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MICRO-IRRIGATION: ADVANCES IN SYSTEM DESIGN AND MANAGEMENT

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Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas

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Abstract Kansas State University initiated studies in 1989 to develop the methodology for successful application of subsurface drip irrigation (SDI) for corn production on the deep silt loam soils of the Central Great Plains, USA. Irrigation water use for corn can be reduced by 35–55% when using SDI compared with more traditional forms of irrigation in the region. Irrigation frequency has not been a critical issue when SDI is used for corn production on the deep silt loam soils of the region. A dripline spacing of 1.5 m has been found to be most economical for corn grown in 0.76 m spaced rows. Nitrogen fertigation was a very effective management tool with SDI, helping to maximize corn grain yield, while obtaining high efficiencies of nitrogen and water use. The research SDI systems have been utilized since 1989 without replacement or major degradation. SDI systems lasting 10–20 years are cost competitive for corn production with the more traditional forms of irrigation in the Great Plains for certain field sizes.

Introduction

Subsurface drip irrigation (SDI) for row crops has received an increased research effort in the last 20 years. Ayars et al. (1999) summarized SDI research results for row crops from 15 years of studies conducted in California by the USDA-ARS. Camp (1998) published an extensive review of SDI research covering both agronomic and horticultural crops as well as design and management considerations. Camp et al. (2000) reviewed some of the historical, present and anticipated future uses of SDI, concluding that research and manufacturing advances have allowed a greater use of SDI for a larger array of lower-value, commodity-type crops.

SDI has not been used extensively in the Great Plains (central USA) for field corn (*Zea mays*) production because of high initial costs and because of the uncertainty about SDI system life. However, with increasing concerns about water conservation and water quality protection, irrigators are looking for more efficient irrigation systems. Kansas State University (KSU) began a research program in 1989 to develop a management system for utilizing SDI for corn production. This paper will describe the results from several KSU research studies, including water use (timing, frequency, and amounts), deep percolation, nitrogen fertilization, dripline spacing; system uniformity in terms of long-term performance, system life, and economics. The KSU results will also be discussed in the context of other similar work at other locations. The research at KSU supplements a larger body of knowledge. In some cases, existing information about SDI use in other regions and with other crops has been transferable. In other cases, it has not. As in many parts of the world, the interaction of climate, soils, and crop production presents unique combinations that require local research to fine-tune the production systems.

Additional expansion of SDI in the Great Plains will depend on good, consistent management required to ensure long system life, and on system design, cost, crop prices, and physical and institutional constraints on water availability. KSU research has defined many of the technical management and design issues, and the adoption of SDI is increasing in the region.

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Procedures

This paper summarizes several studies conducted at the KSU Northwest and Southwest Research-Extension Centers at Colby and Garden City, Kansas, respectively. A complete discussion of all the procedures employed lies beyond the scope of this paper. For further information about the procedures for a particular study, the reader is referred to the cited reference. The following general procedures apply to all studies unless otherwise stated.

The study sites were located on deep, well-drained, loessial, silt loam soils. These medium-textured soils, typical of many western Kansas areas, hold approximately 480 mm of plant-available soil water in the 2.4 m profile at field capacity. The soil texture will allow deep-rooted crops, such as corn, to extract water from these depths if needed. The study areas were nearly level, with land slopes of less than 0.5% at Colby and 0.1% at Garden City. The continental (summer-dominant pattern for precipitation) climate can be described as semi-arid, with an average annual precipitation of 460 mm. The prevalence of precipitation during April, May, and June generally precludes stand establishment problems due to lack of rainfall. The permanent bed arrangement described below also limits the amount of tillage needed immediately prior to planting, thus retaining more seedbed soil water. Daily climatic data used in the studies were obtained from weather stations operating at each of the Centers.

The studies utilized SDI systems installed in 1989–1990 (Lamm et al. 1990). The dual-chamber, turbulent-flow, thin-wall dripline was installed at a depth of approximately 40–45 cm with a 1.5 m spacing between dripline laterals. Emitter spacing was 30 cm, and the dripline flow-rate was 1.86 l h^{-1} m^{-1}. The corn was planted so that each dripline lateral was centered between two corn rows (Fig. 1).

A ridge-till system was used in corn production, with two corn rows 76 cm apart on a 1.5 m bed for most study areas. Flat planting was used for the dripline spacing studies conducted at both locations because matching bed spacing to dripline spacing was impractical with the available tillage and harvesting equipment. Additionally, at Garden City, the corn rows were planted perpendicular to the driplines in the dripline spacing study. The corn was grown using the conventional production practices for each location. Unless otherwise indicated for a particular study, the conventional fertilization practices would be approximately 225 kg ha^{-1} of nitrogen and 45 kg ha^{-1} of phosphorus (P_2O_5). Corn seeding rates varied over the 10-year period from approximately 70,000 to 86,500 seeds ha^{-1}, with the higher seeding rates in the later years, reflecting corn hybrid advancement. Planting dates varied from around 20 April to 10 May, reflecting local weather conditions in a given year. Insecticides were applied at planting in every year. Tractor traffic was confined to the furrows.

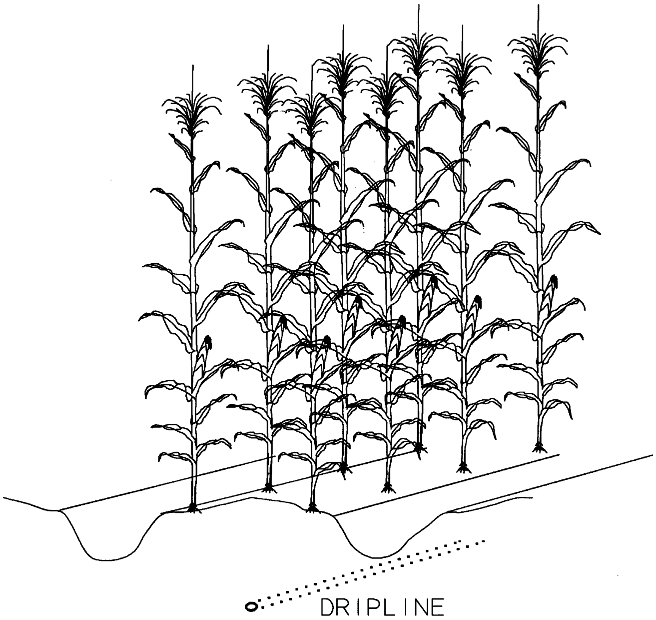

Fig. 1 Physical arrangement of the subsurface dripline in relation to the corn rows. Dripline is centered at a depth of 40–45 cm between two 76 cm spaced corn rows grown on a 1.52 m wide raised bed

Irrigation was scheduled for the studies using a water budget to calculate the root zone depletion, with precipitation and irrigation water amounts as "deposits" and calculated daily water use by corn as "withdrawals". Daily water use was calculated using a modified Penman equation and with crop coefficients calibrated for local conditions. Additional details on the specifics of the water-use calculations were given by Lamm et al. (1995a). The accuracy and validity of using this approach to calculating water use for this region were discussed by Lamm and Rogers (1983, 1985). Treatments were irrigated to replace 100% of their calculated root-zone depletion when the depletion was within the range of 20–35 mm. Soil water amounts were monitored with a neutron probe in 30 cm increments to a depth of 2.4 m approximately once a week during each crop season.

Results and discussion

Irrigation and water use

Water requirement of subsurface drip-irrigated corn

Research studies were conducted at Colby, Kansas from 1989 to 1991 to determine the water requirement of subsurface drip-irrigated corn. Irrigation treatments designed to replace 25, 50, 75, 100, and 125% of evapotranspiration were compared to a control treatment with no in-season irrigation. Corn yields were linearly related to calculated crop water use (Fig. 2); 0.048 Mg ha^{-1} of grain was obtained for each millimeter of water used above a threshold of 325 mm (Lamm et al. 1995a). The daily calculated water use was corrected for daily deep percolation calculated using procedures originally discussed by Miller and Aarstad (1974). More details of this calculation can be found in Lamm et al. (1995a).

The climatic conditions (cumulative evapotranspiration and precipitation) for the 3 years of the study can be characterized as near normal, but there were higher

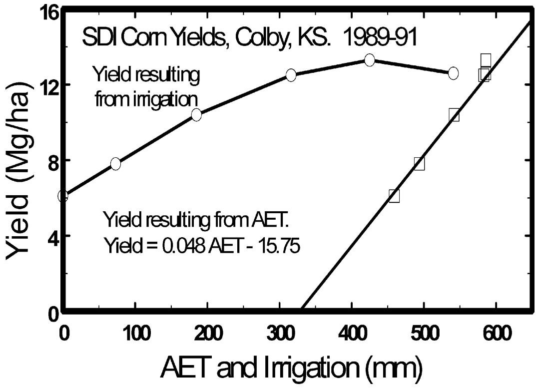

Fig. 2 Corn grain yield as related to cumulative irrigation and cumulative calculated evapotranspiration (*AET*) in a SDI study, Colby, Kansas, USA, 1989–91. Data from Lamm et al. (1995a)

than normal irrigation requirements due to the in-season timing of periods of high evapotranspiration and precipitation events (Lamm et al. 1995a). When compared with a long-term net irrigation requirement of 391 mm for irrigated corn (Soil Conservation Service 1977), careful management of SDI systems reduced net irrigation needs by nearly 25%, while still maintaining top yields of 12.5 Mg ha^{-1}. There was no further statistically significant increase in yield when irrigation was increased beyond 75% AET replacement (Figs. 2 and 3). This roughly coincides with a 25% reduction in irrigation from the long-term net requirement. The 25% reduction in net irrigation could translate into 35–55% savings when compared with sprinkler and furrow irrigation systems that typically operate at 85% and 65% application efficiencies, respectively. The application efficiency of a SDI system can approach 95–99% when carefully managed to limit soil evaporation and deep percolation losses. Indeed, these savings are similar to local producers' anecdotal reports of 50% irrigation savings with SDI compared with furrow irrigation. The relationship between corn yields and total irrigation was nonlinear (Fig. 2), primarily because of greater deep percolation for the heavier irrigation amounts (Fig. 3). The 25% reduction in net irrigation needs was associated primarily with the reduction of in-season deep percolation, a non-beneficial component of the water balance (Lamm et al. 1995a).

Although in-season precipitation and soil water storage provided a large amount of the cumulative calculated water use (AET was 459 mm for the nonirrigated treatment; Fig. 3), timely amounts of irrigation (316 mm) applied by the 0.75 AET treatment increased yields by 6.4 Mg ha^{-1}. This increase in yield only resulted in an additional 9 mm of deep percolation for the 0.75 AET treatment. Some of the 320 mm of irrigation for this treatment went into soil water storage on these deep silt loam soils, since the total AET was only 583 m. Other researchers have either reported higher corn yields or higher water-use efficiencies when using micro irrigation for corn. Clark (1979) compared the relative efficiencies of trickle, sprinkler, and furrow irrigation for corn production in Texas. He found irrigation water-use efficiencies (i.e., the ratio of crop yield increase to irrigation applied) of 0.0140, 0.0119, and 0.0115 Mg ha^{-1} mm^{-1} with the three respective systems. In a limited study in Italy, Safontas and di Paola (1985) reported yield increases of up to 35% with drip irrigation as compared with sprinkler irrigation for maize. Camp et al. (1989) evaluated drip irrigation for corn production in the southeastern Coastal Plain of the USA. They found that subsurface drip irrigation required less irrigation water than surface drip irrigation did.

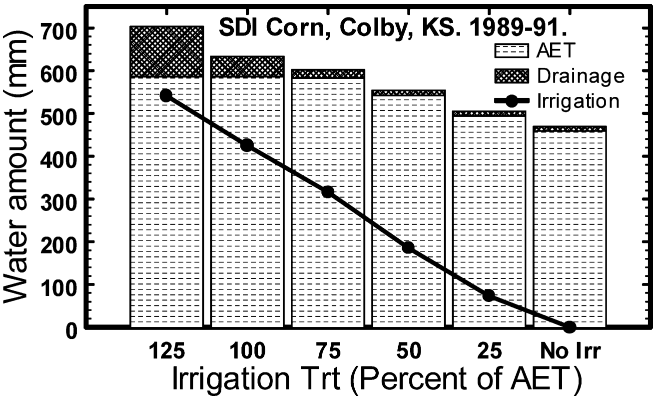

Fig. 3 Cumulative calculated evapotranspiration (*AET*) and seasonal deep percolation as related to irrigation treatment in a SDI study, Colby, Kansas, USA, 1989–1991. Data from Lamm et al. (1995a)

Frequency of subsurface drip irrigation

Typically, a smaller volume of soil is wetted with SDI than by other types of irrigation systems, and as a result, crop rooting may be limited. Crops may benefit from frequent irrigation under this condition. However, frequencies of 1, 3, 5, or 7 days produced similar high corn yields of 11.9–12.5 Mg ha^{-1} (Caldwell et al. 1994). Higher irrigation water-use efficiencies were obtained with the longer 7 day frequency because of better storage of in-season precipitation and because of reduction in deep percolation below the root zone (Caldwell et al. 1994). The results indicate little need to perform frequent subsurface drip irrigation events for fully irrigated corn on the deep silt loam soils of western Kansas. These deep soils and a deep-rooted crop such as corn have the ability to buffer out a large amount of temporal water stress that would normally occur on shallow-rooted crops on shallow soils. Although, high frequency is generally touted as a major advantage of micro irrigation, this is not the general case for corn in this region. Howell et al. (1997) also found that daily or weekly frequencies did not affect corn yields for either surface or subsurface drip irrigation on a clay loam soil in Texas. Camp et al. (1989) reported that irrigation frequency (continuous or pulsed irrigation) did not affect micro irrigated corn yields on loamy sands in the Atlantic Coastal Plain. Camp (1998) reviewed several SDI studies concerning irrigation frequency and concluded that some crops respond to high frequency on some soils and some do not. Horticultural crops on shallow or coarse-textured soils tend to respond more positively to more frequent irrigation. Some unpublished evidence indicates that daily irrigation events may be beneficial under deficit irrigation conditions where a slow, seasonal mining of the soil water is occurring or in cases where frequent fertigation is practiced. Several of the more advanced research studies currently underway at Kansas State University routinely utilize daily irrigation events.

Dripline spacing

Increasing the spacing of dripline laterals is one of the most important factors in reducing the high investment costs of SDI. Soil type, dripline installation depth, crop type, and the reliability and amount of in-season precipitation are probably the major factors that determine the maximum dripline spacing. Research studies at Colby and Garden City, Kansas, have determined that driplines spaced 1.5 m apart are most economical for corn grown in rows spaced 0.76 m apart on the deep silt loam soils of this semi-arid region (Lamm et al. 1997a; Manges et al. 1995). Wider dripline spacings of 2.1 or 3 m resulted in decreased yields and excessively deep percolation (Lamm et al. 1995b, 1997a; Darusman et al. 1997) but may have some application in regions having higher precipitation (Powell and Wright 1993). Higher seasonal precipitation levels can reduce the time period of water stress on the crop and the yield reductions resulting from wider spacings may be less than the costs associated with closer spacings. Camp (1998) concluded, after reviewing several SDI research studies, that alternate-row spacing of driplines (approximately 1.5 m) was adequate for most uniformly spaced row crops. Conceptually, optimum dripline spacing is related to the crop and its ability to explore for soil water in the root zone; the soil texturing and layering, and how soil water is redistributed; precipitation reliability to relieve water stress and the comparative costs of driplines, yield and possibly offsite environmental hazards of water movement. Two excellent discussions of how irrigation water application is affected by these factors are given by Seginer (1978, 1979).

Nitrogen fertilization

Because SDI systems have a high degree of uniformity when designed properly and can apply small amounts of irrigation frequently, they provide excellent opportunities to better manage nitrogen fertilization. Injecting small amounts of nitrogen solution into the irrigation water can “spoon-feed” the crop, while minimizing the pool of nitrogen in the soil that could be available for percolation into the groundwater. Bar-Yosef (1999) reported a number of potential agronomic advantages for fertigation with SDI over surface drip irrigation. They include

- nutrients supplied to center of root system
- drier soil surfaces and the reduced soil surface fertility help reduce weed germination
- roots grow deeper, thus buffering the plant against water and nutrient stresses.

In a study conducted at Colby, Kansas, no differences occurred in corn yields between preplant surface-applied nitrogen, and nitrogen injected into the driplines throughout the season. However, residual soil-nitrogen levels were higher where nitrogen was injected, suggesting that similar corn yields might be obtained at lower amounts of injected nitrogen (Lamm and Manges 1991). In a subsequent study, a best management practice (BMP) was developed for in-season nitrogen fertigation of corn (Lamm et al. 1997b). Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water-use efficiency (WUE) were utilized as criteria for evaluating six different nitrogen fertigation rates: 0, 90, 135, 180, 225, and 275 kg ha^{-1} of nitrogen. The resultant BMP was a nitrogen fertigation level of 180 kg ha^{-1}; other nonfertigation applications brought the total applied nitrogen to approximately 215 kg ha^{-1}. The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of AET, which will help limit leaching without reducing corn yield. Corn yield, ANU, and WUE all plateaued at the same level of total applied nitrogen, which corresponded to the 180 kg ha^{-1} nitrogen fertigation rate (Fig. 4). Average yields for the 180 kg ha^{-1} nitrogen fertigation rate were 13.4 Mg ha^{-1}. The ratio of corn yield to ANU for the 180 kg ha^{-1} nitrogen fertigation rate was a high 53:1. These results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

System life and economics

Typically, SDI has much higher investment costs than other pressurized irrigation systems such as full-sized, 50 ha, center pivot sprinklers. However, there are realistic scenarios where SDI can compete directly with center pivot sprinklers for corn production in the Central Great Plains (O’Brien et al. 1998). One example concerns decreasing field size (Fig. 5), because then the ratio of center pivot sprinkler costs to irrigated acres increases rapidly. Bosch et al. (1992) also reported similar economic competitiveness of micro irrigation with center pivot sprinkler irrigation for field sizes smaller than 60 ha.

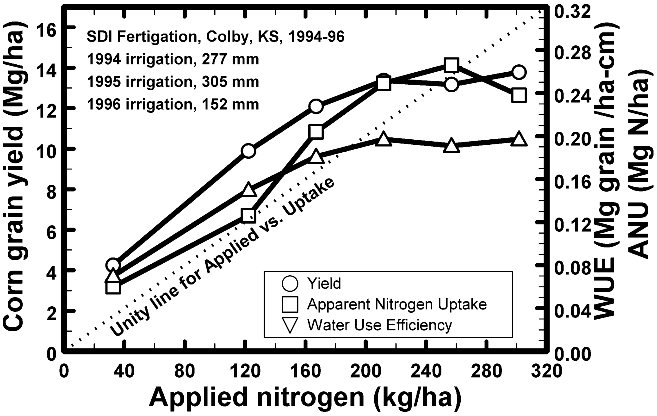

Fig. 4 Average (1994–1996) corn yield, apparent nitrogen uptake in the above-ground biomass, and water-use efficiency as related to the total applied nitrogen (pre-season amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation-applied nitrogen by 35 kg ha^{-1}. Note: Irrigation amounts varied between years. Adapted from Lamm et al. (1997b)

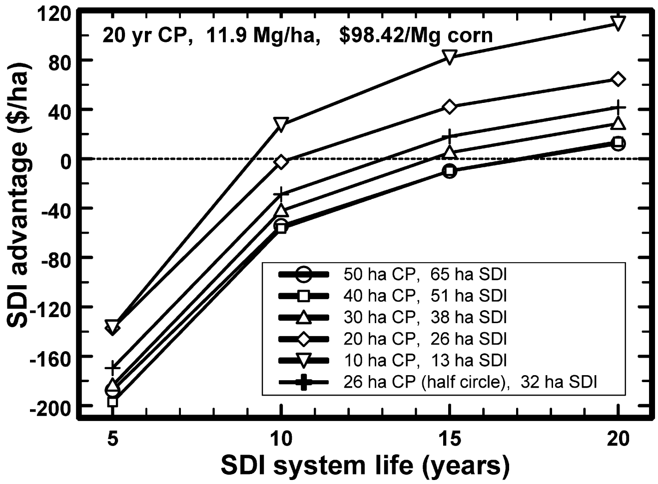

Fig. 5 Net returns advantage of SDI over center pivot (*CP*) sprinkler irrigation as affected by system size and SDI life. Assumptions are that CP system life is 20 years, average corn yield is 11.9 Mg ha^{-1}, and corn grain price is US$98.42 Mg^{-1}. Adapted from O'Brien et al. (1998)

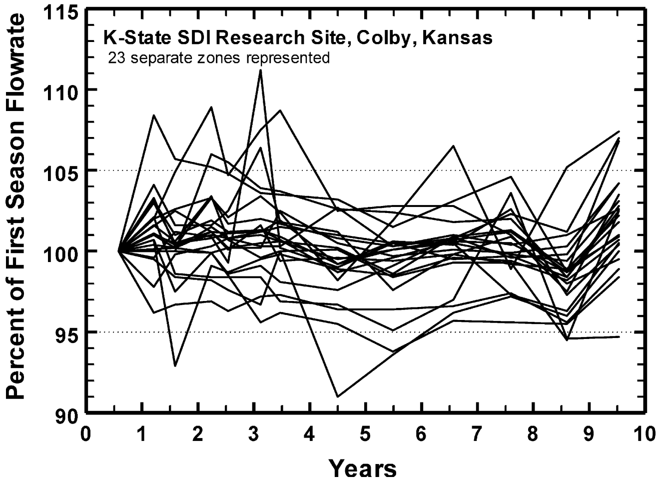

Fig. 6 Variation in zone flow-rates for 23 separate zones during the 10 year period from 1989 to 1998 at KSU SDI research site, Colby, Kansas

The life of a SDI system must be at least 10–15 years to reasonably approach economic competitiveness with full-sized, 50 ha, center pivot sprinkler systems that typically last 20 years (Fig. 5). Using careful and consistent maintenance, a 15–20 year SDI system life appears to be obtainable when high-quality water from the Ogallala aquifer is used. The system performance in KSU SDI research plots has been monitored annually since 1989. Pressures and flow-rates for each zone have been measured at the end of each irrigation season to allow comparisons of long-term flow-rate degradation. The time series representation of a study area (23 separate zones) at Colby, Kansas indicates that in the vast majority of cases, flow-rates did not vary by more than ±3% over the 10 seasons (Fig. 6). In fact, flow-rates at the close of 1998 were generally 0–3% higher than those in 1989. This study area has received shock chlorination approximately 2–3 times each season, but has not received any other chemical amendments such as acid or fertilizer. The water source at this site has a total dissolved solids (TDS) of 279 mg l^{1} hardness of 189.1 mg l^{-1}, and pH of 7.8. Traditional classifications would identify this water source as a moderate chemical plugging hazard (Bucks and Nakayama 1980). It is possible that the depth of the SDI system (0.40–0.45 m) may have reduced the chemical plugging hazards because of lower temperature fluctuations and negligible evaporation directly from the dripline.

Concluding statements

Research progress has been steady since 1989. In many, but not all cases, the Kansas research is achieving results similar to those from corn research conducted at other institutions. The KSU research attempts to supplement quality research conducted at many sites around the world. Some of these KSU research results are also transferable to other regions, particularly for similar type crops, soils, and climates. However, this relatively large block of regional research information is very useful to irrigators in this region not accustomed to micro irrigation. Irrigators are watching the results of KSU closely. Some irrigators have begun to experiment with the technology, and most appear happy with the results they are obtaining. The authors hope that KSU's development of a knowledge base in advance of the irrigator adoption phase can minimize the misapplication of SDI technology and overall system failures. Economics of the typical Great Plains row crops will not allow frequent system replacement or major renovations. Irrigators must carefully monitor and maintain the SDI system to assure a long system life.

Continued or new areas of research are concentrating on optimizing allocations of water, seed, and nutrients, utilizing livestock wastewater, developing preliminary information about SDI use with other crops besides corn, water and chemical application uniformity, and, finally, system design characteristics and economics with a view to improving system longevity.

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