structure thereby increasing water holding capacity, reducing bulk density and facilitating aeration. Soil organic matter is also an important reservoir for plant nutrients. It is therefore important that we understand how cropping practices impact soil organic matter to minimize or prevent any negative impacts. In this study, we were interested in how fallow frequency, continuous cropping, fertilizer use, green manure and forage crops influenced soil organic matter.

The status of soil organic matter is determined from soil organic carbon (SOC) and nitrogen (SON) measurements. Soil samples were collected in 1987, 30 years after the start of the study. The use of fertilizer increased soil organic carbon in the ContW rotation but not in the F-W or F-W-W. The reduction in fallow frequency was accompanied by increases in SOC. Even though no fertilizer was used, the inclusion of a green manure or forage crop increased SOC and soil organic nitrogen[1,11] (Table 3).

To gain more insight into the effects of these rotations on soil quality attributes, detailed measurements were undertaken to quantify nitrogen mineralization or cycling in the soil after 30 years using the parameter "initial potential rate of N mineralization". This was done in order to distinguish between both the absolute and qualitative changes in SON according to the rotations used. The findings were that fertilizers were just as effective as green manure or forage legumes for increasing the quality and quantity of soil organic matter[2] (Table 4).

There is a close association between soil organic matter and microbial biomass such that both usually increase or decrease together; however, changes in microbial biomass are more readily observed. The effects of rotation were greater for microbial biomass nitrogen than microbial biomass carbon. The mineralization of carbon was also a good parameter for delineating treatment effects. Close examination of the microbial carbon to nitrogen ratio indicated that the microbial suite of organisms had been modified in the rotations where soil organic matter had increased, in this case ContW (fertilized), Gm-W-W and F-W-W-H-H-H. This shift in microbial populations was, in turn, related to the amount of crop residues returned to the soil and their carbon and nitrogen content[1].

In 1990, all the rotations were converted to no-till and in 1996, the soil from the various rotations was again sampled for SOC and SON content[7]. After 6 years of no-till, fertilizer increased SOC and SON while the unfertilized rotations did not show an increase in either SOC or SON. With the conversion to no-till, nitrogen fertilizer rates were also increased to reflect higher levels of soil moisture availability from enhanced moisture conservation which led to higher grain yields and more residues returned to the soil. Microbial biomass carbon was also increased by 40%, which is a reflection of higher plant residue inputs into the soil, indicating the close relationship between soil organic matter and overall microbial activity[6].

In 2007, after 50 years since the start of the rotation and 16 years since the conversion to no-till[11], the rotations were sampled again for SOC and SON. SOC in the unfertilized F-W and F-W-W rotations still remained unchanged from 1997, although ContW (unfertilized) showed slight increases. The Gm-W-W rotation also showed no increase, probably because phosphorus was limiting crop production and overall grain yields had decreased. The ContW (fertilized) and F-W-W-H-H-H rotation which had increased substantially in the first 30 years did not show further increases over the last 10 years. It is speculated that the soil had reached a steady state for SOC; however, it could also be due to lack of crop diversity, especially in the ContW (fertilized) rotation and the cumulative effects of not adding P after 50 years of cropping in the F-W-W-H-H-H rotation.

What do these rotations teach us about soil organic matter and microbial biomass and other soil quality attributes? If soil organic matter is going to be maintained or increased, the adoption of no-till combined with continuous cropping practices and proper fertilization practices and/or legumes in rotation represents one way of attaining that goal. At a minimum, it is essential that the nitrogen and phosphorus exported in the grain be adequately replaced.

What is the long-term impact of straw removal on soil productivity and quality?
Crop residues are considered the feedstock of choice for the production of ethanol, but harvesting crop residues may negatively impact soil productivity over time. With one of the rotations having crop residues removed every crop year, this study offered the possibility to answer this important question. There were two identical F-W-W (fertilized) rotations except in one of them the residues were baled and removed every crop year (i.e two out of 3 years). SOC levels and grain yields were compared between the two rotations after thirty, forty and fifty years[3,7,9,11]. Measurements of SOC and SON showed no effects after 30[3], 40[7] and 50 years[9,11] years of straw removal, and spring wheat grain yields and grain protein concentrations were also unaffected (Table 5). Over the 50 year period, it was estimated that only about 22% of the above-ground residues other than grain were removed through the straw baling operation with the remainder comprised of chaff, stubble and roots.

A more recent study verified the observations obtained from this work[10]. They used two different soil organic matter simulation models to predict soil organic matter following straw removal. The models showed that after 50 years, a 25% removal rate of above ground crop residues would have negligible effects on soil organic matter, which was consistent with our results, but that removal rates of 50% or higher would negatively impact soil organic matter levels.

Therefore, it would appear that some crop residues can be removed intermittently and in modest amounts from Black Chernozemic soils without affecting overall crop productivity and soil quality providing that residue removal does not result in wind or water erosion.

Does the use of inorganic phosphorus fertilizers lead to higher levels of cadmium in the grain?
People are always raising concerns about food safety. One concern in particular is regarding the possible accumulation of cadmium in food as a result of using inorganic phosphorus fertilizers. Cadmium is a heavy metal and is considered toxic because it tends to accumulate in the body. Phosphorus fertilizers are known to contain various amounts of cadmium, depending on the rock source used to make the fertilizer. The study at Indian Head along with other similar studies at Swift Current and Lethbridge provided a unique opportunity to answer this question given that some of the rotations had never received inorganic phosphorus fertilizers, while others did. This study showed that the levels of cadmium in spring wheat grown in these rotations were more likely to be affected by crop sequence, environmental conditions, and parent material of the soil, than by long-term P fertilization[12]. This is encouraging news given that P fertilizer is necessary to maintain soil productivity, nutrient availability and crop production.

5. Can the repeated frequent use of inorganic nitrogen fertilizers lead to nitrate accumulations or leaching in the soil?
Plants take up nitrogen in two forms, as nitrate (NO_3^-) or as ammonium (NH_4^+). As a negatively charged ion, nitrate can easily leach, and when levels in the soil get too high, nitrate can potentially leach below the rooting zone and eventually lead to ground water contamination. Under wet surface soil conditions, nitrates can be lost through denitrification, a process mediated by certain soil microbes. Given that the ammonium ion is positive, it is attracted to the negatively charged clay particles and therefore not subject to leaching losses like nitrates; however, the nitrification process, which is also mediated by soil microbes in the soil, will rapidly convert ammonium to nitrate under aerobic conditions.

This long-term study allowed us to investigate the potential role of summer fallow frequency, use of N fertilizers, use of legume green manure and forage crops on potential nitrate accumulations in the soil profile. Measurements were taken after 34 years to a depth of 4.5 m (14.8 feet)[4]. As the frequency of fallow increases, more nitrates were present in the profile due to increased nitrogen mineralization from tillage and lack of crop uptake during the fallow period. As would be expected, this was especially so during the fallow phase of the rotation. If the fallow period coincided with a year of above-average rainfall, there was a greater likelihood of nitrate movement below the rooting zone. When considering the impact of forage crops, greater nitrates were observed in the profile in comparison to the F-W-W (unfertilized rotation), particularly in the 0-1.5 m soil layer. For the GM-W-W, similar nitrate levels as F-W-W (unfertilized) were present in the 1.5m soil layer, but higher levels of nitrates were present in the lower profile with the green manure crop. The incorporation of nitrogen rich residues from either green manure or forage crops during the fallow period leads to greater levels of soil nitrates below the rooting depth of wheat. When examining the impact of fertilizers, we noted that the comparable fertilized and unfertilized rotations had similar levels of nitrates in the soil profile. The study was converted to no-till in 1991 and measurements of nitrates in the top 1.2 m of the soil profile were completed again at this time[8]. Although crop rotation affected nitrate concentrations in the top 0-0.3 m of the soil profile, the overall amounts were very low in absolute terms and even lower at deeper depths (up to 1.2 m). This suggests that with the use of no-till, even though higher rates of N fertilizers were being used, the rotations have had a positive effect by slowing down the production of nitrates[8]. Based on the results from these studies, one can formulate some important conclusions. Continuous cropping combined with no-till and recommended rates of N fertilizers will not lead to accumulations of nitrates in the soil profile. These results provide more compelling evidence that summer fallow should be discouraged, especially in the sub-humid areas of the Canadian Prairies; however, care must be used when including legume green manure crops in rotations to minimize fallow frequency.

Does a soil with a history of proper fertilization respond better to fertilizer than a poorly fertilized or unfertilized soil?

Con Campbell, scientist emeritus from the Swift Current Research Center, conducted a very interesting greenhouse study using soil samples (0-15 cm) that he collected in the spring of 1993 from select rotations after two successive wheat crops. He then conducted a nitrogen and phosphorus rate study in controlled conditions in the growth chamber using inorganic fertilizers[5]. The rotations from which soils were collected at Indian Head were F-W-W (unfertilized), F-W-W (fertilized), ContW (unfertilized), ContW (fertilized), GmW-W and F-W-W-H-H-H (unfertilized). The fertilized crop rotation did not respond to P while unfertilized ones did. The response to N was proportional to the nitrogen mineralization potential of the soil as previously described[2]. This suggests that soils with low soil organic matter due to erosion or poor soil and crop management practices cannot be made to produce equally to comparable soils that have higher soil organic matter by simply adding more inorganic fertilizers. In other words, if you want to build crop yields over time, you need to start by building the soil quality attributes. This provides compelling evidence for the need to at least maintain current levels of soil organic matter in order to sustain crop productivity. However, given the continual decrease in the global arable land base from soil degradation and urbanization, we will need to increase the productivity of a shrinking land base by increasing the production capacity of existing soils through increases in soil organic matter.

Future:

While it is difficult to predict how financial, material and human resources will be allocated for research in the future, for the time being, there are no intentions to terminate this study or to change the rotations currently in place. There is however, an opportunity to add new rotations, if so desired. Currently there are 33 plots per replicate but only 24 plots in each replicate are being used for the nine rotations described in Table 1. These nine blank plots, as we describe them are simply being cropped using a cereal-canola rotation using locally accepted soil and crop management practices. Currently we avoid any use of insecticide or fungicides. The last time an insecticide was used was in 1994 to control orange blossom wheat midge.

Given the results presented in this article and the more than 50 years of data collection, some additional questions could be answered with this study. For example:

1. What are the impacts of spring wheat based rotations on microbial diversity and do these communities change when legume green

manure or forage crops are included in the in the rotation? Are these changes consistent across the various agro-ecological zones of the prairies with similar rotations?

2. What are the impacts of crop rotations on soil organic matter composition, that is, its chemical make-up? Can we identify certain soil organic matter fractions as indicators of soil health based on their biochemical composition?
3. Given the 50+ year history of the study and the fact that wheat has been grown continuously on some plots this may provide a unique opportunity to study root and leaf disease dynamics? Is it possible to isolate potential biological control agents for root and leaf diseases in spring wheat using these plots?
4. Explore more fully the concept of soil building to increase soil organic matter and determine if it is possible to restore soil organic matter to the original levels observed under native prairie conditions. What methods of soil and crop management practices could be used to increase soil organic matter to levels found under native prairie?

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Table 1. Description of the various spring wheat based cropping sequences present in the Indian Head Long-Term Rotations.

Rotations[a]	Abbreviation	Fertilizer[e]
Continuous Wheat	ContW	Yes
Continuous Wheat	ContW	No
Fallow-Wheat	F-W	Yes
Fallow-Wheat	F-W	No
Fallow-Wheat-Wheat	F-W-W	Yes
Fallow-Wheat-Wheat (straw removed)[b]	F-W-W	Yes
Fallow-Wheat-Wheat	F-W-W	No
Green Manure-Wheat-Wheat[c]	Gm-W-W	No
Fallow-Wheat-Wheat-Hay-Hay-Hay[d]	F-W-W-H-H-H	No

[a] The site is located at the Indian Head Research Farm, Indian Head, SK (latitude 50°32'N and longitude 103 °31'W). The soil is classified as a Indian Head heavy clay, a Rego thin Black Chernozem (Udic Haploboroll). The management of the plots was converted from conventional tillage to no-till in 1991. From 1990 onwards, the fallow phases of the rotations were managed with herbicides only. Refer to Campbell et al. 2011 for more information.
[b] During the wheat phase of this rotation, the straw was removed yearly with a baler.
[c] From 1958 to 1991, sweet clover (*Melilotus officinalis* L.) was used as the green manure crop and from 1992 to present it was changed to lentil (*Lens culinaris* L.) because of problems with the sweet clover weevil due to the close proximity of the plots.
[d] From 1958 to 1991, a mixture of alfalfa (Medicago sativa L.) and bromegrass (Bromus inernis L.) was used and from 1992 to present, only alfalfa has been used.
[e] Fertilizer nitrogen rates (kg ha^{-1} $year^{-1}$) for wheat on fallow were 6 for the years 1956-1986 and 57 for the years 1987-2007. For wheat on stubble, fertilizer nitrogen rates (kg ha^{-1} $year^{-1}$) were 21 for the years 1956-1986 and 85 for the years 1987-2007.

Table 2. Crop rotations, average yields[a] of rotation phases and yields relative to unfertilized fallow-wheat, stubble-wheat and first-year hay, and annualized wheat production[d] of rotations in 50 years (1958-2007) at Indian Head, Saskatchewan (Campbell et al. 2011).

Treatment[b]	Wheat on fallow	Wheat on stubble	Hay_1	Hay_2	Hay_3	Annualized wheat production w (kg ha yr-[1])	% of F-W
F-W	1901 (100)[c]					959	100
F-W (N+P)	2504 (132)					1252	131
F-W-W	2024 (106)	986 (100)[c]				1005	105
F-W-W (N+P)	2610 (137)	2111 (214)				1577	164
Cont W		940 (95)				940	98
Cont W (N+P)		2075 (210)				2075	216
Gm-W-W	2165 (114)	1354 (137)				1175	123
F-W-W-H_1-H_2-H_3	2389 (126)	1808 (183)	1374 (100)	2557 (186)	2709 (197)	700	73

[a] kg ha-[1]; avg 1958 - 2007.
[b] F=fallow, W=spring wheat, Cont=continuous, LGM=legumes green manure, H=brome-alfalfa-hay, N=N fertilizer, P=phosphorus fertilizer.
[c] Values in parentheses are relative to F-W unfertilized=100 for fallow or partial fallow (LGM) systems and relative to unfertilized stubble wheat in F-W-W=100 for stubble wheat systems. For hay, values (in parentheses) are relative to first year hay=100.
[d] For F-W=yield x 0.5 for F-W-W & LGM-W-W=(sum of fallow-wheat & stubble-wheat) x 0.33; for Cont W=yield; for hay system=(sum of fallow-wheat & stubble-wheat) x 0.167.

Table 3. Total soil organic carbon and nitrogen in the 0-15cm soil layer depths from the various crop rotations and soil samples taken in September of 2007 after 50 years of cropping (taken from Lemke et al. 2012).

Crop Rotation	Soil Organic Carbon (t ha^{-1})	Soil Organic Nitrogen (t ha^{-1})
F-W (unfertilized)	30.32	3.02
F-W (fertilized)	32.84	3.18
F-W-W (unfertilized)	30.80	3.02
F-W-W (fertilized)	34.34	3.34
Gm-W-W (unfertilized)	33.53	3.26
F-W-W-H-H-H (unfertilized)	39.61	3.83
Cont W (unfertilized)	34.58	3.27
Cont W (fertilized)	38.24	3.69
Significance	**0.02**	**0.03**
LSD ($p<0.05$)	**6.3**	**0.6**

Table 4. Relative estimates of potential mineralizable N from the various crop rotations at Indian Head (adapted from Campbell et al. 1991b).

Crop Rotation	Relative Values (Cont W fertilized =100)
Cont W (fertilized)	100
Cont W (unfertilized)	65
F-W-W-H-H-H (unfertilized)	92
Gm-W-W (unfertilized)	83
F-W-W (fertilized)	69
F-W-W (fertilized with straw removed)	60
F-W-W (unfertilized)	53
F-W (fertilized)	60
F-W (unfertilized)	45

Table 5. The effects of nitrogen fertilizer and straw removal on spring wheat grain yield (kg ha^{-1}) and grain protein (%) collected from the Indian Head Long-Term Crop Rotations. The grain yields reported are for the period 1988-2007 and grain protein for the period 2003-2007 (Lafond et al. 2009).

Rotation	Straw Baled	Grain Yield (kg ha^{-1})		Grain Protein (%)	
		Fallow	Stubble	Fallow	Stubble
F-W-W	**No**	2533	2162	14.7	14.6
F-W-W	**Yes**	2586	2259	15.0	14.8
s.e.		**149**		**0.5**	
Contrasts		***p*-values**			
Baled vs not Baled		ns[a]		ns	
Fallow Phase: Baled vs not Baled		ns		ns	
Stubble Phase: Baled vs not Baled		ns		ns	

[a] Values followed by ns means that the p-values were >0.05 and therefore considered not significant.

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