Precision fertigation for sustainable agriculture in Saudi Arabia

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Abstract

Agriculture in Saudi Arabia is dependent on finite water resources. Efficient use of depleting water resources is a dire necessity to attain sustainability. Precision fertigation technology helps in optimizing input use in agricultural activities. Investigations were carried out to study the response of wheat and alfalfa to precision fertigation. Field experiments were conducted in two center pivot fields each measuring 50 ha. Split plot design was adopted for the two experiments each with three replications. For both wheat and alfalfa, four irrigation treatments allocated to main plots included $I_1$: Irrigation at 100\% ETc, $I_2$: Irrigation at 90\% ETc, $I_3$: Irrigation at 80\% ETc and $I_4$: Irrigation at 70\% ETc. Three fertilizer levels formed sub-plot treatments in both the experiments. In wheat experiment, three levels of fertilizer nitrogen, phosphorus (P$_2$O$_5$) and potassium (K$_2$O) formed the sub plot treatments. The three fertilizer levels were defined as F1 (Low): 300:200:200 kg ha$^{-1}$; F2 (Medium): 400:250:250 kg ha$^{-1}$ and F3 (High): 500:300:300 kg ha$^{-1}$. In alfalfa experiment, three fertilizer levels included were Low (126:92:300), Medium (234:138:400) and High (342:184:500) (kg N:P$_2$O$_5$K$_2$O/ha/year). Results of the studies indicated that precision fertigation could help to save 20 and 30 per cent of water used in the production of alfalfa and wheat without sacrificing the yield.

Keywords: Precision fertigation, yield mapping, wheat, alfalfa, Saudi Arabia

Introduction

Wheat and alfalfa are two important crops among the very few crops cultivated in Saudi Arabia. Wheat is cultivated on an area of 219,505 ha producing 1,349,389 metric tons of grain. An average yield of 4.5 t ha$^{-1}$ with fertilizer productivity of 40 kg wheat per kg fertilizer nutrient was reported (FAO, 2000). Oweis \textit{et al.} (2000) reported that WUE in wheat can be substantially improved by adopting deficit irrigation to satisfy up to 66\% of irrigation requirement in West Asia and North Africa (WANA) regions. The amount of irrigation water used for spring wheat in Saudi Arabia varied from 600 ha$^{-1}$ mm$^{-1}$ in central region (Alderfasi, 2000) to 1200 ha$^{-1}$ mm$^{-1}$ in Al-Hassa region (Al-Barak, 2006).
Forage production sector represents 23% of the total cropping area, where alfalfa is viewed as the most important fodder crop cultivated in Saudi Arabia (Abusuwar and Bakhashwain, 2012). Alfalfa is highly demanding for water, where the annual evapotranspiration of desert-grown alfalfa was estimated to be in excess of 1,900 mm year\(^{-1}\) (Phene, 2004). With mean annual average rainfall of around 100 mm, agriculture sector in Saudi Arabia relies mostly on finite water resources that are dwindling at a rapid rate. Crops are irrigated through center/linear pivots using water pumped from deep aquifers. In order to optimize the use of inputs, such as water and fertilizers, the present study was undertaken with the following objectives:

(i) To study the response of spring wheat and alfalfa to irrigation and nutrient levels.

(ii) To develop and evaluate site-specific precision fertigation schedule for wheat and alfalfa crops.

**Materials and Methods**

**Study site**

The experiment was conducted on a farmer’s field located between Al-Kharj and Haradh regions of Saudi Arabia within the latitudes of 24º10' 22.77" and 24º12' 37.25" N and the longitudes of 47º56' 14.60" and 48º05' 08.56" E (Figure 1).

**Experimental details - Wheat**

An experiment was laid out in split plot design with three replications. The area covered by two spans formed one replication. The soil texture was clay loam with a pH of 7.58. Hard red spring wheat (Triticum aestivum L.) seed (cv. Yecora Rojo) at 250 kg ha\(^{-1}\) was sown on January 1, 2012. Four irrigation treatments allocated to main plots were I\(_1\): Irrigation at 100% ET\(_c\), I\(_2\): Irrigation at 90% ET\(_c\), I\(_3\): Irrigation at 80% ET\(_c\) and I\(_4\): Irrigation at 70% ET\(_c\) and three levels of fertilizer nitrogen, phosphorus (P\(_2\)O\(_5\)) and potassium (K\(_2\)O) to the sub plots. The three fertilizer levels were defined as F\(_1\) (Low): 300:200:200 kg ha\(^{-1}\); F\(_2\) (Medium): 400:250:250 kg ha\(^{-1}\) and F\(_3\) (High): 500:300:300 kg ha\(^{-1}\). All of the phosphorus (Di-ammonium phosphate) and potassium (Potassium sulphate) was band placed as basal. The remaining amount of nitrogen was applied as foliar spray in eleven splits starting from two weeks until ten weeks after sowing. After each irrigation cycle, nitrogen was applied at 20, 30 and 40 kg ha\(^{-1}\) in F\(_1\), F\(_2\) and F\(_3\), respectively. Irrigation requirement was worked out based on daily mean ET values recorded on the farm for the period between 1995 and 2011 (Allen et al., 1998). Irrigation treatments were imposed by adjusting the pivot speed to deliver the required amount of water in each treatment.
Experimental details – Alfalfa

The field experiment was conducted on a sandy clay loam soil 50 ha field under center pivot irrigation system to determine the optimum levels of irrigation and fertilizer rate to optimize hay yield of alfalfa. Initially, the experiment was laid out in a split plot design with three replications (Fig. 2). Four main treatments consisting of irrigation at 100% (I1), 90% (I2), 80% (I3) and 70% (I4) Evapotranspiration (ETc) were randomly allocated to the four quadrants of the field. Three fertilizer levels: Low (126:92:300), Medium (234:138:400) and High (342:184:500) (kg N:P2O5:K2O/ha/year) were randomly allocated to the sub-plots. The area covered by two pivot spans formed one replication. Two spans near the centre of the pivot and half over hung span at the outer end were treated as buffer zones (Fig 1A). Using the zone based Variable Rate Irrigation (VRI) system; four irrigation treatments (I1 to I4) were imposed as sub plot treatments in both of the management zones in May 2012. The fertilizer levels formed the main plot treatments (Fig 2B). Frequency of irrigation varied from three to five days. Irrigation requirement was worked out based on daily mean ET values (1995-2011) recorded on the farm, as per Allen et al (1998).

Yield data

In case of wheat, the crop was combine harvested on May 9, 2012, and the grain yield was recorded by weighing the combine harvested wheat corresponding to each treatment. Whereas, for alfalfa crop, hay yield monitor (Model 880) of Harvest Tec, USA was installed on large square baler (Claas 3000) to record the harvested yield at the time of baling.

Satellite imagery

Aster images corresponding to growth stage 1, GS 1-(735 GDD) (February 17, 2012); GS 2(1047 GDD) (March 4, 2012); GS 3-(1353 GDD) (March 20, 2012); (April, 5, 2012); GS 4-(GDD 2111) (April 21, 2012) of wheat crop were acquired from Japan Space Systems (http://ims.aster.ersdac.jspacesystems.or.jp) and used in developing wheat grain yield map.

Yield Mapping

Wheat grain yield and alfalfa hay yield maps were generated by adopting standard methods. Wheat grain yield map was prepared from the wheat yield (WY) data calculated by multiplying above ground biomass (AGB) by harvest index (HI) as described by Xin et al. (2009). AGB was estimated based on the function of radiation use efficiency and Photosynthetically Active Radiation (PAR). PAR was estimated from the NDVI(P) with the function of FPAR. Cumulative NDVI (CNDVI) was derived by averaging predicted NDVI (i.e.
NDVI<sub>(P)</sub> of three stages (GS 2, 3 and 4) as described by Tucker et al. (1985) to compute mean AGB for the whole season. Subsequently, grain yield was estimated based on variations in pre and post NDVI<sub>(P)</sub> of grain filling stage.

Alfalfa hay yield monitor data of two cuts made in September and October 2012 were filtered using automated low pass filter of Erdas Imagine (Ver. 2010). The yield maps were prepared by interpolating the filtered point data to a 4 by 4 m grid using ordinary kriging (Dobermann et al, 2003) tool of ESRI GIS (Ver. 2010). During the preparation of yield maps, low or high yielding strips and points associated with significant turning and maneuvering of the baler were removed as described by Wiebold et al (2003). Short segments which were affected by start or end-pass delays were also removed as per Simbahan et al (2004). The actual weight of 60 bales at an average moisture content of 13% was recorded and used to correct the apparent yield data of hay yield monitor. Moisture content of each bale was measured using a moisture probe (Delmhorst F-2000, Digital Hay Moisture Meter with 18 Inch Probe).

Results and Discussion

Response of wheat to irrigation and fertilizer levels

*Effect of irrigation and fertilizer levels on wheat grain yield and Water Use Efficiency (WUE)*

Crop yield integrates the effects of various soil, climate and management factors that vary across space and time. Irrigation and fertilizer levels significantly influenced the wheat grain yield (Table 1). Irrigating the crop at 100% ET<sub>c</sub> resulted in higher grain yield (5.68 t ha<sup>-1</sup>) than the lower irrigation levels. Lower level of fertilizer application at 300:200:200 kg of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O ha<sup>-1</sup> recorded higher grain yield of 5.67 t ha<sup>-1</sup> than medium and the high fertilizer levels. Treatment combinations of lower fertilizer level and irrigation at 100, or 90 or 80% ET<sub>c</sub> were superior to irrigation at 70% ET<sub>c</sub>. However, irrigation at 70% ET<sub>c</sub> with medium fertilizer level produced a yield of 6.06 t ha<sup>-1</sup>, which was on par with irrigation levels of 100 or 90% ET<sub>c</sub> with lower fertilizer level (6.09 and 6.08 t ha<sup>-1</sup>). Thus, saving in water of up to 30% can be assumed possible. The amount of water applied varied from 568 to 796 ha<sup>-1</sup> mm<sup>-1</sup>, with WUE vales ranging from 6.88 to 10.67 kg ha<sup>-1</sup> mm<sup>-1</sup> (Table 2).

Although highest rate of irrigation (at 100% ET<sub>c</sub>) resulted in significantly higher grain yield than the lowest rate of irrigation (at 70% ET<sub>c</sub> (Table 1), higher WUE of 9.74 kg ha<sup>-1</sup> mm<sup>-1</sup> was observed with the lowest rate of irrigation than with the highest rate of irrigation (7.13 kg ha<sup>-1</sup> mm<sup>-1</sup>). Irrigation effectively increases crop yield although water-use efficiency (WUE) decreases as the irrigation rate increases (Al-Kaisi & Yin, 2003). Hussain and Al-Jaloud (1995) obtained wheat grain yield of 5.01 t ha<sup>-1</sup>, with WUE of 2.67 to 12.24 kg grain ha<sup>-1</sup> mm<sup>-1</sup> in Saudi Arabia. Alderfasi (2000) did not observe significant
effect of irrigation levels on grain yield of four wheat genotypes grown on sandy loam soil in the central region (Riyadh area) of Saudi Arabia. However, they observed very high WUE of 23 to 31.8 kg ha$^{-1}$ mm$^{-1}$ by irrigating the crop at 100 mm CPE (600 mm water). Al-Barrak (2006) obtained wheat grain yield of 6.5 tons ha$^{-1}$ with WUE of 6.5 kg m$^{-3}$ on a sandy loam soil in Al-Hassa region of Saudi Arabia. It was further reported that the increase in the amount of irrigation over and above 12000 m$^3$ ha$^{-1}$ did not increase the yield. Similarly, Mustafa et al. (1989) reported that 1146 mm ha$^{-1}$ (11460 m$^3$ ha$^{-1}$) was needed to produce 6.5 tons ha$^{-1}$ of wheat grain in Tabuk region of Saudi Arabia. The highest amount of irrigation water applied in this study (between Al-Kharj and Haradh regions) was 796 mm ha$^{-1}$ with irrigation at 100% ETc, as against 600 mm ha$^{-1}$ in the central region, 1200 mm ha$^{-1}$ in Al-Hassa region and 1146 mm ha$^{-1}$ in Tabuk regions. The regional differences justify assessment of irrigation needs of crops in different regions within Saudi Arabia.

**Wheat Grain Yield Map**

The wheat grain yield map was computed from the cumulative NDVI derived from ASTER images of crop growth stages GS 2, 3 and 4. In the grain yield map (Fig. 1B), higher yields were found in the northern half of the field. The cNDVI derived grain yield was marginally higher in MZ-1 than in MZ-2 (Table 3). In both of the management zones, higher grain yield of 6.16 to 6.26 t ha$^{-1}$ was observed at 100% ETc, with the three fertilizer levels (Table 3). However, in MZ-2, similar grain yields (6.07 to 6.25 t ha$^{-1}$) were also observed with irrigation at 70% ETc at medium and high levels of fertilizers. Application of lower level of fertilizers (300: 200:200: kg ha$^{-1}$ of N:P$_2$O$_5$:K$_2$O) was sufficient to meet the crop requirements and produced significantly higher measured grain yield (Table 1). Similar lack of response of spring wheat to higher N fertilizer levels was reported by Wang et al. (2012) who obtained 7.4% higher grain yield at 221 kg N ha$^{-1}$ than at 300 kg N ha$^{-1}$. Further increase in the levels of fertilizers caused yield reduction. The yield reduction might be due to the excessive vegetative growth that could have resulted in moisture stress during grain filling stage. The observed differential response of wheat was due to the synergistic effect of irrigation and fertilizer levels. When the quantity of irrigation water was sufficient, lower level of fertilizer was enough to produce the maximum yield. However, when the quantity of irrigation water was reduced, lower fertilizer level did not suffice and medium and higher fertilizer levels, especially those of phosphorus and potassium, were necessary to maintain the higher yield levels.

The higher grain yield seen in northern part of the field, corroborates well with the higher grain yield harvested (Table 1) with irrigation at 100% ETc with all the three fertilizer levels and irrigation at 70% ETc with medium and high levels of fertilizers. The variability in the grain yield was mainly due to the effect of treatments rather than due to the differences between the management zones. Similar observations were reported by Lobell et al. (2002), wherein the majority of the variability (88.6%) in wheat grain yield was observed within
treatments and was attributed mainly to variations in management. Doraiswamy et al. (1996) found that spring wheat yield simulated from Landsat TM data was similar to country average and farm level reported yields. Lee et al. (2010) also developed a yield map from ASTER satellite imagery for mapping within-field yield variability and as a surrogate to yield monitor data.

**Effect of precision fertigation on alfalfa hay yield**

Irrigation and fertilizer treatments significantly influenced the hay yield (HY) in both cuts made in September (1st cut) and October (2nd cut), 2012 (Fig. 3). The Variable Rate Irrigation (VRI) showed benefits in the 1st cut. In MZ 1, the highest yield of 4.093 t/ha was obtained with the treatment combination of irrigation at 100 % ETc and medium fertilizer level, whereas in MZ 2, the highest of 3.897 t/ha was obtained with the treatment combination of irrigation at 80 % ETc and medium fertilizer level. These two treatment combinations in the respective management zones were significantly superior to all other treatment combinations. For both cuts and in both zones, medium fertilizer level proved superior to the other levels. These results are evident in the yield maps (Fig.3) generated, for both cuts, from yield monitor data. For both cuts, higher hay yielding areas can be seen in the southern and northern parts of the field. These areas were mostly associated with the medium and the high fertilizer levels in both management zones. However, the areas that received the low rate of fertilizer (eastern and western parts of the field) exhibited low yielding capacity in both management zones (Fig.3).

**September cut**

On the overall mean, irrigation at 80 % ETc resulted in the highest yield of 3.493 t/ha (Table 3), which was on par only with 100 % ETc treatment. The average yield of 3.627 t/ha recorded for this treatment (I3) in MZ-2 was superior to the average yields associated with the remaining irrigation treatments. However, on the average, the yield obtained in MZ-1 with irrigation at 70 % ETc (3.271 t/ha) was on par with the remaining irrigation treatments. It can be inferred that Variable Rate Irrigation (VRI) at 70% ETc in MZ-1 and at 80 % ETc in MZ-2 can result in a substantial saving in water that can range from 20 to 30%. On the average across all irrigation treatments, medium fertilizer level resulted in similar yields of 3.763 and 3.788 t/ha in MZ-1 and MZ-2, respectively, which was superior to the other fertilizer levels.

**October cut**

As in September cut, irrigation at 80 % ETc resulted, on the overall mean, in the highest yield of 2.152 t/ha (Table 4). However, it was on par with irrigation at 90 % ETc. On the average, the highest yield of 2.224 t/ha was associated with I3 in MZ 2, which was similar to the findings related to September cut data. However, in MZ 1, the highest average yield of 2.111 t/ha was obtained with
irrigation at 90% ETc. Nevertheless, this treatment was on par with irrigation at 80% ETc. From Table 4, it can be inferred that irrigation at 80% ETc is the optimum in both management zones, suggesting a saving of irrigation water of up to 20%. Medium fertilizer level resulted, on the average, in the highest yield of 2.451 and 2.333 t/ha in MZ-1 and MZ-2, respectively, which was superior to the other fertilizer levels in both management zones.

Conclusions

Irrigation at 70% ETc coupled with application of 400:250:250 kg ha\(^{-1}\) of N:P\(_2\)O\(_5\):K\(_2\)O resulted in water saving of 30% without affecting the yield. Yield map generated from the Cumulative NDVI helped in assessing the effect of different treatments on wheat grain yield in the absence of yield monitor. GS 2 of wheat corresponding to 1047 GDD or 63 days after sowing showed good correlation with grain yield. In alfalfa, irrigation at 80% ETc combined with medium fertilizer level treatment was found to produce the optimum yield in two cuts. This is translated to a saving of up to 20% in irrigation water without sacrificing the hay yield of alfalfa.

Acknowledgements

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References


Fig. 1 (A) Management zone map; (B) Wheat grain yield map

Fig. 2 Layout plans of the alfalfa field experiment, (A) Before the deployment of Variable Rate Irrigation System (VRI) (i.e. January to May 2012) and (B) After installation of VRI (i.e. May to November 2012).

Fig. 3 Hay yield maps of alfalfa for (A) September, 2012 cut and (B) October, 2012 cut.
Table 1: Effect of irrigation and fertilizer levels on wheat grain yield (t ha\(^{-1}\))

<table>
<thead>
<tr>
<th>Irrigation Levels</th>
<th>Fertilizer Levels (N:P(_2)O(_5):K(_2)O kg ha(^{-1}))</th>
<th>300:200:200</th>
<th>400:250:250</th>
<th>500:300:300</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation at 100%ET(_c)</td>
<td>6.09</td>
<td>5.36</td>
<td>5.58</td>
<td>5.68</td>
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<tr>
<td>Irrigation at 90%ET(_c)</td>
<td>6.08</td>
<td>5.22</td>
<td>4.95</td>
<td>5.41</td>
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<tr>
<td>Irrigation at 80%ET(_c)</td>
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<td>5.41</td>
<td>4.92</td>
<td>5.41</td>
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<tr>
<td>Irrigation at 70%ET(_c)</td>
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<td>5.96</td>
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<tr>
<td>Mean</td>
<td>5.67</td>
<td>5.51</td>
<td>5.35</td>
<td>5.51</td>
<td></td>
</tr>
</tbody>
</table>

LSD\(_{0.05}\) for comparison between irrigation level means: 0.09
For comparison between fertilizer levels means: 0.06
Comparison between two fertilizer level means at the same irrigation treatment: 0.13
Comparison between two irrigation level means at the same or different fertilizer treatments: 0.11

Table 2: Effect of irrigation and fertilizer levels (N:P\(_2\)O\(_5\):K\(_2\)O kg ha\(^{-1}\)) on grain yield and water use efficiency of spring wheat

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Water applied (mm)</th>
<th>Grain Yield (kg ha(^{-1}))</th>
<th>Water use efficiency (kg ha(^{-1}) mm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1F1</td>
<td>796</td>
<td>6090</td>
<td>7.65</td>
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<td>I1F2</td>
<td>796</td>
<td>5360</td>
<td>6.73</td>
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<tr>
<td>I1F3</td>
<td>796</td>
<td>5580</td>
<td>7.01</td>
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<tr>
<td>I2F1</td>
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<td>6080</td>
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</tr>
<tr>
<td>I2F2</td>
<td>720</td>
<td>5220</td>
<td>7.25</td>
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<td>I2F3</td>
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<tr>
<td>I3F1</td>
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<td>10.67</td>
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<tr>
<td>I4F3</td>
<td>568</td>
<td>5960</td>
<td>10.49</td>
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I1F1 = Irrigation at 100% ETc. + 300:200:200; I1F2 = Irrigation at 100% ETc. + 400:250:250; I1F3 = Irrigation at 100% ETc. + 500:300:300; I2F1 = Irrigation at 90% ETc. + 300:200:200; I2F2 = Irrigation at 90% ETc. + 400:250:250; I2F3 = Irrigation at 90% ETc. + 500:300:300; I3F1 = Irrigation at 80% ETc. + 300:200:200; I3F2 = Irrigation at 80% ETc. + 400:250:250; I3F3 = Irrigation at 80% ETc. + 500:300:300; I4F1 = Irrigation at 70% ETc. + 300:200:200; I4F2 = Irrigation at 70% ETc. + 400:250:250; I4F3 = Irrigation at 70% ETc. + 500:300:300.
Table 3. Effect of precision fertigation on alfalfa hay yield (t/ha) of September 2012 cut

<table>
<thead>
<tr>
<th>Irrigation Levels</th>
<th>Management Zone – 1</th>
<th>Management Zone – 2</th>
<th>Overall Mean</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
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<td>2.98</td>
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<tr>
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<td>2.957</td>
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<td>3</td>
<td>6</td>
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</table>

To compare means of:

1) Management Zone Levels (MZ) LSD
2) Fertilizer levels (F) NS
3) Irrigation Levels (I) 0.2469
4) Same level of MZ Vs. F NS
5) MZ Vs. F
6) Same level of MZ Vs. I 0.1953
7) MZ Vs. I 0.1581
8) Same level of F Vs. I 0.2392
9) F Vs. I 0.1019
10) Same combination of MZ and F Vs. I 0.3383
11) Same level of MZ and I Vs. F 0.1441
12) MZ Vs. Same combinations of F and I NS
Table 4. Effect of precision fertigation on alfalfa hay yield (t/ha) of October 2012 cut

<table>
<thead>
<tr>
<th>Irrigation Levels</th>
<th>Management Zone – 1</th>
<th>Management Zone – 2</th>
<th>Overall Mean</th>
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<td></td>
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<tr>
<td>I1</td>
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<td>I3</td>
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<td>I4</td>
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<tr>
<td>Mean</td>
<td>1.69</td>
<td>2.45</td>
<td>1.93</td>
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</table>

LSD

1) Management Zone Levels (MZ) NS
2) Fertilizer levels (F) 0.142
3) Irrigation Levels (I) 0.118
4) Same level of MZ Vs. F 0.201
5) MZ Vs. F 0.165
6) Same level of MZ Vs. I 0.167
7) MZ Vs. I NS
8) Same level of F Vs. I 0.205
9) F Vs. I NS
10) Same combination of MZ and F Vs. I NS
11) Same level of MZ and I Vs. F NS
12) MZ Vs. Same combinations of F and I NS