Final Report

Subsurface Drip Irrigation Systems: Assessment and Development of Best Management Practices

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Project Duration: 03/01/2003 – 02/28/2006

Project Overview:

Microirrigation such as subsurface drip irrigation (SDI) has many advantages for agriculture and the environment. However, many theoretical and design problems related to the application of SDI need further study. For example, how do we quantitatively describe the interrelationships among soil, water and plant? This research project addresses these concerns and provides answers to questions related to irrigation techniques and water-use efficiency.

Initial objectives of the research were to:

1: Compare traditional flood irrigation with an innovative SDI method.
2: Develop BMP for SDI to optimize crop productivity and profits, maximize water-use efficiency, and minimize groundwater contamination.

Project modifications were necessary during the study. The project field study was originally designed to take place at the Midvale irrigation district of Wyoming, however, because the original collaborator identified in the proposal was no longer willing to assist with the project as originally planned and other potential collaborators were only interested in performing the study on a large scale, the field study was changed and occurred at the University of Wyoming's Experimental farm in west Laramie. The Water Research Program (WRP) was notified that the field site had been moved in the 1st year project update.

The necessary relocation of SDI study site impacted activities related to project objective 1. The relocation site lacked access to flood irrigation water over the growing season. Lack of water is primarily because of drought and water allocation issues. Lack of available water due to drought was also a concern at the original field site. Also lacking at the field site are conveyance structures for flood irrigation water. Considering these constraints, sprinkler irrigation was substituted for flood irrigation for comparing the two systems. Sprinkler application does not generate sufficient runoff and leaching to make meaningful measurements and conclusions. This impacted research objective 2 and groundwater contamination aspects were not included in the research.

Students Supported with research funding:

Graduate Students:

Youquan Jiang, initially studied for a PhD Civil Engineering, and subsequently a MS, Renewable Resources, University of Wyoming. Degrees were not completed and the student has left the University of Wyoming.

Xinmei Hao, PhD, Renewable Resources, University of Wyoming, degree was completed in 2006, student was only partially supported with project funding.

Undergraduate students; these students assisted with experimental site installation, setup and harvest collection.

Christopher York, BS Civil Engineering, University of Wyoming
Diogo Lousa, BS Civil Engineering, University of Wyoming
Dan McGillvary, BS Civil Engineering, University of Wyoming

Presentations resulting form this research:

George F. Vance. Subsurface Drip Irrigation of Alfalfa. W1128 Regional Research Committee on Reducing Barriers to Adoption of miccroirrigation, Honolulu, HI. October 2007.

Youquan Jiang, Drew W. Johnson, George F. Vance and David E. Legg. Subsurface Drip Irrigation for Alfalfa Production in Wyoming, University of Wyoming Graduate Research Symposium, April 2006.

Publications resulting from this research:

Johnson, D.W., Y. Jiang, G. F. Vance, D. E. Legg and D. E. Peck, Subsurface Drip Emitter Spacing and Depth Effects for Alfalfa Irrigation in Wyoming, Submitted for publication to Biosystems Engineering, March 2008.

Hao, X., R. Zhang, and A. Kravchenko. 2005. Effects of Root Density Distribution Models on Root Water Uptake and Water Flow under Irrigation. *Soil Science* 170:167-174. [*]

Hao, X., R. Zhang, and A. Kravchenko. 2005. A Mass-conservative Switching Method for Simulating Saturated-unsaturated Flow. *Journal of Hydrology* 311: 254-265. [*]

Hao, X. and R. Zhang. 2004. A hybrid mass-conservative scheme for simulating variably saturated flow in soils with large outflow flux. Proceedings of *Computational Methods in Water Resources 2004 Conference*. UNC-Chapel Hill, North Carolina. [*]

[*] These publications are related to the research project with partial student support provided from the research project. Additional details may be obtained by contacting Dr. Renduo Zhang, at zhangrd@mail.sysu.edu.cn. Dr. Zhang was an original PI on the project before leaving the University of Wyoming

Major Findings and Conclusions

Results of this study were determined from alfalfa yields measured for three drip emitter depths (30, 50 and 70 cm) and three drip emitter spacings (60, 90 and 120 cm). Measured alfalfa yields were compared to HYDRUS-2D simulations of root water uptake for the different drip irrigation scenarios. The results of this study indicate that SDI can increase alfalfa biomass production as compared to sprinkler irrigation, and that the narrow spacing (60 and 90 cm) SDI treatments resulted in greater yield increases in alfalfa biomass production than wider 120 cm spacing SDI treatments. An economic analysis indicated that alfalfa grown under a 90 cm spacing SDI system should be able to generate sufficient revenue to cover costs associated with using SDI technology.

Details related to the field site measurements and modeling work conducted to make these conclusions are described in the following sections of this document.

Experiment site

The field site was located on the University of Wyoming's Experimental farm in the Laramie Basin of southeastern Wyoming, which has an elevation of 2195 m above sea level. Average annual temperature of the study area is 5 °C with annual precipitation of 27 cm, and a frost-free period of 98 days (USDA, 2006). The Laramie Basin is a depositional remnant of a mid to late Wisconsin periglacial environment (Spackman and Munn, 1984). Soils in the Laramie Basin were formed by a sequence of alluvial deposition and carbonate accumulation. Soils are classified as Rock River sandy loam (fine-loamy, mixed, superactive, frigid Ustic Calciargids), which is approximately 0-8 cm of sandy loam, 8-43 cm of sandy clay loam, and 43-150 cm of fine sandy loam and sandy loam. Hydraulic conductivity of the Rock River soil is moderate, and water availability is high (USDA, 2006). The study site was originally a pasture that was used in a field study of pesticide transport in soil during 1993 – 1995 (Zhang et al., 2000). The field site had not been tilled until initiating the SDI study in 2004.

Site Preparation

The field site is approximately 90 × 30 m (Figure 1). The field was plowed to 20 cm depth, rototilled, and leveled in July 2003. A contour data analysis using theodolite and GPS at 60 locations evenly distributed across the field indicated the field had a 1 degree southeast slope. Average shallow (30 cm) saturated hydraulic conductivity for the field site was 2.3 m d^{-1} as determined using the infiltrometer test method (ASTM, 2002). Deeper soil (40 – 60 cm in depth) saturated hydraulic conductivity was on average 0.023 m d^{-1} as determined by auguring and collecting soil samples that were tested by both the constant head and falling head methods in the laboratory. The study site was divided into three zones, an SDI zone of 60 × 30 m, a sprinkler irrigation zone of 15 × 30 m and a non-irrigated 15 × 30 m control zone. The SDI zone was divided into 9 plots (Figure 1). Logistical constraints with regards to availability of land for the experimental area, as well as funds for the purchase of materials, limited the number of available plots for the experiment. We therefore partitioned each plot into three subplots. Preliminary analyses on soil characteristics indicated no differences among plots prior to alfalfa seeding and installation of irrigation tubing, so we used the subplots as replications in subsequent statistical analyses.

In SDI plots, water was supplied by micro discharge from emitters on drip tubing. Drip tubing spacing was the same as emitter spacing on the drip lines. Parameters studied in our SDI system included two factors, depth and spacing of the buried emitters, with three treatment levels. Three depths of 30, 50 and 70 cm and three spacings of 60, 90 and 120 cm were studied. There were nine total treatments of the two factors studied, and thus nine different SDI plots randomly located in the SDI zone. Placement of the SDI lines occurred in 2004. The measured locations for drip lines and supply lines were marked before digging trenches. The size of the supply lines were 2.5 cm in inner diameter (ID) and the drip lines with emitters were 1.2 cm ID. Connecting drip lines to the supply lines was done by using connectors supplied by Netafim (Fresno, CA).

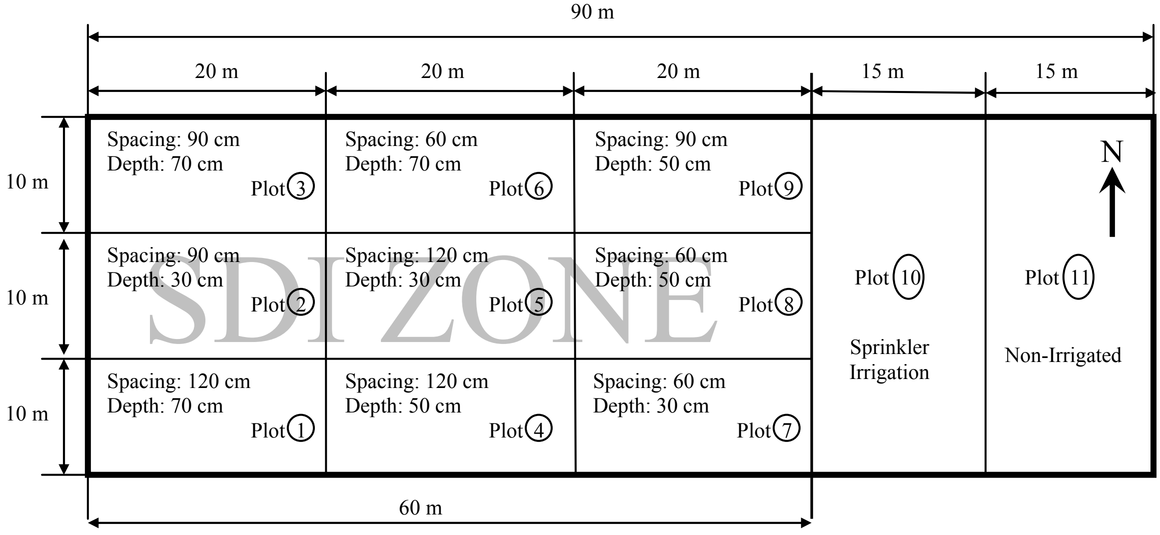


Figure 1 - Layout of the field site showing plot dimensions and the nine subsurface drip irrigation (SDI) zone emitter spacings and depths, sprinkler, and non-irrigated treatments.

The emitters on drip lines (Netafim USA, Uniram 540 0.4GPH, Fresno, CA) were advanced pressure compensating to ensure uniform flow rate over a pressure range of 48 – 140 kPa.
City water, obtained from a spigot located near the field, was the irrigation water source. Individual supply lines were connected to a controlling/measuring system located inside a nearby pole barn. Water supplies to each plot were measured by flowmeters (Netafim, model M, Fresno, CA), and quantitatively controlled by a computer module (Eldar Shanny, model 0700371362, Yad-Mordechay, Israel). The amount of water supplied was based on published historical monthly evaportranspiration (ET) rates for alfalfa growth in Laramie, WY (Pochop et al., 1992).

Alfalfa Seeding and Irrigation Management

Alfalfa was seeded after plowing, rototilling and leveling of the study site in fall 2004. Fall planting is not common in the region but was tried in an attempt to avoid the need for surface irrigation to initiate seed germination. Winter kill occurred due to an early frost, which required us to replant the following spring. Alfalfa was seeded in mid May 2005 at a seeding density of 2.0 gram/m^2. After sprinkler irrigating to initiate seed germination, excellent germination and crop growth was established. In the 2005 seeding year, sprinkler irrigation was used for about one month. After the alfalfa germinated and resulted in a 15 cm height with sufficient coverage, water supply was managed using SDI for the SDI zones and sprinkler irrigation in the sprinkler zone. Water application was adjusted by the average monthly ET without considering the current monthly precipitation. The same amount of water per unit area was supplied to all plots by the end of July 2005. At the beginning of August 2005, water supply at the consumptive use rate (1.0 ET) was applied to the 9 SDI plots and the sprinkler zone until harvest on September 1, 2005.

In 2006, water was supplied at different fractions of consumptive use (ET) in an attempt to compare performance of different SDI parameters under alternative water supply scenarios. For 2006, all nine SDI plots and the sprinkler irrigated plot were supplied water at a level of 0.7 ET for the first harvest on June 14, 2006, 0.4 ET for the second harvest on July 30, 2006, and 0.4 ET for the third harvest on September 22, 2006. All SDI plots and the sprinkler irrigated plot were supplied water at a level of 0.5 ET for the two harvests in 2007. Precipitation varied throughout the growing seasons and total water application, the sum of irrigation supply and precipitation, as a ratio to historical ET is shown in Figure 2.

Weed Control

Common weeds in this field were Canada thistle (*Cirsium arvense* (L.) Scop.), common lambsquarters (*Chenopodium album* L.), and hoary cress (*Cardaria draba* (L.) Desv.). To reduce the impact of weeds on alfalfa growth, a herbicide treatment of glyphosate (Roundup UltraMax, Monsanto Co., 840 g acid equivalent per hectare) with non-ionic surfactant (Preference, Agriliance LLC, 0.25% volume/volume) and ammonium sulfate (5% weight/volume), was applied 20 days prior to alfalfa planting in April, 2005. Post emergence applications of imazamox (Raptor, BASF Co., 36 g per hectare) plus the non-ionic surfactant and liquid nitrogen (2% volume/volume) were applied in June and July to selectively remove weeds from the alfalfa crop. No herbicide treatments were applied for the 2006 and 2007 growing seasons.

Plant sampling, harvest and analysis

Biomass production of alfalfa is most rapid during the growth phase until early flowering, after which production decreases (Kilcher and Heinrichs, 1974; Koch, 1987). Plant sampling and harvests were conducted at the emergence of alfalfa flowering (approximately 10%). Sampling frames used in the plant collection processes were 50 × 50 cm (e.g., 0.25 m^2). Each plot was equally divided into three subplots, and five samples were randomly collected from each subplot by hand clipping. Alfalfa biomass was clipped and stored in paper bags that were marked by a unique sample location identifier.

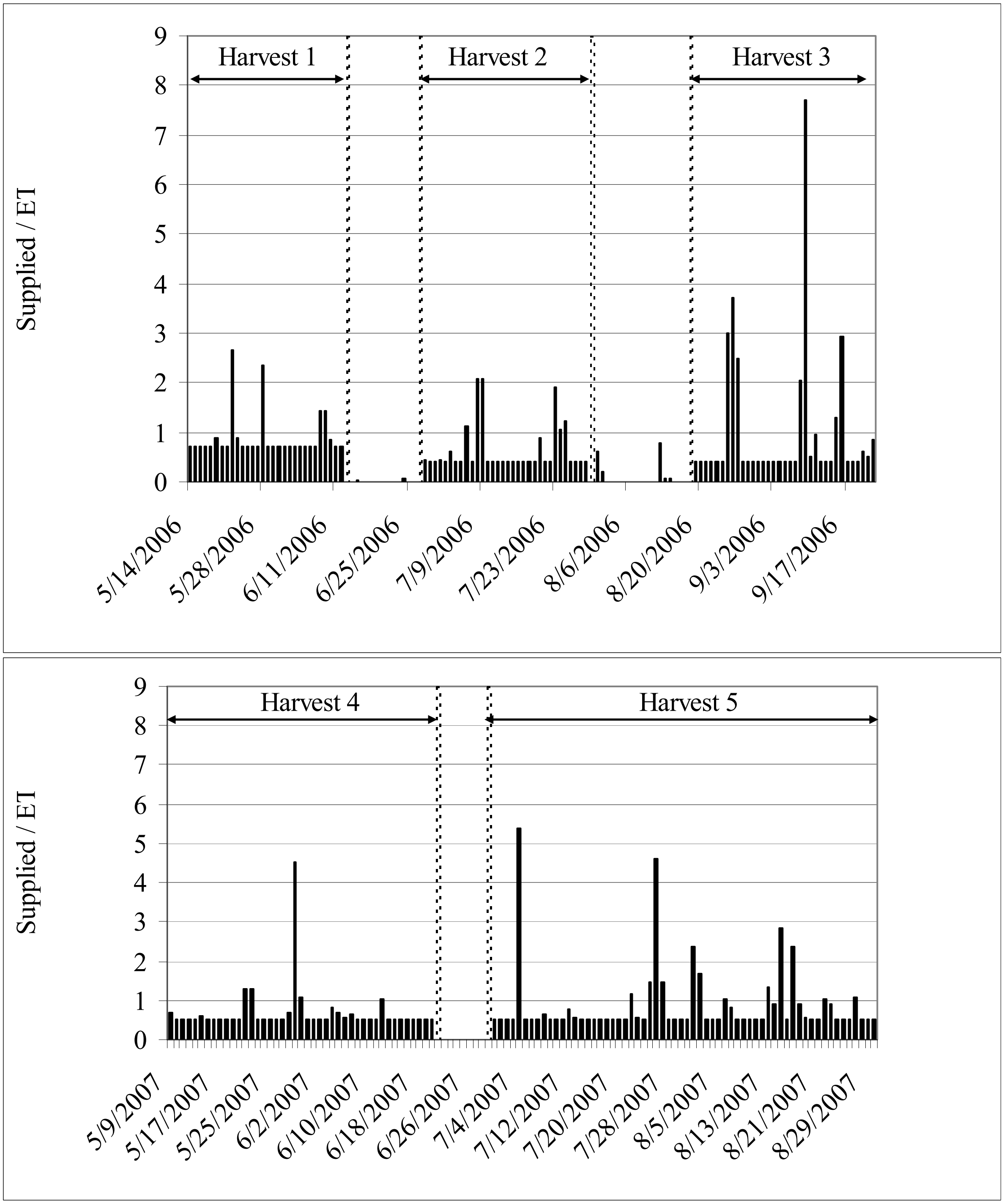


Figure 2 –Daily water supplied to experimental plots, adjusted for precipitation relative to ET for the 2006 and 2007 growing seasons.

In the seeding year (2005), a total of 165 samples were collected in SDI and sprinkler irrigated plots at the end of the growing season. In our first production year (2006), alfalfa was sampled and harvested three times with a total of 495 samples collected from eleven plots (SDI, sprinkler, and non-irrigated sites). In 2007, alfalfa was sampled and harvested two times with a total of 330 samples collected from the eleven plots. All samples were dried in an oven at 75°C for one week. A scale was used to weigh the dry alfalfa biomass weight.

Statistical Analyses

Two statistical analyses were conducted using data collected from the nine SDI, sprinkler, and non-irrigation plots during the 2006 and 2007 harvests. The first analysis tested the null hypothesis that spacing and depth do not interact ($\alpha = 0.1$). A two-factorial analysis of variance, set in a completely randomized design was used. If the interaction term was significant in this first analysis, then means were separated using the LSMEANS option of the Statistical Analysis System (SAS Institute, version 9.1). The second analysis considered all spacing × depth combinations as treatments along with the sprinkler and the non-irrigated applications for a total of 11 treatments. These treatments were analyzed in a one way analysis of variance set in a completely randomized design. If the F test indicated there were differences among treatments, mean separations were conducted using Fisher's protected LSD. Statistical calculations were facilitated by use of the GLM procedure of the Statistical Analysis System (SAS Institute, version 9.1).

Numerical Modeling

The numerical model HYDRUS-2D was used to investigate how emitter spacing and depth design parameters impact alfalfa root water uptake within the field plots. Simulated alfalfa yields were compared to measured alfalfa yields for each of the alternative spacing × depth scenarios. The HYDRUS-2D model solves the governing 2D Richard's equation using the van Genuchten-Mualem constitutive relationships. In the modeling analysis, the drip tubing was treated as a line source (Skaggs et al., 2004) and effects of individual emitters neglected. Natural precipitation and irrigation water supplied through the drip tubing for the second harvest of 2006 was input into HYDRUS-2D along with soil hydraulic properties of the field site (see site description). The following hydraulic HYDRUS 2-D parameters were used for the sandy loam soil layer: θ_s = 0.41, θ_r = 0.065, α= 0.075 n = 1.89, K_s = 106.1 cm d^{-1} and l =0.5. Parameters θ_s = 0.39, θ_r = 0.1, α= 0.059, ν = 1.48, K_s = 31.44 cm d^{-1} and l =0.5 were used for the sandy clay loam layer. These are the default values for sandy loam and sandy clay loam from the HYDRUS-2D soil catalog.

Uptake parameters for alfalfa, as described by Feddes et al. (1978), were also inputs to the model, where HYDRUS-2D allows the Feddes' parameters to be selected for alfalfa from a built-in database. Typical active rooting depths after 1-2 years of alfalfa growth in sub-humid environments are between 1-2 m (Auckly and Guitjens, 1995) and the root zone during simulations was assumed to be at a midpoint depth of 1.5 meters. Both uniform and linear root distributions were used in the simulations. Because no natural precipitation occurred and irrigation water was not supplied for approximately two weeks prior to second harvest, the initial pressure head of the field site prior to irrigating was assumed to be equal to the value at which alfalfa can no longer uptake water at the maximum possible rate (-1500 cm) (Feddes et al., 1978). Alternatively, the wilting point of alfalfa (-8000 cm pressure head) (Feddes et al., 1978), could have been used, but visual observations at the time prior to irrigation of the second harvest did not support a wilting point assumption.

HYDRUS-2D uses the Galerkin finite-element method to solve Richard's equation. Symmetry at the midpoints between adjacent drip lines was assumed and the mesh was rectangular except for where the drip line was represented by a half circle of 0.6 cm radius with the center located at the depth of the drip lines. During irrigation, the drip tubing boundary had a constant water flux of 420 cm d^{-1} for all emitter spacing. This value was calculated based upon the daily amount of water supplied, area of drip tubing in each treatment, and required irrigation times. Irrigation times were 20, 30 and 40 minutes for the 60, 90 and 120 cm drip tubing spacing, respectively, and varied with length of drip tape used for each emitter spacing. The irrigation time used in the simulation for the narrow 60 cm spacing approximately matched required irrigation time necessary for the 60 cm spacing during the field trials to supply water at 0.4 ET. Significantly longer irrigation times were required for the wider drip line spacing in the field trials than those used in the simulations. This is because fewer emitters were present along the length of each drip tape at wider emitter spacing.

Effects of emitter spacing along the length of drip tape were neglected when treating the system as a line source. When irrigation ceased, the drip line boundary became a zero flux boundary. The remaining portion of the left boundary and the right boundary were zero flux boundary conditions due to symmetry. The upper boundary for the soil surface was an atmospheric boundary condition with an assumed zero evaporation loss (Skaggs et al., 2004). The computational domain was large and the bottom boundary did not affect the simulations.

Results and Discussion

Yields obtained for the five individual harvests are shown in Figure 3. Total average yield for all SDI treatments was 18.3 Mg ha^{-1} for 2006 and 15.2 Mg ha^{-1} for 2007, with 15.0 Mg ha $^{-1}$ for 2006 and 13.8 Mg ha-1 for 2007 for the sprinkler treatment and 13.6 Mg ha^{-1} for 2006 and 13.4 Mg ha^{-1} for 2007 for the control treatment. The relatively high yield obtained for the control plot was higher than expected, and may have been influenced by the topography of the field. No separation was provided between plots, so runoff from the upslope surface irrigation plot likely influenced the non-irrigated plot's yields. Subsurface drip irrigation plots were upslope of the sprinkler plot and were therefore not influenced by runoff. Similarly, runoff from the SDI plots was presumably minimal, and therefore did not influence the sprinkler zone's yields.

Differences between treatments varied across the five harvests depending upon the amount of natural precipitation. Larger differences between the SDI plots and the sprinkler and non-irrigated plots were observed when irrigation represented a larger proportion of total water supplied (irrigation plus precipitation). The largest difference between treatments (standard deviation of 17%) occurred in the first harvest when water supplied via irrigation was 80% of total water supplied. The smallest difference between treatments occurred in the last harvest (standard deviation of 2%) when water supplied via irrigation was 60% of total water supplied

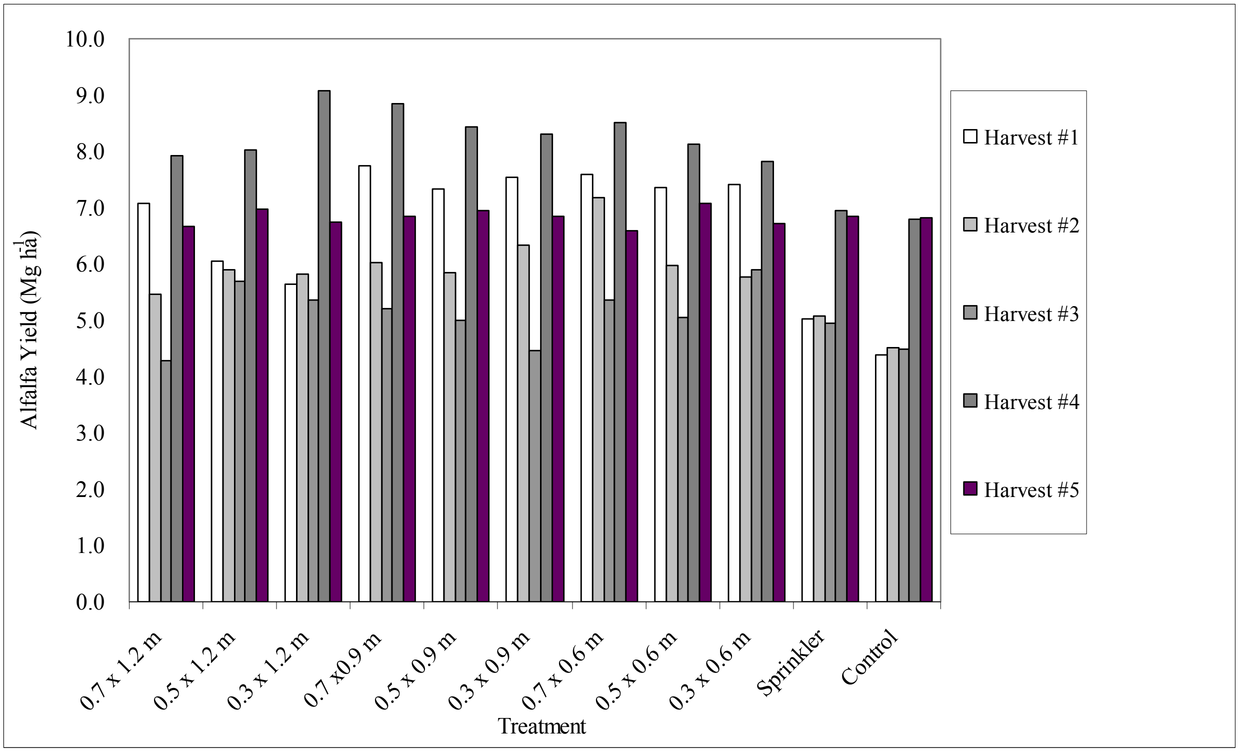


Figure 3 - Yields from each of five harvests for the nine subsurface drip irrigation (SDI), sprinkler and non-irrigated treatments. SDI treatments represent drip line depths and emitter spacings. Irrigation amounts and precipitation varied as indicated for the five harvests (see Figure 2).

Statistical analysis of the total alfalfa yields over two growing seasons for different treatments are shown in Table 1 where different letters for the *t*-grouping from the LSMEANS output indicate significant differences between treatments at the $P < 0.1$ .level.

Table 1 – Statistical analysis results comparing measured two-year total alfalfa yields of alternative subsurface drip irrigation (SDI), sprinkler and non-irrigated treatments*.

Irrigation Treatments	**Depth (cm)**	**Spacing (cm)**	**Two-year Total Alfalfa Yield (Mg/ha)**
SDI	70	60	35.2^{a}
SDI	70	90	34.6^{ab}
SDI	30	60	33.6^{bc}
SDI	50	60	33.6^{bc}
SDI	50	90	33.6^{bc}
SDI	30	90	33.5^{bc}
SDI	50	120	32.7^{cd}
SDI	30	120	32.6^{cd}
SDI	70	120	31.4^{d}
Sprinkler			28.9^{e}
Non-irrigated			27.0^{f}

* Lower case letters following alfalfa yields indicate significance at the $P < 0.1$ level.

Treatments with two letters in the *t*-grouping are transition plots for neighbor groups where total alfalfa yields were not significantly different. Overall, the SDI treatments had significantly higher yields than the sprinkler and non-irrigated treatments. The highest two-year total yield, 35.2 Mg ha^{-1}, was obtained in the 70 cm depth × 60 cm spacing SDI treatment. This yield was significantly greater than in all other treatments except the 70 cm depth × 90 cm spacing SDI treatment. The lowest two-year total yield among the SDI treatments, 31.4 Mg ha^{-1}, was obtained in the 70 cm depth × 120 cm spacing SDI treatment. The sprinkler and non-irrigated treatments had significantly lower yields than the SDI treatments.

The relationships between yield and drip emitter spacing and depth are shown in Figure 4. The two-factorial analysis of variance found no depth effect ($F_{2,\ 18}$, $P = 0.5275$), a strong spacing effect ($F_{2,\ 18} = 8.96$, $P = 0.002$), and no depth × spacing interaction ($F_{4,\ 18} = 2.08$, $P = 0.1264$). Results indicate narrower spacing (90 cm or less), irrespective of depth, produce greater alfalfa yields. Note, however, that the highest two-year total yields were obtained from the 70 cm depth treatments.

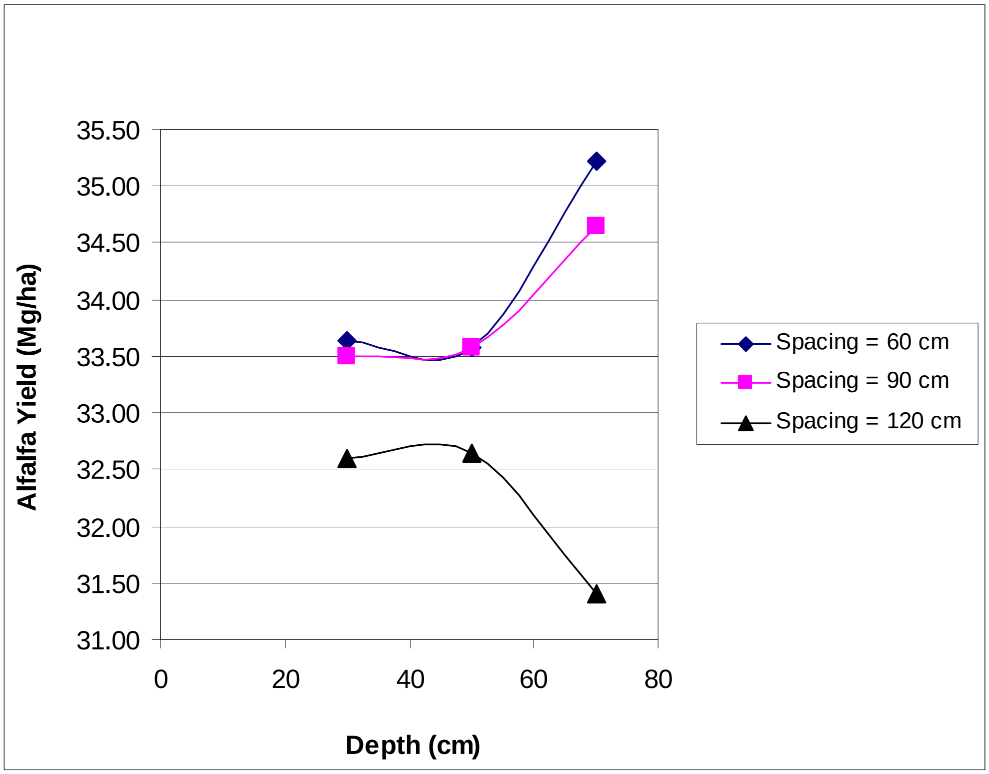


Figure 4 – Two-year total alfalfa yields for alternative subsurface drip irrigation (SDI) tubing depth and emitter spacing treatments.

Simulated water root uptake in undisturbed soil from the HYRDUS-2D model is shown in Figure 5. In general, root uptake and evapotranspiration rates correspond to yields (Auckly and Guitjens, 1995). The simulated values indicate greater yields for the narrow emitter placements. The simulated values also indicate better yields for deeper emitter placements; the depth effect is more apparent if a uniform root distribution model is assumed. The effect of emitter depth on soil water content at the end of the simulation time is shown in Figure 6 for the 60 cm spacing. More uniform water content is apparent with deeper emitter placements; that is, greater simulated root water uptake is primarily due to deeper and hence more uniform wetting zones. The simulations show that both emitter spacing and depth influence simulated root water uptake and yield. This is in contrast to results from field measurements in this study and those of Alam et al., (2002a) which show that emitter spacing alone influences yield. Discrepancies between the measured and simulated results may be attributed to the assumed root distributions. Alfalfa rooting distributions are known to vary with water application scenarios (Abdul-Jabbar et al., 1982; Vaughan et al., 2002) and different rooting distributions among the SDI treatments may have existed within the field, compensating for different water distributions resulting from the various emitter depths used.

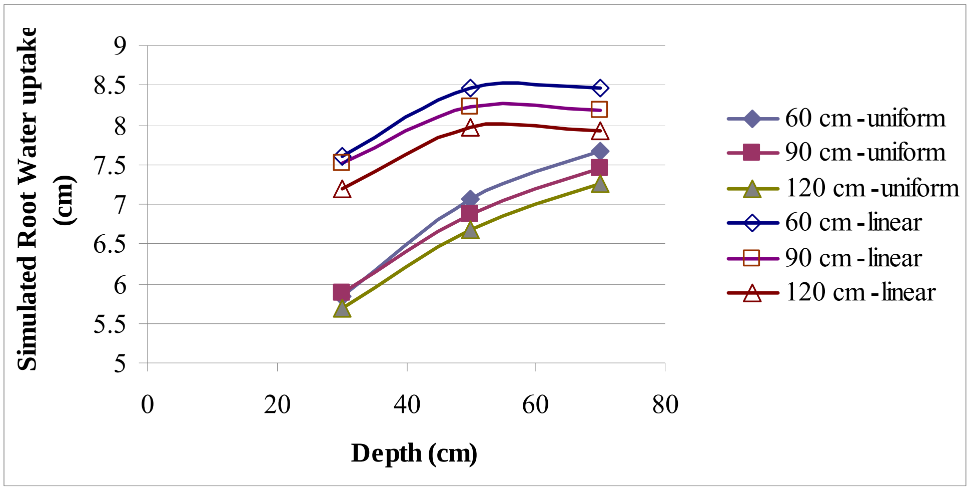
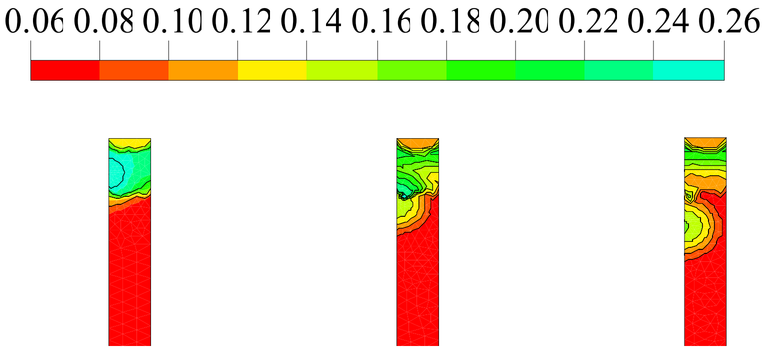


Figure 5 - HYDRUS-2D simulations of alfalfa water root uptake during the second 2006 harvest for two root distributions, subsurface drip irrigation (SDI) emitter depth, and spacing combinations.



Depth = 30 cm

Depth = 50 cm

Depth = 70 cm

Figure 6 – Simulated soil water content for the 60 cm spacing emitters buried at three depths. More uniform water distribution within the root zone occurs with deeper depth.

Economic Analysis

Results of this study indicate that SDI can increase alfalfa biomass production as compared to sprinkler irrigation and natural precipitation, and that 70 x 60 cm and 70 x 90 cm depth by spacing SDI treatments resulted in the largest biomass production. All of the 60 and 90 cm spacing treatments were statistically the same, except for the 70 x 60 depth by spacing treatment.

Therefore, we selected the 90 cm spacing treatment for the following economic analysis, which calculates the break-even alfalfa yield for SDI applications. The break-even yield is such that total revenue just covers total cost for a given output price.

Cost data from Breazeale et al. (2000) were used for this analysis. Breazeale et al. (2000) conducted a break-even analysis for a 65-ha field of alfalfa in Nevada with a 45 cm depth × 100 cm spacing SDI treatment. They reported an investment cost of \$2,980 ha^{-1} for an SDI system with 100 cm spacing, which was comparable to a \$2,562 ha^{-1} investment cost for SDI systems using this spacing (Alam et al., 2002b). The cost is also similar to the \$2,866 ha^{-1} investment cost that Klauzer (2005, personal communication) reported for an SDI system with 75 cm spacing. O'Brien et al. (1998), in contrast, suggested an investment cost of only \$1,331 ha^{-1} for an SDI system with 150 cm spacing. Adjusting this estimate for 100 cm spacing increases the required length of drip line by 3,333 m ha^{-1}. Assuming the cost of drip line is \$0.1473 m^{-1} (as extrapolated from Breazeale, and including the cost of fittings), investment cost increases by roughly \$491 ha^{-1}. The adjusted investment cost of \$1,822 ha^{-1} is still lower than other studies' estimates. The remaining cost discrepancies are attributable in part to different assumptions about the cost of drip line, filtration, and installation.

Investment cost data from Breazeale et al. (2000) were adopted in this study for the following reasons: (1) the focus of their study was alfalfa hay production, (2) their cost estimate was relatively consistent with other estimates found in the literature, and (3) their cost estimate was slightly higher than estimates in other studies, and thus generates conservative break-even yields. For this economic analysis, as in Breazeale et al. (2000), a theoretical 65-ha field was used; however, SDI spacing was assumed to be slightly narrower (90 cm rather than 100 cm) than used by Breazeale et al. (2000). Investment cost for the purchase and installation of the SDI system was therefore adjusted to account for more narrowly spaced drip lines. The narrower spacing required an additional 1,111 m ha^{-1} of drip line as well as additional fittings, which increased investment cost by approximately \$164 ha^{-1}, from \$2,980 to \$3,144 ha^{-1}.

The next step in the break-even analysis was to tabulate the annual total cost of producing alfalfa hay under SDI. Breazeale et al. (2000) cost data was again used with only slight modification. The investment cost of \$3,144 ha^{-1} was first depreciated over its 15 year useful life on a straight-line basis, such that the annualized investment cost (or depreciation cost) was \$210 ha^{-1}. The opportunity cost of invested funds, other fixed costs (e.g., land taxes and the annualized cost of establishing the alfalfa stand), and variable costs of alfalfa hay production summed to \$1,142 ha^{-1} (Breazeale et al., 2000). The total annual cost of SDI alfalfa hay production, assuming 90 cm SDI spacing, was therefore \$1,352 per hectare. Total cost does not include the cost of water, which varies widely throughout the western U.S. Additionally, it does not account for the investment and operating costs generated by the sprinkler irrigation system used in this study to germinate and establish the alfalfa stand. A fall-planted alfalfa stand would have to receive sufficient natural precipitation to germinate and become established. However, the cost estimates provided here offer a preliminary assessment of potential profitability, and can be adjusted to represent unique costs incurred or avoided by an individual producer.

The final step in the break-even analysis was to calculate the minimum yield required for total revenue to just equal total cost for a given output price. This was accomplished by dividing the total cost per hectare by the price received per Mg of alfalfa hay. Table 2 reports the break-even annual yields for various alfalfa hay prices.

Table 2 – Break-even yields (Mg ha^{-1}) for SDI alfalfa hay production, given alternative alfalfa hay prices.

		Price Received for Alfalfa Hay ($ Mg^{-1})				
Total Cost ($ ha^{-1})		$90	$100	$110	$120	$130
$1,352		15.0	13.5	12.3	11.3	10.4

The highest annual yield required to break even was 15.0 Mg ha^{-1} (or a total of 30 Mg ha^{-1} over two years), which occurs under a low output price of $90 Mg^{-1}. The average annual yield from the ×90 cm spacing SDI treatments for the two years of study was approximately 17.0 Mg ha^{-1}, which implies that the net return for SDI alfalfa production would be greater than zero at a low output price of $90 Mg^{-1}. Given a high output price of $130 Mg^{-1}, only 10.4 Mg ha^{-1} would be needed to break even. Net returns for SDI alfalfa hay assuming an output of 17.0 Mg ha^{-1} and an output price of $130 Mg^{-1} would equal about $900 ha^{-1}.

The above analysis indicates that alfalfa grown under a ×90 cm spacing SDI system would generate sufficient revenue to cover total cost. A producer could potentially enjoy large positive net returns if management and weather conditions similar to those in the experiment occurred. Management of a small plot differs, however, from that of an entire field, so yields at the field-level might be lower than those achieved in this study. Seed germination and the first month of alfalfa growth in the experimental plot, for example, was supported by sprinkler irrigation. The availability of a supplemental irrigation system for seed germination is unlikely in a commercial production setting, so yields might be lower. Field-level experiments and producer-led demonstrations are needed to determine, with more confidence, the profitability of SDI alfalfa at a commercial scale.

The break-even analysis indicates the potential for a producer to cover production costs of SDI alfalfa. However, it does not indicate whether net returns to SDI alfalfa exceed net returns to alfalfa grown under other irrigation systems, such as a center pivot. Cost data for center pivot-irrigated alfalfa were insufficient for a meaningful comparison to the cost data for SDI alfalfa provided in Breazeale et al. (2000). O'Brien et al. (1998) provided a detailed economic comparison of center pivot versus subsurface drip irrigation, but the analysis was for corn, rather than alfalfa. A more extensive meta-analysis of the existing literature, a companion study to Breazeale et al. (2000), or new enterprise budgets for southeast Wyoming would be necessary to address the relative profitability of alfalfa under alternative irrigation systems. Such efforts were beyond the scope of this project, and therefore remain an area for future research.

Summary and Conclusions

Field tests showed that the highest two year yield, 35.2 Mg ha^{-1}, was obtained in the 70 cm depth × 60 cm spacing SDI treatment, which was significantly different than all other treatments except the 70 cm depth × 90 cm spacing. The sprinkler and non-irrigated treatments had significantly lower yields than all SDI treatments. While the two highest yields were generated by the 70 cm depth treatments, results indicate narrower spacing (90 cm or less), irrespective of depth, produce greater alfalfa yields. HYRDUS-2D simulations show that both emitter spacing and depth influence root water uptake. This is in contrast to results from field measurements, which show that emitter spacing alone influences yield. Differences may be due to assumed root distributions in the simulations. The economic analysis indicated that alfalfa grown under a ×90 cm spacing SDI system would generate sufficient revenue to cover total cost. A producer could potentially enjoy large positive net returns if management and weather conditions were similar to those in this SDI study.

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Appendix A – Harvest Data

(See Figure 1 for Treatment Number Descriptions)

Treat	sub plot	repln.	2006_1	2006_2	2006_3	Total' 06 (Mg/ha)	2007_1	2007_2	Total'07 (Mg/ha)
1	1	1	7.77	4.73	4.50	17.00	8.39	6.11	14.49
1	1	2	6.56	5.80	3.43	15.78	6.86	5.76	12.62
1	1	3	6.65	5.28	4.41	16.34	6.45	6.29	12.74
1	1	4	5.90	5.27	2.89	14.06	7.21	6.52	13.74
1	1	5	5.53	5.07	5.01	15.61	8.50	7.28	15.78
1	2	1	7.86	6.56	4.24	18.66	9.11	5.63	14.74
1	2	2	6.54	4.83	3.95	15.32	8.79	6.54	15.33
1	2	3	7.44	4.72	4.36	16.52	7.80	6.65	14.45
1	2	4	7.52	6.13	3.86	17.50	6.39	5.23	11.62
1	2	5	8.06	5.83	3.60	17.49	7.79	8.20	15.99
1	3	1	9.17	4.99	4.82	18.98	6.93	7.08	14.01
1	3	2	7.21	5.76	4.76	17.74	9.90	7.41	17.32
1	3	3	7.72	6.59	4.40	18.71	7.66	8.53	16.19
1	3	4	5.66	5.20	5.42	16.27	8.90	7.02	15.93
1	3	5	6.50	4.98	4.76	16.24	8.09	5.68	13.77
2	1	1	6.65	6.84	4.00	17.49	7.47	6.31	13.79
2	1	2	6.88	6.68	4.49	18.06	7.58	8.25	15.83
2	1	3	6.04	5.74	3.98	15.75	8.69	5.06	13.75
2	1	4	6.23	5.60	4.39	16.22	8.63	7.14	15.77
2	1	5	9.68	6.22	4.75	20.65	8.10	6.81	14.91
2	2	1	7.99	6.28	5.22	19.49	7.52	6.57	14.09
2	2	2	9.53	6.70	3.92	20.15	6.63	8.34	14.97
2	2	3	7.64	7.29	4.72	19.64	7.88	6.63	14.51
2	2	4	5.44	6.23	4.32	16.00	6.78	6.10	12.89
2	2	5	7.33	6.62	4.52	18.48	9.26	6.03	15.29
2	3	1	6.52	4.83	4.35	15.70	10.26	6.50	16.76
2	3	2	7.28	6.41	4.55	18.24	9.19	8.60	17.79
2	3	3	9.88	5.54	4.80	20.22	8.37	6.39	14.76
2	3	4	7.04	7.98	4.38	19.39	9.93	6.57	16.50
2	3	5	9.08	6.19	4.39	19.66	8.35	7.44	15.79
3	1	1	6.85	6.30	5.82	18.97	7.71	7.95	15.66
3	1	2	8.88	6.20	4.87	19.94	7.97	6.41	14.37
3	1	3	7.65	5.66	5.29	18.60	6.26	6.94	13.20
3	1	4	7.30	5.71	5.94	18.94	7.88	8.33	16.21
3	1	5	8.44	5.94	4.83	19.22	8.76	6.78	15.54
3	2	1	8.19	7.32	5.49	21.00	8.86	5.74	14.60
3	2	2	6.81	6.64	4.95	18.40	10.25	6.44	16.69
3	2	3	7.85	5.16	5.24	18.26	9.93	7.75	17.67
3	2	4	5.21	5.98	5.02	16.22	8.13	6.63	14.76
3	2	5	8.84	6.28	5.24	20.36	9.29	9.12	18.41
3	3	1	6.87	5.15	5.44	17.46	10.30	5.30	15.61
3	3	2	6.70	6.41	4.66	17.76	9.20	6.17	15.37
3	3	3	8.88	6.21	5.44	20.54	9.70	5.95	15.64
3	3	4	8.64	5.58	4.58	18.80	10.15	5.94	16.09
3	3	5	9.01	5.85	5.24	20.11	8.17	7.09	15.25
4	1	1	5.57	5.86	5.17	16.60	8.79	6.77	15.56
4	1	2	6.49	5.24	6.58	18.32	8.26	7.14	15.40

4	1	3	6.41	5.73	4.80	16.94	8.52	7.00	15.52
4	1	4	5.19	5.54	5.71	16.44	8.68	7.63	16.31
4	1	5	5.67	6.77	4.88	17.32	7.11	5.29	12.40
4	2	1	7.84	7.04	7.47	22.36	8.68	7.72	16.40
4	2	2	6.16	6.28	6.32	18.76	7.11	8.12	15.24
4	2	3	4.83	5.71	4.94	15.49	7.90	7.27	15.18
4	2	4	5.74	5.29	6.03	17.06	9.09	7.09	16.18
4	2	5	6.64	5.83	5.05	17.52	8.25	8.15	16.40
4	3	1	7.37	6.45	6.87	20.69	7.87	5.64	13.52
4	3	2	4.88	4.53	4.92	14.33	7.05	7.70	14.75
4	3	3	6.56	5.60	6.08	18.24	7.39	6.07	13.46
4	3	4	5.62	6.19	4.54	16.35	8.95	6.33	15.28
4	3	5	5.98	6.41	6.09	18.48	6.66	6.62	13.28
5	1	1	6.42	4.79	5.70	16.91	8.73	5.61	14.34
5	1	2	4.96	6.58	4.94	16.48	10.08	5.95	16.03
5	1	3	4.79	5.07	6.14	16.00	10.11	4.84	14.95
5	1	4	5.76	5.24	4.73	15.73	7.96	6.34	14.30
5	1	5	6.45	5.42	6.45	18.32	10.12	7.92	18.04
5	2	1	6.09	5.24	5.75	17.08	7.13	7.46	14.59
5	2	2	6.16	5.55	5.44	17.16	8.14	6.50	14.63
5	2	3	5.33	5.46	5.37	16.16	9.63	5.91	15.53
5	2	4	5.18	6.07	6.10	17.35	9.17	8.04	17.21
5	2	5	5.74	5.58	6.86	18.18	9.09	5.91	15.00
5	3	1	5.16	6.15	4.50	15.81	9.27	8.04	17.31
5	3	2	4.86	6.25	4.92	16.04	9.71	8.90	18.61
5	3	3	5.98	7.00	3.98	16.96	9.54	6.11	15.65
5	3	4	4.81	6.27	5.48	16.56	9.08	8.69	17.77
5	3	5	6.84	6.44	3.95	17.24	8.34	4.77	13.11
6	1	1	9.07	7.80	4.52	21.40	9.96	7.14	17.10
6	1	2	9.29	6.46	5.86	21.61	6.43	4.23	10.66
6	1	3	6.62	6.71	4.73	18.06	8.17	6.79	14.96
6	1	4	6.82	8.02	5.08	19.92	8.79	4.28	13.07
6	1	5	7.01	7.25	5.19	19.45	8.82	6.39	15.20
6	2	1	7.01	7.37	6.50	20.88	9.04	7.82	16.86
6	2	2	8.62	7.86	5.25	21.73	8.83	6.77	15.60
6	2	3	6.48	6.80	4.60	17.88	9.87	6.69	16.55
6	2	4	8.16	6.72	5.72	20.59	7.71	7.49	15.19
6	2	5	8.98	7.18	6.59	22.75	8.89	5.92	14.81
6	3	1	8.25	7.46	5.68	21.39	8.14	7.46	15.60
6	3	2	7.05	6.31	5.04	18.40	7.32	6.36	13.68
6	3	3	6.68	7.74	5.88	20.29	8.79	7.61	16.40
6	3	4	7.60	6.80	4.74	19.14	8.40	6.74	15.14
6	3	5	6.32	7.06	4.98	18.36	8.63	7.02	15.64
7	1	1	8.01	6.29	5.92	20.22	6.27	5.21	11.48
7	1	2	7.53	5.26	5.74	18.53	7.28	7.37	14.65
7	1	3	6.27	7.20	5.73	19.20	7.70	6.76	14.46
7	1	4	6.89	5.28	5.74	17.92	9.28	5.83	15.12
7	1	5	6.15	5.98	5.84	17.96	9.78	6.40	16.18
7	2	1	8.15	4.98	5.42	18.56	7.50	7.72	15.22
7	2	2	7.04	5.92	6.83	19.79	5.81	8.20	14.00

7	2	3	6.88	5.30	6.47	18.64	9.45	7.61	17.06
7	2	4	8.63	5.91	6.02	20.56	8.22	8.39	16.62
7	2	5	7.10	5.53	5.99	18.62	6.64	7.42	14.06
7	3	1	6.87	5.49	5.53	17.90	7.89	6.20	14.08
7	3	2	6.38	5.88	5.75	18.01	8.11	6.84	14.94
7	3	3	7.83	5.42	6.02	19.27	7.92	5.31	13.23
7	3	4	9.26	6.26	5.08	20.60	7.94	7.06	15.01
7	3	5	8.24	5.81	6.41	20.46	7.69	4.59	12.27
8	1	1	7.86	5.11	4.15	17.13	8.17	8.00	16.17
8	1	2	6.70	5.69	4.02	16.40	8.09	8.30	16.39
8	1	3	8.80	5.17	3.36	17.32	8.34	7.07	15.41
8	1	4	8.38	6.51	4.91	19.79	8.25	7.11	15.36
8	1	5	7.53	5.64	4.35	17.53	7.45	7.50	14.94
8	2	1	7.82	6.74	5.80	20.36	7.80	5.65	13.44
8	2	2	7.11	6.20	4.41	17.72	6.98	6.24	13.22
8	2	3	8.23	6.10	5.14	19.47	6.94	8.99	15.94
8	2	4	6.08	5.98	4.90	16.97	6.89	7.65	14.54
8	2	5	9.04	6.27	5.74	21.05	8.33	5.85	14.18
8	3	1	7.40	6.01	7.38	20.79	8.47	6.38	14.85
8	3	2	6.85	5.59	6.56	19.00	7.88	7.05	14.93
8	3	3	5.48	6.01	5.08	16.57	9.34	7.04	16.38
8	3	4	6.50	6.68	5.88	19.05	9.08	5.79	14.87
8	3	5	6.43	6.06	3.90	16.38	9.88	7.61	17.49
9	1	1	7.65	7.66	5.41	20.72	8.28	6.59	14.87
9	1	2	8.05	5.61	4.22	17.88	8.45	7.84	16.29
9	1	3	7.60	5.78	4.54	17.92	9.51	5.62	15.13
9	1	4	7.16	6.77	4.27	18.20	9.08	7.54	16.62
9	1	5	7.09	6.50	4.34	17.92	8.77	8.12	16.89
9	2	1	7.63	5.86	4.46	17.95	8.92	5.83	14.75
9	2	2	6.72	5.43	4.40	16.55	7.53	4.86	12.39
9	2	3	7.98	5.98	5.22	19.18	7.58	6.48	14.06
9	2	4	7.27	5.41	5.17	17.85	9.04	6.79	15.83
9	2	5	7.30	5.70	4.99	17.99	6.82	9.70	16.52
9	3	1	6.98	5.33	6.36	18.68	9.42	5.24	14.66
9	3	2	8.26	5.81	5.24	19.31	8.44	6.52	14.97
9	3	3	7.46	5.51	4.29	17.26	7.80	8.13	15.93
9	3	4	6.48	4.99	5.52	16.99	8.56	8.55	17.11
9	3	5	6.51	5.41	6.76	18.68	8.16	6.36	14.52
10	1	1	4.90	6.63	5.21	16.73	7.65	6.11	13.75
10	1	2	6.50	5.59	4.76	16.86	6.87	6.31	13.18
10	1	3	4.11	4.65	5.23	13.99	7.32	7.08	14.40
10	1	4	5.01	5.36	4.69	15.06	6.10	5.77	11.87
10	1	5	4.68	5.74	4.80	15.21	6.95	5.87	12.82
10	2	1	4.82	4.45	4.76	14.03	6.99	6.19	13.19
10	2	2	4.94	4.30	4.14	13.38	7.18	7.89	15.07
10	2	3	4.68	4.37	4.83	13.88	6.52	5.81	12.33
10	2	4	4.79	5.31	5.62	15.72	6.10	8.03	14.12
10	2	5	4.86	4.55	4.13	13.54	6.13	6.52	12.65
10	3	1	4.74	6.20	4.84	15.78	6.10	6.74	12.85
10	3	2	5.50	4.10	4.90	14.51	8.22	9.19	17.41

10	3	3	4.37	4.66	5.77	14.80	6.55	7.40	13.96
10	3	4	5.96	5.53	5.28	16.77	7.77	7.01	14.78
10	3	5	5.68	4.60	5.14	15.42	7.84	6.81	14.65
11	1	1	4.19	3.80	5.57	13.56	7.99	6.16	14.15
11	1	2	4.33	6.10	5.15	15.58	5.46	5.70	11.16
11	1	3	3.28	4.46	4.74	12.48	6.95	6.64	13.59
11	1	4	4.16	3.84	4.38	12.39	5.00	5.66	10.67
11	1	5	4.55	4.54	4.74	13.83	5.48	8.13	13.62
11	2	1	4.18	4.72	3.91	12.80	6.29	6.17	12.47
11	2	2	4.83	5.03	3.81	13.67	6.26	7.44	13.70
11	2	3	4.42	3.91	4.78	13.11	7.69	7.08	14.77
11	2	4	4.66	4.47	4.63	13.76	6.65	6.38	13.03
11	2	5	4.72	4.19	3.42	12.34	7.22	4.62	11.84
11	3	1	4.66	4.58	4.77	14.01	8.54	7.57	16.11
11	3	2	4.50	4.32	4.52	13.34	7.75	7.49	15.24
11	3	3	5.07	3.99	4.72	13.78	6.19	9.04	15.23
11	3	4	4.32	5.48	3.83	13.63	7.80	6.63	14.42
11	3	5	4.07	4.47	4.28	12.81	6.62	7.51	14.12