UNIVERSIDADE FEDERAL DE LAVRAS

RAFAEL MENEZES PEREIRA

CROP EVAPOTRANSPIRATION, CROP COEFFICIENT AND IRRIGATION MANAGEMENT FOR SUGARCANE IN NICARAGUA

LAVRAS - MG
2022

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Dissertação apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Recursos Hídricos, área de concentração de Irrigação e Drenagem, para obtenção do título de Mestre.

Prof. Dr. Felipe Schwerz
Orientador
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Aprovada em 20 de junho de 2022

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RESUMO

A cana-de-açúcar é uma cultura de grande importância na economia da Nicarágua, participando com notável importância do PIB deste país. A pauta de sustentabilidade está cada vez mais ativa nas agendas das empresas e governos e a agricultura tem uma grande importância neste contexto. Desta forma, o uso racional dos recursos utilizados para a produção agrícola, em especial a água, deve ser utilizado de maneira cada vez mais racional. Cerca de 60% da cultura da cana-de-açúcar é irrigada em Nicarágua, contudo a falta de informação que apoiam uma melhor gestão hídrica e um melhor desempenho agronômico das culturas ainda é um desafio a ser superado. Portanto, dois experimentos foram conduzidos na usina Casur em solo vertissolo irrigado por sulco. No primeiro ensaio, usando o balanço hídrico de água no solo, se determinou a evapotranspiração da cultura, coeficiente da cultura e se comparou o Kc obtido nestes ensaios com os valores propostos pela FAO. Durante o experimento a evapotranspiração total da cultura (ETc) foi de 1346.6 mm, resultando em um Kc médio de 0.9. Os valores de Kc para os estádios fenológicos inicial, perfilhamento, rápido crescimento e maturação foram 0.37, 0.91, 1.11 e 0.71 respectivamente. Os valores de Kc propostos pela FAO superestimam em 11.89% os definidos localmente. Para o segundo experimento foram estabelecidos 2 turnos de rega, sendo o turno de rega variável, baseado na umidade do solo (ISw) e turno de rega fixo (IFI). Este último irrigado a cada 31 dias que é prática local. Foram avaliados em escala temporal parâmetros biométricos e de produtividade agrícola e os mesmos também foram medidos durante a colheita. Também foi medido a produtividade da água de irrigação e água total. Na escala temporal as plantas no tratamento IFI apresentaram crescimento compensatório, recuperando-se do estresse hídrico por falta de água praticamente em todas as variáveis biométricas. A produtividade agrícola foi estatisticamente diferente entre os tratamentos, onde ISw e IFI apresentaram 97.87 e 83.84 Mg ha-1 respectivamente. A eficiência do uso da água de irrigação e total foram similares para ambos os tratamentos. Baseado nos resultados encontrados, a determinação da ETc e Kc local assim como o a gestão de irrigação baseada na umidade do solo, são recomendadas para um uso racional dos recursos hídricos na Nicarágua. O estudo mostrou um menor requerimento hídrico frente a recomendação da FAO, uma melhor resposta agronômica da cana-de-açúcar irrigada com base na umidade do solo sem comprometimento da eficiência do uso da água.

Palavras-chave: Saccharum officinarum. Manejo de Irrigação. Crescimento Compensatório. Irrigação por sulcos. Produtividade da água

ABSTRACT

Sugarcane is a crop with great importance in the Nicaragua’s economy and has an important contribution to the country's GDP. The sustainability is a topic that is increasingly active on the agendas of companies and governments and agriculture is a big player in this context. In this way, it is very important to use rationally the resources destined for the crop production, in special the water. Almost 70% of the sugarcane field are irrigated in Nicaragua. However, the lack of information that supports better irrigation management towards better crop agronomical performance and water use efficiency, still a challenge to overcome in Nicaragua. Therefore, two experiments were carried out at the Casur sugarcane mill in a vertisol soil with furrow irrigation. In the first trial, using the soil water balance, the crop evapotranspiration and crop coefficient were determined and the values of Kc obtained was compared with those proposed by FAO. During the experiment, the total crop evapotranspiration (ETc) was 1346.6 mm. The Kc values for the growth phenological stage initial, tillering, grand growth and maturation were 0.37, 0.91, 1.11 and 0.71 respectively, resulting in an average of 0.9. The Kc values proposed by FAO overestimate those defined locally by 11.11%. For the second experiment, two irrigation strategies were established, one based on soil moisture content (ISw) and another with irrigation with fixed interval (IFI). The last one was watered every 31 days, which is local practice. Sugarcane yield and growth variables parameters were evaluated on a time scale and they were also measured during harvest. Irrigation and total water use efficiency was also measured. In the temporal scale, plants in the IFI treatment showed compensatory growth, recovering from water-deficit-stress due to lack of water in the soil, in almost all growth variables. Sugarcane yield was statistically different between treatments, where ISw and IFI presented 93.87 and 83.84 Mg ha^{-1} respectively. The irrigation and total water use efficiency were similar for both treatments. Based on the results found, the determination of local ETc and Kc, as well the irrigation management based on soil moisture are recommended for a rational use of water resources in Nicaragua. The study showed a lower crop water requirement compared to the FAO recommendation and a better sugarcane yield using the soil moisture content as irrigation strategy without compromising the water use efficiency.

Keywords: Saccharum officinarum. Water Management. Compensatory Growth. Crop Production. Water Use Efficiency. Furrow Irrigation.

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1. INTRODUÇÃO

A cultura da cana-de-açúcar (*Saccharum spp.*), é uma monocotiledônea da família das *Poaceae* cultivada em mais de 120 países segundo (Santos et al., 2019). Esta cultura é umas das fontes de energia renovável mais promissoras e eficientes na produção de biomassa ou matéria seca cujo produtos são amplamente utilizados mundialmente. Cerca de 75% do açúcar utilizado mundialmente é proveniente da cana-de-açúcar (Guo et al., 2021), contudo outros produtos de consumo humano são resultantes dessa planta como o álcool, melado, polietileno e etc. Não se pode deixar de mencionar que nos últimos anos a cogeração de energia elétrica proveniente do bagaço vem participando cada vez em maior proporção da matriz energética de vários países como fonte renovável de energia.

A cultura da cana-de-açúcar na Nicarágua tem grande importância na economia local. No ano de 2021, segundo o *Comité Nacional de Productores de Azúcar (CNPA),* foram moídas aproximadamente 6,8 milhões de toneladas de cana em uma área de 71,5 mil hectares gerando uma produtividade média no pais de 95.5 Mg ha^{-1} (CNPA, 2021). Segundo a mesma fonte, o setor sucroenergético nicaraguense gerou nesta safra mais de 136 mil empregos. Majoritariamente a cultura da cana neste país é cultivada sob algum sistema de irrigação, já que do ponto de vista agrometeorológico e econômico, existe a necessidade de irrigação suplementar para o completo desenvolvimento da cultura e maior rentabilidade. A cana-de-açúcar é uma cultura altamente demandante de água e o estresse hídrico em alguma etapa da cultura pode provocar sérias perdas de produtividade (Guo et al., 2021; Inman-Bamber and Smith, 2005; Santos et al., 2019).

Mundialmente a agricultura é responsável pelo consumo de cerca de 70% da água bombeada (FAO AQUASTAT, 2022). Além disso, estimasse que em 2005 havia mais de 306 milhões de hectares cultivados com irrigação (Siebert et al., 2015), acentuando ainda mais a necessidade do uso racional da água. Contudo, em virtude da crescente demanda de água pelos centros urbanos e industriais este recurso estará cada vez mais limitado para uso agrícola. Ainda que nos últimos anos a tecnologia tenha avançado notavelmente na agricultura, sua essência é muito dependente do clima em especial da disponibilidade hídrica, e a criação de novas fontes de água para exploração fica cada vez mais difícil seja por aspectos econômicos, sociais, regulatórios ou mesmo por disponibilidade hídrica. Sem deixar de lado as evidentes provas de mudanças climáticas que vem alterando o regime hídrico e outros parâmetros climatológicos de diversas regiões do globo. Segundo Gourdji et al. (2015) a américa central vem passando por mudanças climáticas que estão promovendo aquecimento desta região e chuvas menos frequentes além de mudanças no período chuvoso. De acordo com Dingre & Gorantiwar (2020) 80% da cana-de-açúcar é cultiva em regiões onde há algum histórico de escassez hídrica. Sendo assim, faz-se cada vez mais importante o uso de técnicas que permitam o uso adequado e eficiente dos recursos hídricos.

Uma das formas mais comuns de se manejar a irrigação é através da determinação do requerimento hídrico da cultura ou evapotranspiração da cultura (ETc) que por sua complexidade de estimação se determina indiretamente por duas etapas. Primeiramente se determina a Evapotranspiração de Referência (ET_0), cujo método chamado Penman-Monteith FAO é o mais amplamente aceito e logo se incorpora o coeficiente da cultura (Kc) que considera os detalhes da cultura (Allen et al., 1998).

Desta forma, foram conduzidos dois experimentos, sendo o experimento I cujo os objetivos foi determinar a ETc e Kc para a cultura da cana-de-açúcar cultivada em Nicarágua, e comparar o requerimento hídrico da cultura utilizando o Kc estimado localmente com o Kc proposto pela FAO-56. Já o experimento II teve como objetivo comparar a produtividade da cultura e variáveis morfofisiológicas em dois sistemas de planejamento de irrigação, sendo um com TRF - turno de rega fixo (calendário) e outro considerando a umidade do solo ou e a evapotranspiração de referência (ET_0), tratamento definido como TRV – turno de rega variável.

1.1. HIPÓTESE

Artigo I: A determinação local do consumo hídrico da cultura e de seu Kc para a cana-de-açúcar cultivada em solo vertissolo na Nicarágua, proporcionara o uso mais eficiente da água se comparado ao manejo utilizando dados médios propostos pela FAO-56.

Artigo II: O manejo de irrigação considerando a umidade disponível no solo em comparação ao manejo com turno de rega fixo, permitirá que a cana alcance uma resposta produtiva superior em parâmetros biométricos ou de crescimento e produtividade (Mg ha^{-1}). Além de aumentar a produtividade total da água (Mg ha^{-1} mm^{-1}).

1.2. JUSTIFICATIVA

Como na Nicarágua, assim como em outros países da américa central, a cultura da cana-de-açúcar é cultivada sob algum sistema de irrigação. Portanto, faz-se importante conhecer com mais detalhes e localmente tanto o consumo hídrico da cultura, o coeficiente da cultura assim como estratégias de manejo de irrigação para esta cultura, de forma a permitir o uso mais eficiente da água. Apesar do grande número de informações referente ao requerimento hídrico e Kc em cana-de-açúcar em vários lugares do mundo, estas informações básicas para o manejo de irrigação ainda não foram desenvolvidas para a região de Rivas em Nicarágua. Portanto, estudos como este, podem permitir que agricultores, empresa e seus técnicos tomem decisões mais assertivas quanto ao manejo de irrigação, subsidiando uma produção mais sustentável do ponto de vista de pegada hídrica. Além, da responsabilidade técnica do presente estudo, devido à falta de publicações e instituições de pesquisa na área de irrigação e manejo de água em Nicarágua, este trabalho toma também a importância social no contexto de acesso a informação.

2. OBJETIVOS

2.1.1. OBJETIVO GERAL

Quantificar a evapotranspiração da cultura (ETc) e o coeficiente da cultura (Kc) para cana-de-açúcar cultivada em solo vertissolo na Nicarágua assim como comparar dois métodos de manejo de irrigação, um baseado em turno de rega fixo e outro considerando a umidade no solo e sua resposta na produtividade da cultura.

2.1.2. OBJETIVOS ESPECÍFICOS

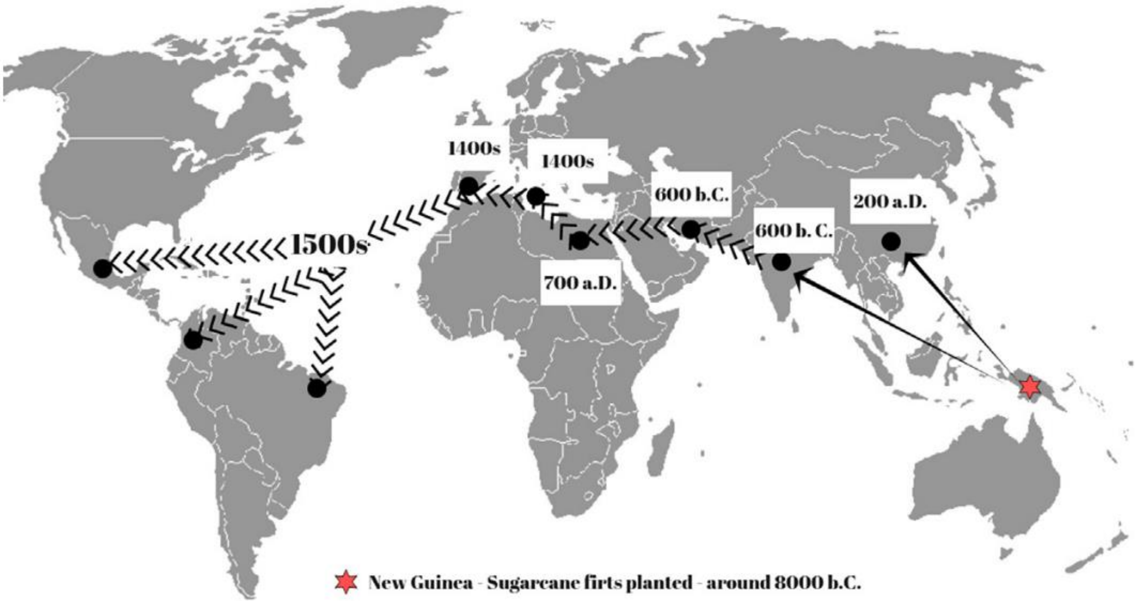
- Determinar a evapotranspiração da cultura (ETc) e o coeficiente da cultura (Kc) para a cultura da cana-de-açúcar cultivada em solo vertissolo na Nicarágua para os estádios de brotação, perfilhamento, rápido crescimento e maturação;
- Comparar os valores de Kc determinado localmente com o proposto pela FAO-56;
- Avaliar a produtividade da cultura (Mg ha^{-1}) em termos de matéria fresca em ambos os manejos de irrigação;
- Avaliar as variáveis de biométricas ao longo do ciclo da cana-de-açúcar cultivada nos dois manejos de irrigação;
- Determinar a produtividade da água (Mg ha^{-1} mm^{-1}) em ambos os manejos de irrigação.

3. REVISÃO DE LITERATURA

3.1. A cultura da cana-de-açúcar

A cultura da cana-de-açúcar (*Saccharum spp.*), é uma monocotiledônea da família das Poaceae, perene, cultivada em mais de 120 países segundo (Santos et al., 2019). Seu centro de origem foi uma constante disputa entre Papua Nova Guiné e Índia, contudo como algumas espécies de *saccharum* ainda são encontradas em Papua Nova Guiné, se considera este seu centro de origem (Matos et al., 2019). Historicamente a cana passou por vários países e continentes antes de chegar ao novo mundo. Estima-se que a primeira menção sobre a cana-de-açúcar é de aproximadamente 8.000 anos antes de cristo em e chegou as américas em aproximadamente 1500 d.C. assim como mostra a figura 1.

Figura 1. Caminho da cana-de-açúcar desde sua origem até a chegada nas Américas.



Fonte: Adaptado de Matos et al., (2019)

A cana-de-açúcar, atualmente segundo (FAO, 2020), ocupa uma área global de 26,4 milhões de hectares aproximadamente. Sendo uma planta, cujos colmos são fibrosos e armazenam sacarose, esta planta é muito versatilidade já que é utilizada para a produção de vários produtos e subprodutos em sua cadeia produtiva. Cerca de 75% do açúcar consumido mundialmente é proveniente de cana (Guo et al., 2021) contudo, como mencionado anteriormente, outros produtos são muito importantes como o etanol, melado e alguns subprodutos como a torta de filtro e vinhaça, ambos utilizados como fertilizantes ricos em matéria orgânica e outros nutrientes, e o bagaço, biocombustível fonte principal para geração de energia elétrica nas usinas cogeradoras.

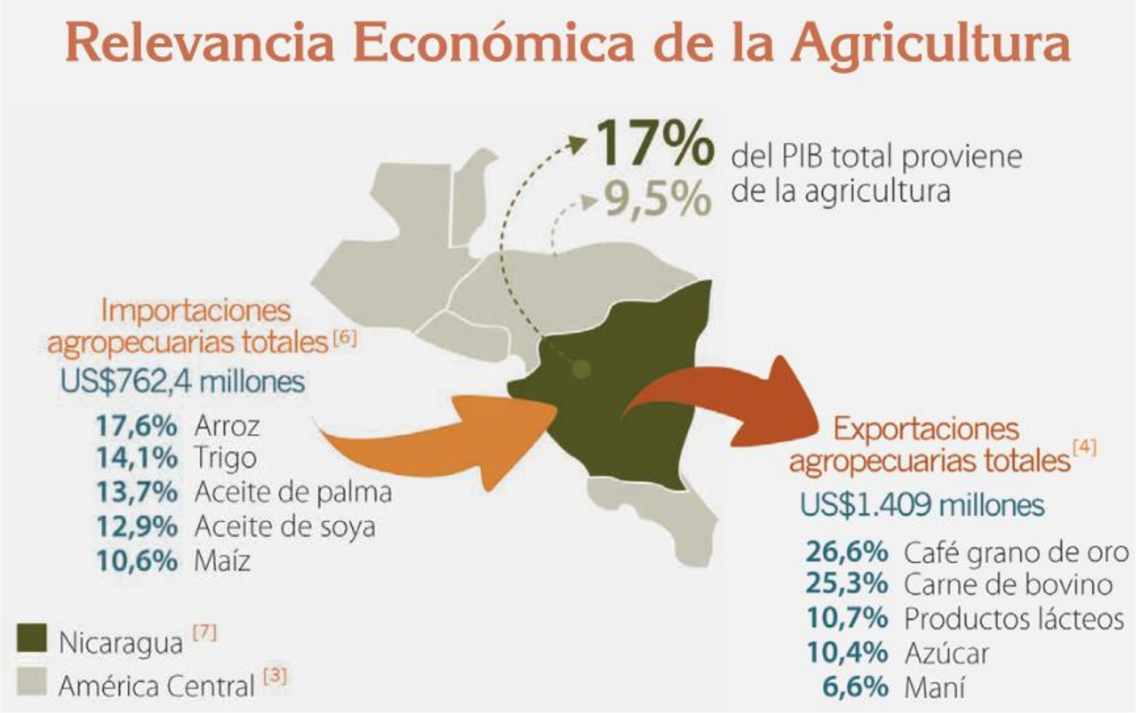
2.1.1 A cultura da cana-de-açúcar na Nicarágua

A agricultura, incluindo pesca e silvicultura é um dos setores de maior importância na

Nicarágua, participando em cerca de 8-9% do PIB e a agricultura representa cerca de 77% das exportações totais (CIAT, 2015). A figura 2 ilustra em um infográfico a participação da agricultura no PIB da Nicarágua, mencionando de forma individual algumas culturas dentro delas a cana-de-açúcar que representa 10,4% das exportações totais agrícolas do país.

No ano de 2021, segundo o *Comité Nacional de Productores de Azúcar (CNPA)*, foram moídas aproximadamente 6,8 milhões de toneladas de cana em uma área de 71,5 mil hectares gerando uma produtividade média no pais de 95.5 Mg ha^{-1} (CNPA, 2021). Segundo a mesma fonte, em seu sítio web, o setor sucroenergético nicaraguense gerou nesta safra mais de 136 mil empregos.

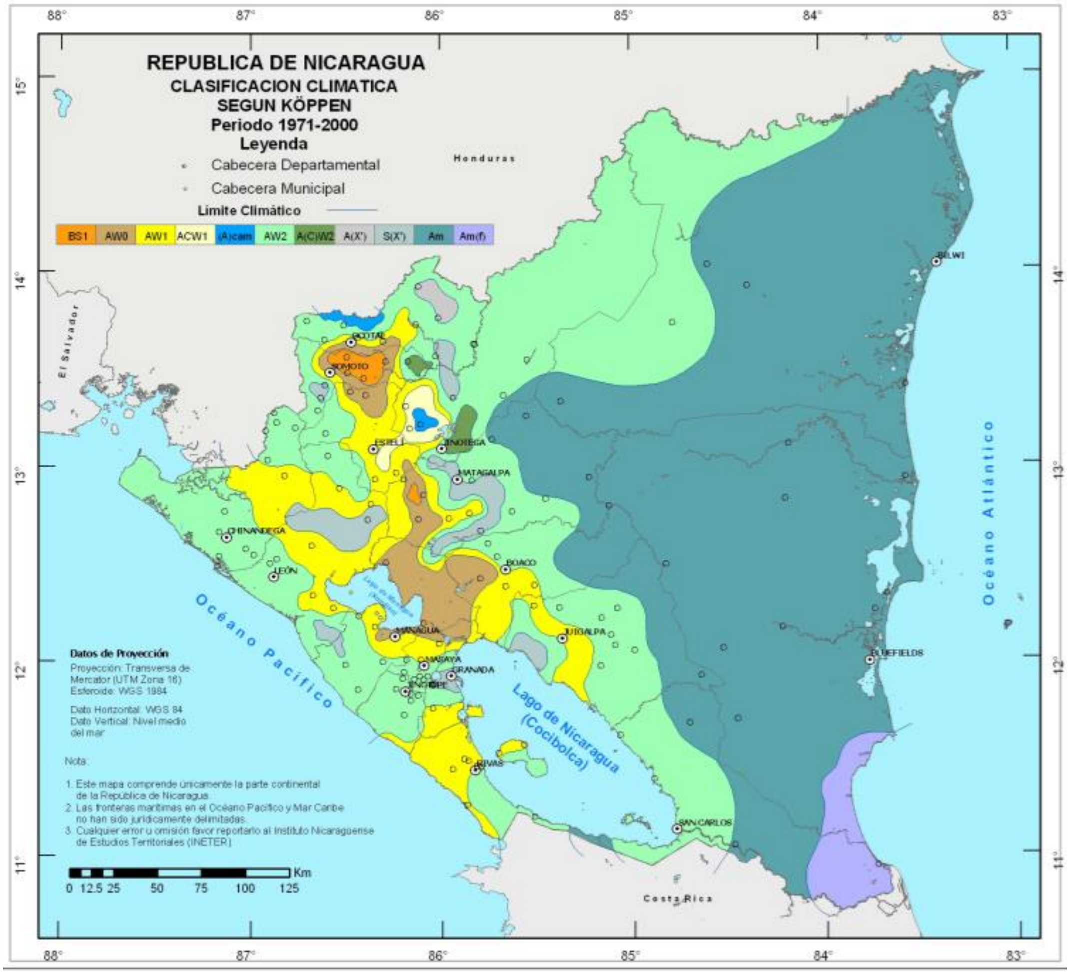
Figura 2. Infográfico ilustrando a relevância da agricultura para a economia em Nicarágua.



Fonte: (CIAT, 2015)

A cana-de-açúcar está localizada majoritariamente na região do pacifico de Nicarágua onde também está o departamento de Rivas. Segundo o *Instituto Nicaraguense de Estudios Territoriales – INETER* esta região, de acordo com a classificação de Köppen, é classificada com clima do tipo Aw, com estação seca de novembro a abril e chuvosa de maio a outubro, com precipitações variando de 600 a 2.000 mm por ano (Figura 3)

Figura 3. Classificação climática segundo Köppen de Nicarágua para o período de 1971 a 2000.



Fonte: Adaptado de INETER (2005).

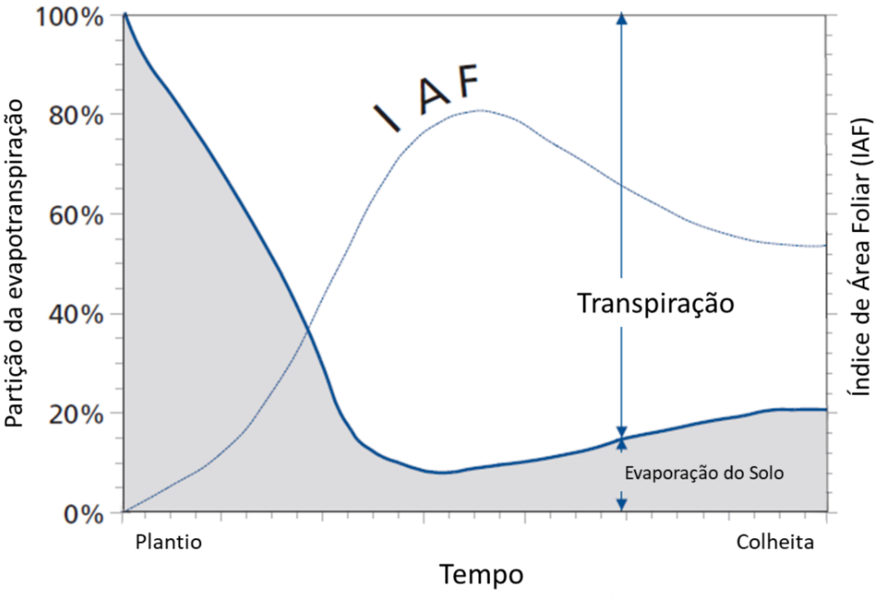
Com clima onde durante 6 meses é comum não haver precipitação pluvial ou muito inferior a evapotranspiração, ventos fortes e intensa radiação solar a evapotranspiração das culturas se faz intensa e é necessária irrigação suplementar em várias culturas. Segundo CIAT (2015), cerca de 72% da área agrícola equipada com sistema de irrigação em Nicarágua está operando com irrigação (Figura 4), confirmando a necessidade de irrigação na agricultura nicaraguense. Segundo a FAO AQUASTAT (2022), Nicarágua possui apenas 11,12% de sua área cultivada com irrigação e desta área, 98% é irrigada por superfície.

3.2. Evapotranspiração (ET)

Evapotranspiração é a combinação do processo de evaporação da água do solo ou da superfície das plantas para a atmosfera e a transpiração que é o movimento de água líquida do solo até a as folhas através do interior das plantas, posteriormente liberada a atmosfera na forma gasosa (Allen et al., 1998; Quej et al., 2019). Ambos processos ocorrem simultaneamente e são difíceis de se distinguir, contudo é sabido que a medida que a cultura vai aumentando sua área foliar, ocorre a redução da incidência de radiação solar sobre o solo por maior cobertura do dossel, ocasionando aumento da taxa de transpiração sobre a evaporação do solo, conforme ilustrado na figura 5.

Este processo é vital para a atividade das plantas, já que é o responsável por sua hidratação e também está diretamente relacionado com as trocas gasosas e acumulo de CO_2 e consequentemente produção de biomassa (Pimentel, 2004). Segundo Pimentel (2004), o princípio da relação entre evapotranspiração e produtividade de matéria seca é que quanto maior a transpiração da planta, maior será sua permanência com estômatos abertos o que permitirá uma maior entrada de CO_2 que será utilizada na fotossíntese.

Figura 4. Partição da evapotranspiração em evaporação e transpiração durante um período agrícola de uma cultura anual.



Fonte: Adaptado de Allen et al. (1998).

3.2.1. Evapotranspiração de Referência (ET_0)

A evapotranspiração de referência (ET_0) traduz a demanda hídrica da atmosfera, independentemente da cultura, estádio fenológico e manejo agronômico. Existem vários métodos que estimam a ET_0, como os propostos por Thornthwaite (1948), Hargreaves e Samani (1982, 1985), Papadakis (1966) e Hamon (1963) os últimos três citados por (Quej et al., 2019). Contudo o método de Penman-Monteith recomendado pela FAO-56 (PM-FAO) é o mais amplamente aceito e utilizado (Quej et al., 2019; Song et al., 2019).

O método de PM-FAO, aborda parâmetros aerodinâmicos e radiativos, considera como cultura de referência uma grama hipotética, entre 8 a 15 cm de altura, extensamente vegetada com cobertura total do solo e sem restrições hídricas (Allen et al., 1998). Sendo, portanto, função exclusiva de variáveis meteorológicas (Marin, 2021), pode ser usada como elemento comparativo entre diferentes lugares e diferentes condições climatológicas. A equação proposta por Allen et al. (1998) PM-FAO, está exemplificada na equação 1.

$$\mathrm{ETo}=\frac{0{,}408.\Delta(R_n\text{-}G)+\gamma\left(\frac{900.U_2}{T+273}\right)(e_s\text{-}e_a)}{\Delta+\gamma(1+0{,}34.U_2)} \tag{1}$$

Nesta equação, a ET_0 está em escala diária e sua unidade de medida é expressa em (mm dia^{-1}). Dentro das variáveis necessárias para sua estimação e suas respectivas unidades de medidas tem-se a (Rn) ou saldo de radiação, (G) que é a densidade do fluxo de calor no solo e ambos são expressos em MJ m^{-2} dia^{-1}; (Δ) que é a declividade da curva de pressão de saturação do vapor d’água medida em kPa $°C^{-1}$; (U_2) ou velocidade do vento em (m s^{-1}) medida a 2 metros da superfície do solo; (T) é a temperatura do ar em °C; (e_s) é a pressão de saturação do vapor de água, (e_a) é a pressão real do vapor, ambos medidos em kPa e por fim (γ) que é a constante psicrométrica medida em MJ kg^{-1}.

3.2.2. Evapotranspiração da cultura (ETc) para cana-de-açúcar

Assim como a ET_0 representa a demanda hídrica da atmosfera, a ETc representa a evapotranspiração de uma cultura agrícola sem interferência de patógenos ou pragas, bem nutrida e hidratada, com umidade do solo suficiente para manter seu metabolismo, cultivada em campo amplo com objetivo de alcançar o máximo potencial produtivo sob as condições climatológicas locais (Allen et al., 1998; Win and Zamora, 2014). É muito comum que o termo ETc e requerimento ou demanda hídrica da cultura sejam utilizadas como sinônimos e mesmo que ambos os valores sejam idênticos, o primeiro indica a quantidade de água liberada a atmosfera através do processo evapotranspirativo enquanto o segundo indica a quantidade de água que deve ser suprida a cultura.

A estimativa da ETc é um processo que envolve a determinação de parâmetros fisiológicos complexos e trabalhosos como albedo, resistência estomática, dossel e etc, para os diferentes estádios fenológicos, tipos de manejo, culturas e etc. Desta forma, a maneira mais usual de se estimar a evapotranspiração da cultura atualmente é pelo método de 2 etapas, no que consiste: (1) determinação da ET_0 utilizando o método mais adequado conforme a disponibilidade de informações climatológicas e (2) multiplicação pelo coeficiente da cultura ou Kc (Allen et al., 1998; Dingre and Gorantiwar, 2020).

A cana-de-açúcar é umas das culturas que tem alto requerimento hídrico, devido sua alta capacidade de produção de biomassa, porém é amplamente cultivada em países, que ironicamente, apresentam alguma restrição hídrica (Dingre and Gorantiwar, 2020). Segundo o mesmo autor, esta é umas das razões pela qual é importante se determinar a ETc em diferentes estádios fenológicos, pois permitirá o uso eficiente dos recursos hídricos destinados a irrigação.

Vários trabalhos foram desenvolvidos com diversas metodologias com o objetivo de estimar a evapotranspiração da cana-de-açúcar. Ainda que em muitos casos, a irrigação suplementar supere os 2000 mm durante o ciclo da cultura seu consumo não ultrapassa este valor (Dingre and Gorantiwar, 2020).

3.3. Coeficiente da cultura (Kc) para cana-de-açúcar

O coeficiente da cultura (Kc) é a razão entre a evapotranspiração da cultura (ETc) e a evapotranspiração de referência (ET_0). Portanto este coeficiente ajusta a demanda evapotranspirativa da atmosfera e a converte em evapotranspiração da cultura. Onde outrora eram considerados apenas parâmetros climatológicos (ET_0) agora abrange detalhes associados a cultura ($ETc = ET_0 \times Kc$) distinguindo-a da grama hipotética.

Como mencionado o Kc abrange detalhes inerentes a cultura e ao manejo agronômico e como as plantas se desenvolvem e crescem cumprindo um determinado ciclo. Uma série de alterações morfofisiológicas ocorrem nesse período, provocando variações na área foliar, aumento de altura, mudança de estado vegetativo para reprodutivo (floração ou inflorescência), frutificação, senescência e etc.. Desta forma é fundamental que este coeficiente seja definido para os diferentes estádios fenológicos e condições ambientais.

Vários trabalhos foram desenvolvidos com objetivo de se determinar o Kc para a cana em suas diferentes etapas fenológicas ao redor do globo, alguns exemplos são encontrados na tabela 1. Em média, para as 3 principais etapas fenológicas da cana-de-açúcar, inicial, médio e final de valores de Kc de 0,41, 1,10 e 0,95 respectivamente.

Tabela 1. Valores de Kc para cana-de-açúcar em estádio inicial, médio e final encontrados por diversos autores em Myanmar, Índia, Brazil e os propostos pela FAO.

Fonte	Inicial	Médio[1]	Final
	Valores de Kc		
(Allen et al., 1998)[2]	0,40	1,25	0,75
(Dingre and Gorantiwar, 2020)	0,40	1,20	0,78
(Win and Zamora, 2014)	0,53	1,25	1,27
(Albuquerque, 2012)[3]	0,15	0,81	0,80
(Albuquerque, 2012)[4]	0,31	1,35	1,25
(Silva et al., 2012)	0,65	1,10	0,85
(Peres, 1988)[5]	0,41	0,73	0,94
Médias	0,41	1,10	0,95

Fonte: Do Autor (2022)

3.4. Manejo de irrigação

O manejo da irrigação constitui-se de um conjunto de procedimentos que visa atender adequadamente as necessidades hídricas da cultura, propiciando o desenvolvimento da cultura e a expressão máxima de sua produtividade. Existem três processos básicos para se conduzir o manejo das irrigações: processos baseados nas condições climáticas, de água do solo e de água nas plantas. Pode ser feita também a conjugação do controle da irrigação via demanda hídrica atmosfera e via solo, o que é desejável, uma vez que os métodos de controle são por estimativas (Silveira et al., 2009).

3.4.1. Turno de rega fixo e variável

Segundo Zonta et al. (2009) os benefícios da irrigação para uma determinada cultura só podem ser alcançados de forma plena quando o sistema for utilizado com critérios de manejo que resultem em aplicações de água em quantidades compatíveis com as necessidades de consumo da cultura. Para que isto ocorra, existem várias formas de se planificar a irrigação que envolvem o turno de rega variável ou fixo.

O termo turno de rega é o período ou intervalo, geralmente em dias, em que serão executados os eventos de irrigação e os adjetivos fixo ou variável reflete como este programa de irrigação será conduzido.

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[1] Considerada etapa de rápido crescimento entre 130 e 300 dias após plantio ou brotação.
[2] Valores médios estabelecidos pela FAO em seu boletim número 56.
[3] Valores para cana soca de segundo ciclo cultivada em sequeiro.
[4] Valores para cana soca de segundo ciclo cultivada sob irrigação.
[5] Valores utilizando PM-FAO como estimador de ET_0.

O turno de rega variável (TRV), geralmente é acompanhado de lâmina de água fixa e exige uma maior mediação de dados em campo, já que é necessário acompanhar a depleção do armazenamento de água no solo. Quando a umidade ou tensão chegar a um valor limite para a cultura a irrigação deve ser feita, sempre repondo a mesma lâmina perdida por ET. Para tanto, é necessário o uso de sensores analógicos ou digitais como tensiômetro, TDR, sonda de umidade ou medições mais trabalhosas como umidade gravimétrica, de forma a permitir acompanhar depleção deste parâmetro até valores limites que não comprometam a produtividade da cultura. O TRV em comparação ao TRF exige maior custo de implementação, já que são necessários sensores ou avaliações periódicas, além de maior custo de mão-de-obra para instalação e leitura dos equipamentos. Segundo Monte et al. (2009) tais características não agradam os produtores que preferem adotar o turno de rega fixo (TRF).

O TRF tem maior praticidade, pois permite que a irrigação seja feita por calendário fixo ou datas programadas, porém o operador deve conhecer o déficit hídrico do solo para que seja aplicada a lâmina d’água capaz de repor a umidade deste solo (Silveira et al., 2009), por isto o TRF tem lâmina variável. Para o manejo adequado do TRF é imperativo o conhecimento da Água Disponível Total no solo – ADT, Água Disponível Real – ADR, Fator de Disponibilidade Hídrica – f, Evapotranspiração de Referência – ET_0, Coeficiente da Cultura – Kc, Evapotranspiração da Cultura – ETc e Lâmina Bruta – LB.

Nota-se que para ambos os métodos, o controle da lâmina de irrigação é fundamental, pois um equívoco ou repetidos equívocos na quantidade de água a ser reposta, pode comprometer o resultado da produção em termos de produtividade ou rentabilidade.

Na Nicarágua não é comum o conhecimento destas constantes, que são determinantes para o manejo adequado da irrigação, por parte de muitos produtores menos ainda seu monitoramento sistemático. Portanto é comum o uso do TRF sem o controle efetivo da lâmina de água, principalmente pelo fato de se utilizar extensamente a irrigação por sulcos, que inerente ao método, aplica lâminas com altos volumes e baixa uniformidade.

3.4.2. Irrigação por Superfície: Irrigação por sulcos

Irrigação por superfície é um dos métodos mais antigos da história, datando de mais de 6.000 anos a.C. na antiga Mesopotâmia (Marlow, 2012; Sojka et al., 2002; Walker, 1989). Dentro desse método existem diferentes configurações como a irrigação inundação, por faixa e por sulcos. O método de irrigação por superfície tem por princípio de aplicação da lâmina de água usando a gravidade como força promotora do avance da água. Portanto, esta flui no campo por diferença de declividade, onde entra pela parte mais alta e escoa pela superfície do solo até o ponto mais baixo do terreno.

No caso da irrigação por sulcos, o princípio é o mesmo, contudo a água flui por canais (sulco), onde este tem espaçamento, forma, declividade e distância definida. A figura 6, mostra um campo cultivado com cana-de-açúcar irrigado por sulcos na usina Casur na Nicarágua.

Figura 5. Irrigação por sulco em solo vertissolo na Usina Casur, Nicarágua.

Fonte: Do Autor (2022)

Este sistema é amplamente utilizado em diversas culturas e em vários países do mundo, principalmente em função do baixo custo de investimento inicial e pela menor complexidade em sua operação. Estima-se que de toda área irrigada no globo, a grande maioria desta é irrigada por superfície (Eldeiry et al., 2005; Varshney, 1995). Na tabela 2 se pode observar que a participação da irrigação por superfície nos continentes é expressiva, sendo que em todo globo este método representa cerca de 78% da área irrigada.

Tabela 2. Estimativa da fração (%) de irrigação em relação a área total irrigada por método, área total irrigada e área irrigada (%) em relação a área total cultivada por continente.

Continente	Fração por método de irrigação (%)			Área total com Irrigação (Mha)	Área total Cultiva (Mha)	Área irrigada (%)
	Localizada	Aspersão	Superfície			
África	12.15	16.90	52.54	14,289.92	276,988.22	5.16
América	10.27	30.63	54.14	53,509.53	368,597.26	14.52
Ásia	1.42	3.77	92.25	232,146.71	590,473.20	39.32
Europa	15.14	38.49	18.93	22,874.88	288,341.27	7.93
Oceania	7.54	36.70	55.62	3,042.33	32,565.70	9.34
Total	4.36	11.50	78.76	325,863.37	1,556,965.65	20.93

Fonte: (FAO AQUASTAT, 2022) Adaptado.

Embora seja o método mais antigo e mais utilizado, cerca de 78% da área total irrigada, este não é o mais eficiente. Sua eficiência oscila entre 30 a 80% enquanto em métodos de irrigação localizado este valor pode ser superior a 90% (Eldeiry et al., 2005; Marlow, 2012; Varshney, 1995). Várias técnicas podem ser utilizadas para aumentar a eficiência aplicação no método de irrigação por sulcos, tais como:

a) Irrigação por sulco alterno;
b) Reutilização de escoamento superficial em campos subsequentes;
c) Minimização de desnível nos sulcos;
d) Irrigação por pulso;
e) *Cutoff* antecipado;
f) Uso de tubos janelados;
g) Uso de sifão;
h) Nivelação de terreno.

Ainda que apresente vantagens do ponto de vista econômico e operacional, da perspectiva técnica ainda existem grandes oportunidades de melhora. Existe a exigência de acondicionamento do terreno onde os sulcos devem ser dispostos em declividade para que a água de irrigação flua e esta mesma declividade pode ocasionar erosão, caso não existam práticas de manejo conservacionista ou controle de vazão de entrada de cada sulco (Fernandez-Gomez et al., 2004).

3.5. Irrigação em cana-de-açúcar: Componentes de produtividade

A cana-de-açúcar é uma cultura de alta demanda hídrica e o estresse hídrico por falta de água pode provocar serias perdas de produtividade (Inman-Bamber and Smith, 2005; Santillán-Fernández et al., 2016; Santos et al., 2019). O estresse hídrico provoca alterações morfológicas e fisiológicas afetando o balanço de carbono, crescimento de parte aérea e radicular e etc., comprometendo seu balanço energético e consequentemente potencial produtivo (Barbosa et al., 2015; Inman-Bamber and Smith, 2005).

Estudando o efeito de diferentes tensões no solo como parâmetro para irrigação em cana no México, Carrillo-ávila et al. (2016) obtiveram 134,72 contra 53,37 Mg ha^{-1} em cana irrigada contra sequeiro. Também em México, Santillán-Fernández et al. (2016) analisaram os dados de produtividade de 54 usinas, considerando a porcentagem de área irrigada e sequeiro de cada uma delas encontrando que nas usinas que tinham pelo menos 50% área irrigada com irrigação que atendia demanda hídrica da cultura, obtiveram 78,63 Mg ha^{-1} enquanto aquelas que tinham menos de 50% da área irrigada, uma produtividade de 67,23 Mg ha^{-1}, uma redução de 14,5%. Na África do Sul, utilizando uma simulação para projetar a produtividade da cana irrigada e sequeiro Jones et al. (2015), estimaram que a produtividade da cultura deveria aumentar, nos cenários avaliados, entre 11 e 14%, proporção similar foi encontrada no Brasil por Santos et al. (2019). Barbosa et al. (2015), comparando o impacto fisiológico do déficit hídrico sobre parâmetros morfológicos e fisiológicos da cana-de-açúcar encontrando um aumento na biomassa seca de 3,6 vezes mais para o tratamento sem estresse hídrico.

4. ARTIGO I – DETERMINATION OF WATER REQUIREMENT AND CROP COEFFICIENT OF SUGARCANE CULTIVATED IN NICARAGUA

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Determination of water requirement and crop coefficient of sugarcane cultivated in Nicaragua

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4.1 ABSTRACT

Sugarcane is one of the main agro-industrial crops in Nicaragua and Central America and one of the crops with the highest evapotranspiration rates. Generally, to estimate the water crop requirement, the two-step procedure is used, where multiplying reference evapotranspiration (ET_0) and crop coefficient (Kc) results in the ETc. To obtain an accurate ETc, it is essential to use the correct ET_0 and Kc. Since the ET_0 can be estimated using different methods and depends on meteorological information, the biggest challenge is using a precise crop coefficient determinate for local conditions. Due to the lack of information to guide water crop requirements, therefore, irrigation management for sugarcane in Nicaragua, this study aimed to determine the crop evapotranspiration and Kc for sugarcane in Nicaragua and to compare the results with those suggested by FAO. The study was performed in a field experiment in Nicaragua at the Casur Sugarcane mill. The experimental area was cultivated in vertisol with the furrow irrigation method. The crop evapotranspiration was determined by field water balance, reference evapotranspiration (ET_0) by the Penman-Monteith FAO approach, and the Kc was computed through the FAO56 methodology. During the crop season, the total ETc was 1346.6 mm, resulting in a 0.90 average of Kc. The determined Kc for initial, tillering, grand growth and maturity was 0.37, 0.91, 1.11, and 0.71, respectively. Comparing the Kc obtained in this study with the Kc proposed by FAO, the second showed average values of 11.11% more than the first. This shows the importance of locally determining the Kc values, parameters that guide irrigation management to use the water resources efficiently. In this context, using the Kc values obtained in this study for sugarcane water management in Nicaragua is recommended.

Keywords: Water Management. Irrigation Schedule. Agrometeorology. Crop Evapotranspiration. Crop Management. Field Water Balance

4.2 INTRODUCTION

Irrigation plays an important role in agriculture as well as in food safety and hunger mitigation (Chichaibelu et al., 2021). Siebert et al. (2015) estimated in the year 1900, 1950, and 2005, 63 Mha, 111 Mha, and 306 Mha of the area under irrigation globally, respectively. Meier et al. (2018) estimate for the year 2012 a global irrigated area of around 367 Mha. Irrigation also has an important participation in agriculture in Central America and Nicaragua. Meier et al. (2018) estimate for the year 2012, around 7.6 Mha were under irrigation in Central America. FAO AQUASTAT (2022) estimates about 0.2 Mha in Nicaragua, of which 98% is under a surface irrigation system. Nicaragua is a country whose economy is based on agriculture, and sugarcane is one of the crops with a significant share in exportation and the Gross National Product - GNP.

The majority of the sugarcane fields in Nicaragua have some irrigation system, and according to Méndez and Zegarra (2016), around 70% of these fields are irrigated. Even with a high percentage of area under irrigation, the majority of the sugarcane farmers do not use or do not have access to any equipment to measure soil water content or meteorological data to estimate reference evapotranspiration (ET0), being empirical the water management for irrigation. This lack of knowledge and technical support was also observed by Fanadzo and Ncube (2018), studying irrigation schemes for smallholders in South Africa. Levidow et al. (2014) mentioned that inadequate knowledge about irrigation and little technical advice are two of the causes for better water use efficiency in the EU.

Those companies or farmers that use crop requirement (ETc) to manage their irrigation by two steps approach (ET0 x Kc) (Allen et al., 1998) estimate ET0 using local meteorological data but not so for Kc, which values used locally, are from other countries or those suggested by FAO which is a trustful source. The use of values not developed locally may overestimate the crop water requirement, reducing profit due to elevation of production cost or not enhancing crop yield. According to local information, irrigation represents ~55% of the sugarcane production cost in Nicaragua in areas under full irrigation.

In addressing the lack of information regarding sugarcane crop evapotranspiration and crop coefficient, this study brings valuable and novel information using soil water balance to estimate those parameters. Several authors also used this approach for sugarcane (Cardoso et al., 2015; Dingre and Gorantiwar, 2020; Silva et al., 2012; Silva et al., 2013).

The knowledge of crop coefficient and crop water requirement for sugarcane, developed locally, will guide companies, farmers, and technicians for better irrigation management, promoting the efficient use of the water resources in agriculture, the possibility to enhance yields, and optimization of production cost. Therefore, this study will contribute to sustainable agriculture development in Nicaragua. In this context, this study aimed to determine the crop evapotranspiration and Kc for sugarcane cultivated in Nicaragua and compare the results with that suggested by FAO.

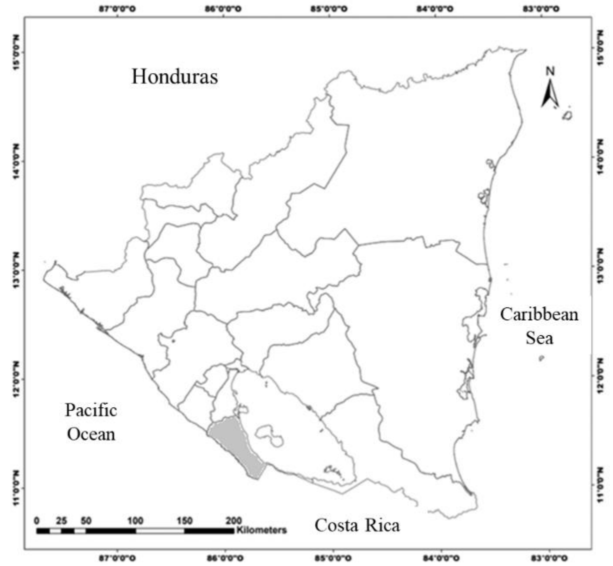
4.3 MATERIAL AND METHODS

4.3.1 Site Characterization

The field experiment was carried out during the crop season 2021 at the Compañía Azucarera del Sur – CASUR sugar mill, located in Potosí, Rivas Department (Figure 1) in the south of Nicaragua, Central America (latitude 11,597 north; longitude 85,884 west; altitude 39 m). The average annual precipitation was 1130 mm, and the rainfall was concentrated from May until November. Also, it is essential to highlight that 40% of the total rainfall occurred in September and October. In some years, this value is higher due to extreme events such as hurricanes and tropical storms. The climatic characteristic of Rivas is a tropical savanna climate, which according to the Koppen classification, is Aw.

The temperature annual mean maximum was 30.9°C in a range between 38.1°C and 21.4°C, and the mean minimum was 24.1°C oscillating between 31.5°C and 11.0°C. The relative humidity annual mean maximum and minimum relative humidity range from 40% to 100% and 95% to 25%. The precipitation annual mean maximum, minimum, and average pan evaporation range from 18.1, 1.1, and 6.4 mm day^{-1}, respectively, while the mean wind speed ranges from 3.6 to 1.9 m s^{-1}.

Figure 1. The geographical location of the experiment. Highlighted in gray is the Rivas Department inside the Nicaragua map.



Source: Author (2022)

4.3.2 Soil measurements

Soil measurements were performed in the experimental area. For collecting the soil, a Dutch auger was used to take samples at the different soil layers, 0-25, 25-50, and 50-75 cm depth. It was taken four subsamples per layer, randomized in the areas which were mixed, forming only one. The field capacity and wilting point were determined in non-disturbed samples using the pressure plate apparatus at -33 kPa and -1500 kPa, respectively. The bulk density of the dry soil was taken using a core sample. Table 1 shows the chemical and physical results.

Table 1. Soil characterization from different soil layers at the experimental site.

Soil Constants	00 - 25	25 - 50	50 – 75	Average
	Soil depth (cm)			
Clay (%)	47.0	53.0	37.0	45.67
Loam (%)	37.1	33.9	46.1	39.03
Sand (%)	15.9	13.1	16.9	15.30
Porosity (g g^{-1})	0.580	0.665	0,581	0.623
Field Capacity (g g^{-1})	0.464	0.470	0.462	0.465
Wilting Point (g g^{-1})	0.325	0.322	0.317	0.321
Bulk Density (Mg m^{-3})	1.47	1.44	1.45	1.45

Source: Author (2022)

This study considered a soil depth of 75 and 100 cm for planning observations and deep percolation measurements. This value was considered following values obtained by other studies as Dingre & Gorantiwar (2020), working with sugarcane in India, reported a maximum root penetration until 75 cm for plant cane and first ratoon. Also, Aquino et al. (2015) found an effective root zone for sugarcane in Brazil at 20 cm and Neto et al. (2018) at 40 cm.

4.3.3 Root zone depth

The observation of the effective root zone was recorded by the destructive method in the 60, 120, 180, 240, 300, and 340 days after planting. 18 plots were planted for those measurements, considering three repetitions per evaluation date. The variety used was the CP72-2086, which is the most planted variety in Nicaragua and Central America. The plots were formed by closed plastic thanks with a 1-meter depth installed above the ground and filled up with soil from the experimental field (Figure 2). At the bottom of each taken, there was a pipe of 0.5 inches opened, with the objective to drain the surplus of water from irrigation or rain and not have any interference by water excess (Figure 2). The same methodology was used by Dingre & Gorantiwar (2020).

Figure 2. Plastic tanks planted with the variety CP72-2086 to measure the effective root zone.

Source: Author (2022)

For the root measurement, the entire root was taken out of the tank and well washed in order to take out all the soil. Once the root was clean, it was stretched without breaking roots, and each 10 cm until the limit of the length of the root was cut. The volume of root in each 10 cm was taken to the oven to dry until constant weight to get dry to weigh. The soil depth that contained 80% of the dry weight of the root was considered an effective root zone.

4.3.4 Soil moisture content and irrigation management

The gravimetric methodology has been widely used since the 1960s (Allen et al., 2011). The soil moisture content was determined each 7 to 10 days long during the crop cycle. Since the first measurement, the soil samples were taken at 0-25, 25-50, and 50-75 cm depth, 10 to 20 cm from the sugarcane stool. The soil moisture for each plot in each evaluation is the average of three samples taken at the beginning of the furrow, avoid the first 5 meters, at the middle, and at the end of the furrow, avoid the last 5 meters.

According to the soil moisture monitoring, irrigation management was carried out. The irrigation schedule was defined according to soil moisture content, never allowing more than 45% depletion of the total available water (TAW) at the root zone. The TAW was determined according to equation 1.

$$\text{TAW} = (\theta_{\text{fc}} - \theta_{\text{wp}}) \text{ x BD x Z} \qquad (1)$$

Where TAW is the total available water (mm); θfc and θwp are the moisture content at field capacity and wilting point, respectively, both in (g g^{-1}); BD is the bulk density of the dry soil (Mg m^{-3}), and Z is the effective root zone depth (mm).

The irrigation method used for this experiment was the furrow irrigation method, which is the most used irrigation method in Nicaragua (FAO AQUASTAT, 2022; Méndez and Zegarra, 2016) and in this sugarcane mill. Also, it is essential to highlight that to determine the correct evapotranspiration of the plant, one of the requirements is to guarantee the well supplying of water (Allen et al., 1998).

In each irrigation, the water depth (WD) was measured with a Parshall flume, where the WD was calculated according to equation 2.

$$\text{WD} = \frac{\text{Q x 0,36 x t}}{\text{S}} \qquad (2)$$

WD is the water depth (mm); Q is the water flow (l s^{-1}), measured with the Parshall flume at the mean water channel, and t is the time of irrigation (h) expended to irrigate an area S in (ha).

4.3.5 Reference evapotranspiration (ET_0)

Daily data of air wind speed, air temperature, sunlight, and relative humidity were collected from the San Fernando weather station. This meteorological station is located inside the areas of Casur, approximately 3 km distance from the experimental field and belongs to INETER (Instituto Nicaraguense de Estudios Territoriales), the governmental institution responsible for meteorological monitoring in Nicaragua. The meteorological data was collected from 31st January 2021, when stared the first ratoon, until 13th January 2022, when sugarcane was harvested. The reference evapotranspiration was estimated using the Penman-Monteith FAO approach (Allen et al., 1998), equation 3.

$$ET_0 = \frac{0{,}408\ \Delta\ (R_n - G) + \gamma\ \left(\frac{900\ U_2}{T + 273}\right)\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0{,}34\ U_2)} \qquad (3)$$

Equation 3 is described the PM-FAO approach, where ET_0 is Reference evapotranspiration (mm day^{-1}); Rn is net radiation at the crop surface (MJ m^{-2} day^{-1}); G is soil heat flux density (MJ m^{-2} day^{-1}); γ is psychrometric constant (kPa $°C^{-1}$); T is mean daily air temperature (°C); U_2 is the wind speed at 2 m height (m s^{-1}); es is the saturation vapor pressure (kPa); ea is the current vapor pressure (kPa), and Δ is the slope of vapor pressure curve (kPa $°C^{-1}$). The net radiation was estimated from the duration of bright sunshine measured with a Campbell-Stokes sunshine recorder (Allen et al., 1998).

4.3.6 Crop evapotranspiration (ETc) and crop coefficient (Kc)

For crop evapotranspiration (ETc), the determination was used the soil water balance methodology proposed by (Allen et al., 1998). Equation 4 is described the inputs and outputs from this equation.

$$ETc = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \qquad (4)$$

Where ETc is crop evapotranspiration (mm day^{-1}), I is the depth of irrigation (mm), P is the rainfall (mm), RO is runoff from the soil surface (mm), DP is deep percolation below the root zone, CR is the capillary rise from the shallow water table, ΔSF is horizontal subsurface flow in or out of the root zone, and ΔSW is the change in soil profile water storage respectively.

Considering the type of soil in the field study, as vertisol, with expansive high clay content and deep shallow water (over 12 meters down), the capillary rise is not considered as well ΔSF. For estimation of runoff was used the software WinSRFR 5.1 (Bautista et al., 2009) and deep percolation was considered the positive changes in the water availability below the root zone (Dastane, 1978; Roark & Healy, 1998). According to Allen et al. (1998), evapotranspiration can be deduced from the change in soil water content at the root zone (ΔSW) over long periods, which was used in this study. In this context, equation 5 represents the water balance model used in the present study.

$$ETc = I + P - RO - DP \pm \Delta SW \qquad (5)$$

The crop coefficient (Kc) was computed as the ratio of crop evapotranspiration and reference evapotranspiration (equation 6). Such as the ETc, the crop coefficient was calculated considering four growth stages: Initial (0 - 45 days after planting or harvesting - DAP), Tillering (45 - 130 DAP), Grand growth (130 – 300 DAP), and Maturation (300 – 345 DAP). These four stages correspond to those defined by Allen et al. (1998), Silva et al. (2012), and Dingre and Gorantiwar (2020).

$$Kc = \frac{ETc}{ETo} \qquad (6)$$

4.3.7 Comparison with FAO-56

As there are no sugarcane crop evapotranspiration proposal neither Kc as well for Nicaragua, the most reliable reference for these values is that proposed by FAO56. Although these values are for sub-humid climatic conditions, a comparison was made between the FAO56 Kc values and those obtained in this study. This reference indicates for the initial stage, mid-season or gran growth, and final or maturation, the Kc of 0.4, 1.25, and 0.75, respectively. The tillering stage was obtained by interpolation, reaching a value of 0.94.

4.3.8 Agronomical practices

The experiment was conducted in a field area in first ratoon sugarcane (2nd cut, crop cycle 2021) planted with the variety CP72-2086, a genotype widely planted in Nicaragua and Central America, with 1.65 m between rows. The past harvest was on 31st January 2021. Five days after the mechanical harvesting, the mulch (dry leaves) was aligned, letting four rows free of mulch. Mechanical cultivation was carried out with a disc harrow at 25 days of age to kill any weeds and better shape the furrows for irrigation. At 60 days, the entire field was mechanically fertilized with 410 kg ha^{-1} of the formulation 25-06-06 (NPK), attending to the crop nutrient demand. Further weed control happened as needed using the herbicides Terbutrin, Ametrine, and 2,4D, and was no necessary use of insecticide or fungicide. The irrigation method and the shape of the furrow are shown in Figure 3.

Figure 3. Furrow irrigation in the field of study.

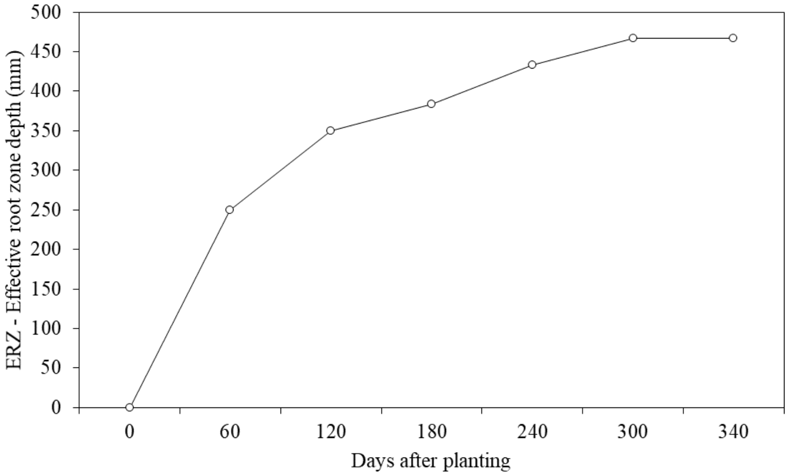
Source: Author (2022)

4.4 RESULTS AND DISCUSSION

4.4.1 Effective root zone depth

The effective root zone (ERZ) depth started at 60 days with 250 mm ending up at 340 days with 467 mm (Figure 4). The rate of ERZ expedites up to the end of the tillering stage (45 – 130 DAP), then it continues to grow but at a less rate up to 300 DAP when the values of ERZ are the same as at 340 DAP. This showed that the root developed during the whole cycle of the crop until maturation (300 – 345 DAP) when stopped. Many studies showed effective root zone reaching the soil layer between 400 to 600 millimeters, which is in accordance with the present study (Evans, 1935; Inforzato & Alvarez, 1957; Laclau & Laclau, 2009; Ohashi et al., 2015).

Figure 4. Measured effective root zone depth (mm) of sugarcane.

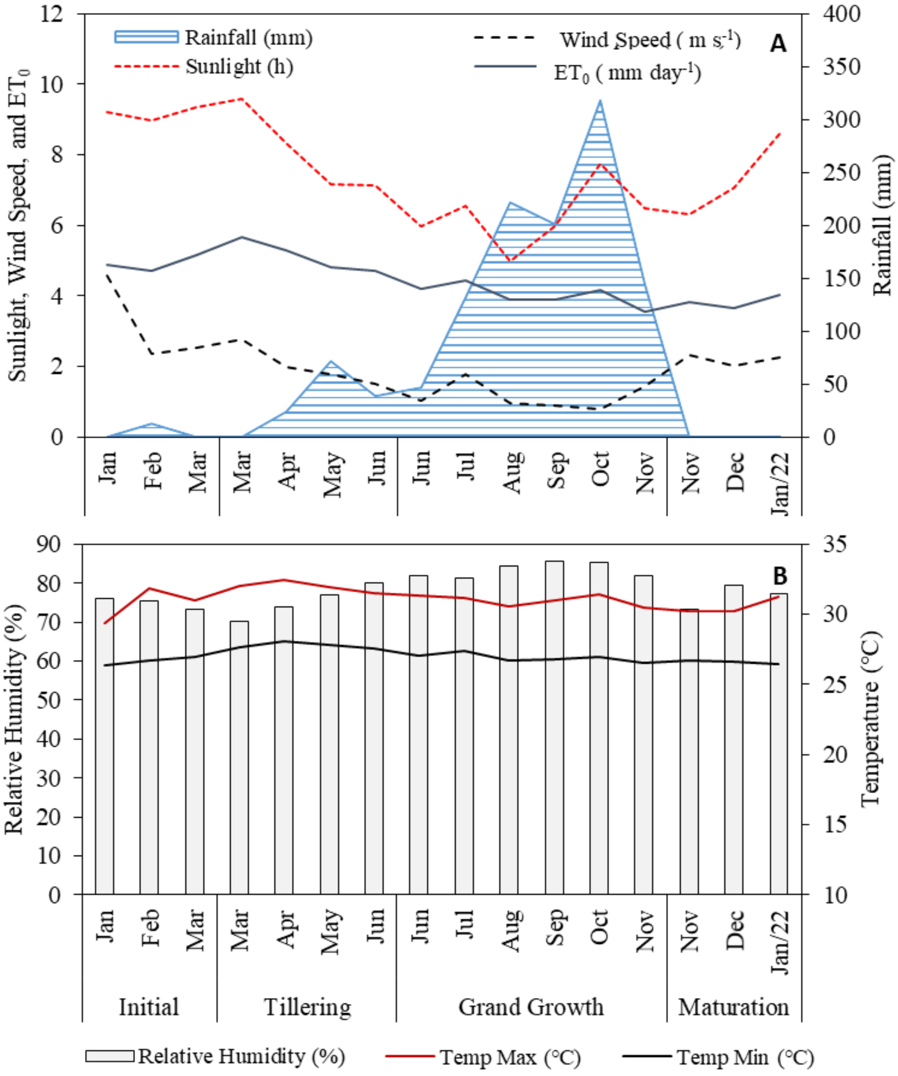


Source: Author (2022)

4.4.2 Weather condition

The characterization of weather conditions during the experimental period can be seen in Figure 5. The monthly average of sunlight (h) values ranged from 4.9 to 9.6, with minimum values reached in August and maximum in March. The sunlight is inversely proportional to rainfall occurrence since this time, clouds covered the sky, and the sunlight was reduced.

Figure 5. Meteorological data from 2021 to January 2022 for each month and sugarcane growth stage. (A) Sunlight, wind speed, ET_0 and rainfall. (B) Relative humidity, mean maximum and minimum temperature.



Source: Author (2022)

During the crop season, the total rainfall accumulated was 1211 mm, starting in February with 12 mm, which was an atypical rain. After that, the rain stared again in April with 24 mm and ending up in November with 144 mm. It is important to highlight that 43% of the total rain occurred in September and October, totalizing 519 millimeters. The rain at initial stage was not enough to supply the crop demand, since the 12 mm in February happened in just one event. Therefore during this period, irrigation was applied to supply the crop requirement. The grand growth period was inside the wet season, with 1064 mm of rain at this time, representing almost 90% of the total rain (Figure 4A). Several authors have shown that 1200 mm of water is enough to attend the crop water requirement (Cardoso et al., 2015; Dingre and Gorantiwar, 2020; Gómez et al., 2016; Silva et al., 2012; Silva et al., 2013; Win and Zamora, 2014), considering that crop evapotranspiration as synonymous of crop water requirement.

Another important point was regarding the crop stage when it was rain-fed, which happened in this experiment during the mid-season or grand growth stage. An important crop strategy used by the sugarcane producers is to ensure the sugarcane fields during the wet season during the grand growth. This strategy guarantees that the plant will be rain-fed during the highest water requirement stage, promoting less irrigation water consumption and hence less water pumping resulting in a reduction in production cost. This management is in accordance with Robertson et al. (1999), which showed that water deficit had more impact on crop yield when the canopy is well-established, in general, during the grand growth stage.

The mean relative humidity ranged from 70% to 77% from January to May (dry season) and from June to December (rain season) ranged from 77% to 82%. The mean maximum and minimum temperature ranged from 32.5°C to 29.4°C and 28.1°C to 26.4°C, respectively. The highest value was reached in April and the lowest in January, with an average thermal amplitude of 4.09°C. Several authors have studied the relation between temperature and sugarcane development stages. For flowering in Brazil, (Araldi et al. (2010) found an ideal temperature ranging between 18°C to 31°C. In Coimbatore (India), sugarcane had better physiological and biochemical performance when it developed under temperatures varying between 28°C to 37°C (Kohila and Gomathi, 2018). Based on previous studies, the air temperature in the field area was ideal for sugarcane production.

Reference evapotranspiration and wind speed had the same behavior, with the highest values between January to March and decreasing until October-November, when they started to rise again. This shows the close connection between these two variables. The monthly average of ET_0 ranged from 3.6 mm day^{-1} to 5.6 mm day^{-1} in November and March, respectively. Also, the wind speed had maximum values in January and minimum in October with 4.6 m s^{-1} and 0.78 m s^{-1}, respectively (Figure 5).

Wind speed has a high impact on the result in the variables that drive the reference evapotranspiration. According to (Allen et al., 1998), the exposed range of wind speed is classified from light to strong. Hence, the other variables have lower variation during the years than the wind speed. Mentioned for the same author before, wind speed affects the evapotranspiration rate in humid conditions to a far lesser extent than under arid conditions, where minor variations in wind speed may result in larger variations in the evapotranspiration rate.

4.4.3 Irrigation water applied and soil moisture content

During the sugarcane cycle, irrigation was required in order to allow good crop development. The irrigation events were carried out between February and June, mainly during the initial and tillering stage. Three irrigation events were necessary during the initial stage, with 15 days interval. For tillering stage (45-130 DAP), five irrigation events were done at 12 days intervals. The reduction on the interval days occurred due to the faster water depletion in the soil due to the increase in crop development, hence an increase in water demand. During this period, 649.9 mm of water was applied from irrigation, which represents 92% of the total water from irrigation.

Only one irrigation was necessary during the grand growth stage with 57.2 mm of water depth. This happened on mid of June, when the rainfall started with more consistency, not requiring irrigation anymore. Table 2 shows the 9 events of irrigation with its respectively water depth (mm), the total applied from irrigation, and the average water depth (mm) per irrigation event.

In total, from irrigation, 707.1 mm was applied. Of this water, 39.7% was in the first 45 DAP (Initial stage) and 52.15% at the tillering stage. The first irrigation was the event that consumed more water, 117 mm or 16.5% of the total. This happened due to the cracking behavior. Since, in order to allow the harvest machinery work on the sugarcane fields, it is necessary to dry the soil until a moisture level where the equipment can traffic without damaging the field letting the soil cracked. In vertisol, because of its cracking behavior when it is dry or drying (Coulombe et al., 1996; Kovda, 2020; Kutilek, 1996), when the irrigation starts, the water starts to flow into the crack before the advance in the surface (Mitchell and Van Genuchten, 1993) rising the water consumption.

Table 2. Irrigation depth (mm) Dates and days after planting or cutting (DAP)

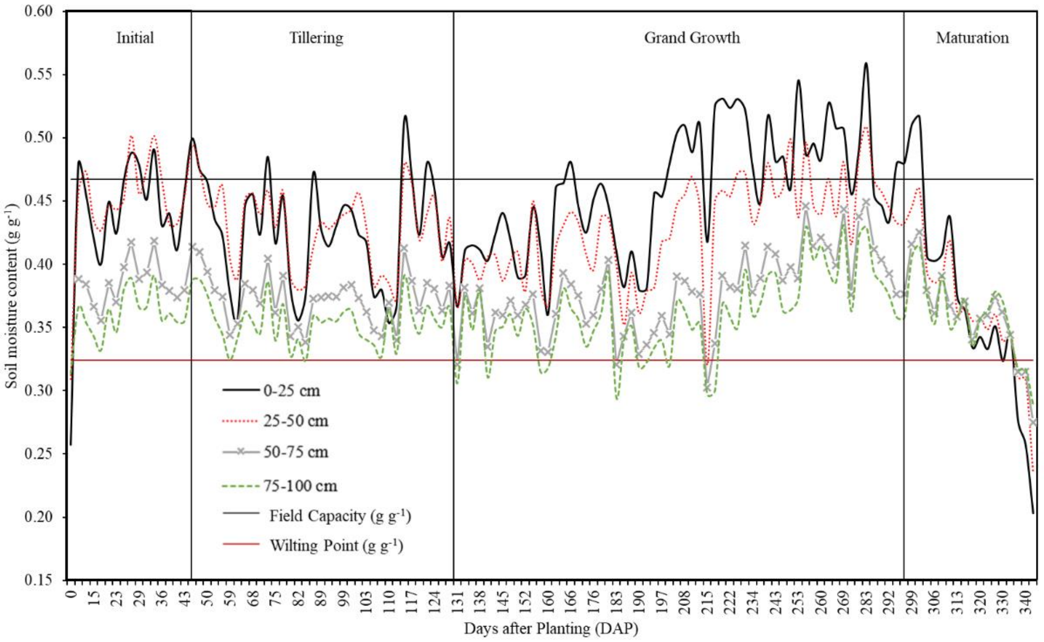
Date	DAP	Growth Stage	Water Depth (mm)
02/12/2021	12	Initial	117.0
02/25/2021	25	Initial	76.1
03/15/2021	43	Initial	88.1
04/07/2021	66	Tillering	84.7
04/14/2021	73	Tillering	61.6
04/27/2021	86	Tillering	86.4
05/12/2021	101	Tillering	79.4
05/26/2021	115	Tillering	56.7
06/25/2021	145	Grand Growth	57.2
Total			707.1
Total average of water depth (mm) per irrigation event			78.6

Source: Author (2022)

Irrigation was responsible for the increase of the soil moisture content during the initial tillering stage since there was no rain enough to recharge the soil. During this time, there was 147 mm of rainfall out of 1211 mm during the whole season. Once the rainfall was established with more consistency, irrigation was not necessary, which occurred during the grand growth stage.

Similar results were found by Magaña et al. (2016) in Mexico, studying the soil moisture tension effect on sugarcane growth and yield. Most significant moisture variations occur at 00-25 and 25-50 cm because of rain and irrigation, and the lowest variation takes place at below 50 cm (Figure 6). The lowest variations below 50 cm depth could be due to the lowest saturated hydraulic conductivity in high clay soils, which reduce the water movement downwards once the up layers are moist.

Figure 6. Gravimetric soil moisture content in the soil profile during the crop season.



Source: Author (2022)

The soil reached the lowest moisture content during the maturation stage, 300 to 345 days after planting. During this time, due to the dry season, this level of moisture is easily achieved by stopping irrigation. In sugarcane, irrigation is often stopped some weeks before harvesting to reduce soil compaction from harvesting machinery and enhance sucrose content. This procedure is called "drying off" (Araújo et al., 2016; Inman-Bamber, 2004).

4.4.4 Crop evapotranspiration (ETc)

Runoff and deep percolation are water losses on the soil water balance or budget related to soil texture, soil type, slope, weather, type and density of vegetation covering the soil, etc. These two movements are very common in furrow irrigation, especially in vertisol (Ahmad, 1996; Kutilek, 1996). In this irrigation system, water flows from the furrow head until the end by gravity. Therefore a non-erosive slope on the flow direction is necessary. To block the end of the furrow is a practice that minimizes runoff, but it is not common in furrow irrigation (Marlow, 2012). Although many practices can be applied to reduce runoff, a furrow irrigation system is very exposed to runoff (Lehrsch et al., 2014). Deep percolation is also another water movement that may reduce irrigation efficiency hence water losses. DP is the water infiltration below the influence of the root zone (Roark & Healy, 1998).

Due to these conditions, RO and DP were measured in this field experiment. RO was inversely proportional to DP with the advance of the crop cycle. RO and DP were 25.1 and 269 mm at the initial stage, respectively. This was expected because the soil was cracked at the beginning of the experiment, which brought on more deep percolation and less runoff. In cracking soil, deep percolation can be very high, and it is considered the principal way of deep moistening (Kutilek, 1996). Once the soil started to be more constantly moist, less cracking or no deep cracking happened, which permitted the water to flow on the surface with less percolation below the root zone. This relation between runoff and deep percolation happens because the water from irrigation or rain first fills up the cracks. While the water advance, infiltration occurs in the soil profile (Fernandez-Gomez et al., 2004; Marlow, 2012). Once the soil swells, the cracks close, and the water flows to the surface, runoff may occur (Ahmad, 1996). The same happened at the grand growth stage, but this time inversely, where RO and DP were 390.9 and 14.1, respectively. All the data from the field water balance are presented in table 3.

Table 3. Field water balance components (mm) during the growth stages for sugarcane observed at the experimental site in Nicaragua.

Growth Stage	Period (days)	I	P	RO	DP	ΔSw	ETc
		mm					
Initial	0-45	281.1	12.0	25.1	269.0	84.6	83.6
Tillering	45-130	368.8	135.0	54.4	21.9	-38.4	389.2
Grand Growth	130-300	57.2	1,064.0	390.8	14.1	38.5	754.8
Maturation	300-345	0.0	0.0	0.0	0.0	-119.0	119.0
Average	345	707.1	1,211.0	470.2	305.1	-34.4	1,346.6

I – Irrigation; P – Rainfall; RO – Runoff; DP – Deep Percolation; ΔSw – Soil moisture storage change; ETc – Crop evapotranspiration.

Source: Author (2022)

The total and mean daily crop evapotranspiration were 1330.08 mm and 3.9 mm day^{-1}, respectively (Table 3). The sugarcane evapotranspiration varies from place to place, depending on crop management, plant genotype, weather conditions, soil, and crop cycle duration (Dingre & Gorantiwar, 2020).

Table 3 shows the ETc values for each growth stage and the total during the crop cycle. In the initial stage, since the crop is starting to grow and the canopy is in development, the crop water requirement is not high. During 45 days, the crop evapotranspiration achieved 83.6 mm, and the daily average was 1.86 mm. During this period, soil evaporation is dominant over the crop transpiration since the ground is not entirely covered (Allen et al., 1998). With the crop development, water consumption started to rise due to the duration of the growth stage and the increase in the transpiration rate. During the tillering stage, which lasts 85 days, the rate of ETc was 4,58 mm day^{-1}, resulting in 389.2 mm of evapotranspiration which is 2.6 times higher than the past previous stage.

The highest value of ETc was found during the grand growth stage (754.8 mm), and for the same period, the average daily water consumption was 4.44 mm day^{-1}. These results are in accordance with several studies that have demonstrated that sugarcane water consumption increase with the crop development, with the highest values during the grand growth stage (Allen et al., 1998; Inman-Bamber & McGlinchey, 2003; Silva et al., 2012).

The maturation stage presented 2.65 mm day^{-1}, 49% less than the daily rate of the past stage. At this stage, leaves start senescence and reduce the vegetative period to maturation, where the plant starts to concentrate sucrose (Inman-Bamber & Smith, 2005; Smit & Singels, 2006). Therefore, with fewer leaves, the rate of evapotranspiration decrease.

Several studies showed the sugarcane water requirement using different approaches. In India, using soil water balance methodology, Dingre and Gorantiwar (2020) found for sugarcane an ETc for the years 2015 and 2016 of 1386 and 1291 mm, respectively. With the same methodology, Albuquerque (2012) in Brazil estimated the sugarcane ETc in the second and third ratoon in 1664 and 1626 mm, respectively. Using a lysimeter, Kyaw and Oscar (2014) reported for Myanmar 1370 mm of water consumption. In table 4, it is possible to see several studies where it shows ETc range, on an annual basis, from 968 to 1687mm, depending on climate conditions and locations from different parts of the world.

Table 4. Values of ETc for sugarcane in different part of the world.

ETc (mm)	Local	Authors
968	Texas, USA	Wiedenfeld (2000)
1021	Texas, USA	Allen et al. (1998)
1060	Florida, USA	Omary and Izuno (1995)
1191	Maui, Hawaii, USA	Anderson et al. (2015)
1339	Maharashtra, India	Dingre and Gorantiwar (2020)
1370	Myanmar	Win and Zamora (2014)
1389	Maui, Hawaii, USA	Anderson et al. (2015)
1438	Brazil	Cardoso et al. (2015)
1687	Brazil	Silva et al. (2012)
1274	Mean	

Source: Author (2022)

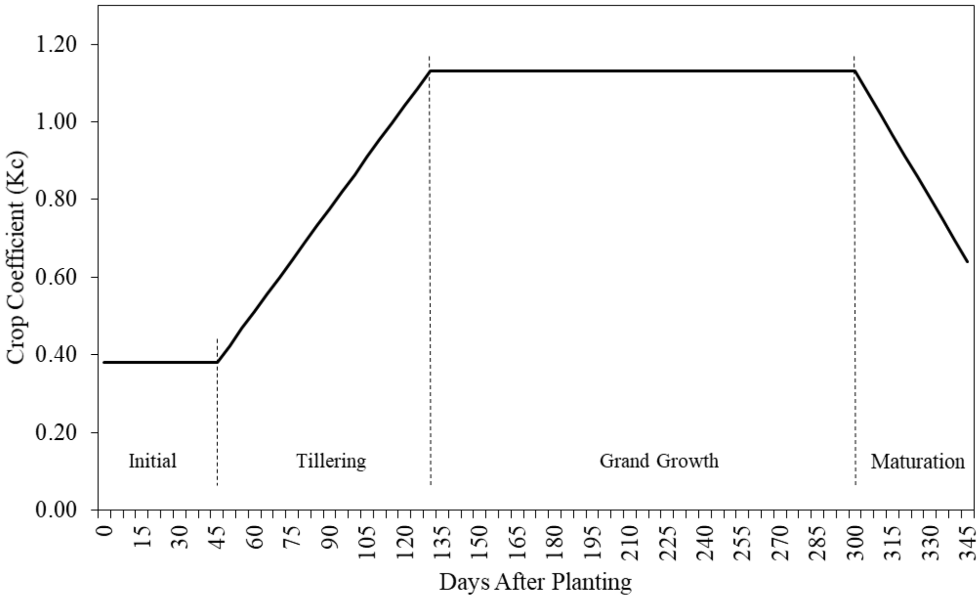
Therefore, sugarcane evapotranspiration amounting to 1347 mm derived by field water balance in this study seems to be appropriate for Nicaragua's conditions (Table 4).

4.4.5 Crop Coefficient (Kc) and Comparison with FAO-56

The average Kc of the experiment ranged from 0.24 to 1.28 (Figure 7). For the initial stage, the values ranged from 0.20 to 0.54, with an average of 0.37. The Kc consistently increased from 0.54 to 1.13 during 45–130 days after planting (DAP). Thus, the average tillering growth stage was 0.91. Thereafter, it showed gradual increases due to crop development in the form of cane elongation and leaf area index (Silva et al., 2012).

At the grand growth stage, the average of Kc was 1.11 with a peak value of 1.28, the highest value. During the late season or maturation (300–345 DAP), the Kc values decreased gradually, ending up at 0.71. Thompson and Boyce (1971), cited by Dingre and Gorantiwar (2020) in a lysimeter study, observed that ETc rates declined by about 30% after the leaf senescence began, an effect that lasted up to crop harvest.

Figure 7. Crop coefficient of sugarcane (Kc) for each growth stage throughout the crop season 2021 in Nicaragua.



Source: Author (2022)

Many authors found different results from Kc than those reported by FAO. Albuquerque (2012) found in Brazil, in the treatments supplying 100% of the ET0, values of Kc for the initial stage of 0.31 and 0.15 for the second and third ratoon. Kc of 0.53, from the same stage, was found in Myanmar (Win & Zamora, 2014). The lowest variation, 7.45%, showed at the initial stage, being similar to the value proposed by FAO-56 (~0.40). For tillering stage, the variation was lowest (2.93%). FAO proposes for this period 0.94 while the present study estimate 0.91.

The grand growth stage is the stage where there is the highest water consumption due to the long period and increase of waterleaf. Although there was a pick of Kc (1.28) in the present study, similar to the value proposed by FAO, the average was the lowest (1.11). This lower value of Kc for this period, in relation to other authors (Albuquerque, 2012; Allen et al., 1998; Dingre & Gorantiwar, 2020; Inman-Bamber & McGlinchey, 2003; Silva et al., 2012; Win & Zamora, 2014) can be explained due to lowest potential of productivity in vertisol. This soil class is very challenging for crop production due to physical, mechanical, and in some cases, chemical restrictions (Coulombe et al., 1996; Kovda, 2020; Kutilek, 1996).

As these soils are very hard when dry and very plastic when moist (Coulombe et al., 1996; Kovda, 2020; Kutilek, 1996), in order to able the mechanization, it is necessary to dry the soil until a point where the machines can traffic without damaging the fields and itself. Probably, because of this, the Kc at the maturation time was lowest than FAO (~ 39%) and also lower than in other studies (Albuquerque, 2012; Allen et al., 1998; Dingre & Gorantiwar, 2020; Inman-Bamber & McGlinchey, 2003; Silva et al., 2012; Win & Zamora, 2014). Another explanation for the lowest value of Kc during maturation takes place in a variety of physiology. As the variety CP72-2086 is susceptive to flowering in the local conditions, we also believe that the bloom between 280-300 DAP could also affect the crop evapotranspiration, hence the crop coefficient. All the values of KcFAO and its comparison against Kcdes are shown in Table 5.

Table 5. Comparison of Kc from FAO-56 and developed at study in Nicaragua.

Growth Stage	Kc_{FAO}	Kc_{des}	Variation %
Initial	0.40	0.37	7.45
Tillering	0.94	0.91	2.93
Grand Growth	1.25	1.11	12.75
Maturation	0.98	0.71	38.81
Average	1.00	0.90	11.11

Kc_{FAO} – values of Kc proposed at the FAO-56; Kc_{des} – Kc developed by the authors; Average is considering 345 days of crop cycle.

Source: Author (2022)

Using the same values of reference evapotranspiration estimated for this study and calculating the crop water requirement using the Kc by FAO, the water consumption would be 11.11 % superior to the needed. This could limit water resources for other crops and reduce net incomes due to increased production cost without yield increase.

4.5 CONCLUSION

Sugarcane has import role in the economy in Nicaragua, Central America, and the Caribbean. The present study showed the importance of defining local parameters that guide irrigation, therefore, water resources. This study provides information through field water balance, the ETc, and Kc for the variety CP72-2086 cultivated in a Vertisol.

The total evapotranspiration (ETc) obtained was 1346.6 mm, and Kc for initial, tillering, grand growth, and maturation was 0.37, 0.91, 1.11, and 0.71, respectively, with values ranging from 0.24 to 1.28.

The values of Kc FAO compared with those found in this study were, on average, 11.11% superior. An overestimation of the water requirement can lead to excessive applied water, reducing water availability for other crops, reducing water use efficiency, and decreasing crop yield due to waterlogging.

The information obtained in this study is essential to assist in the management of irrigation by sugarcane producers in Nicaragua and the region, which will lead to better use of this crucial natural resource.

With the results of Kc and the precise estimation of ET_0 for the place of interest, the producers can improve the decision-making of the real need for irrigation in the sugarcane plantations, whereas before, this was not possible due to the lack of information related to the Kc of sugarcane.

4.6 ACKNOWLEDGEMENTS

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4.7 DECLARATION OF COMPETING INTEREST

There is no conflict of interest for this study.

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5. ARTIGO II – IRRIGATION MANAGEMENT ON GROWTH, CROP YIELD AND WATER USE EFFCICIENCY OF SUGARCANE CULTIVATED IN NICARAGUA

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Irrigation management on growth, crop yield and water use efficiency of sugarcane cultivated in Nicaragua

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5.1 ABSTRACT

One of the greatest challenges in crop science worldwide is to generate a balance between crop production and water management. In a context of sustainability and vertical production growth, the knowledge of water relations is fundamental to improved crop management in irrigated and rainfed sugarcane fields, as well in other crops. The adequate irrigation management can be a strategy to improve the use of water resources towards better agronomic and operational efficiency. Nicaragua, due to its lack of information and research about irrigation, has a great opportunity and need to increase crop yields and enhance water efficiency. Therefore, the aim of this study was to evaluate the response of sugarcane growth, yield and water use efficiency under different irrigation management strategy. The study was performed in a field area from Casur Sugarcane mill in Nicaragua. The experimental area was cultivated in high clay soil, with the variety CP72-2086 in 2nd cut with furrow irrigation method. Two treatments was evaluated, irrigation based on soil moisture (ISw) and irrigation with fixed interval (IFI) and its effect on growth variables and crop yield. On a temporal analysis, the plants showed compensatory growth in IFI, recovering from water-deficit-stress in mostly measured variables. Sugarcane yield was statistically different between treatments with 97.87 and 83.84 Mg ha^{-1} for ISw and IFI respectively. The water use efficiency was similar for both irrigation strategies. Based on the results founded by the authors, it is recommendable to manage irrigation base on soil moisture content because of the best growth response and sugarcane yield.

Keywords: Saccharum officinarum. Water Management. Compensatory Growth. Crop growth. Soil Moisture. Furrow Irrigation.

5.2 INTRODUCTION

Sugarcane is one the most expressive crop cultivated in Nicaragua. The sugarcane chain in Nicaragua is responsible for more than 4% of the Gross National Product (GNP), which represent 210 MI dollars. This crop was also responsible for 10% of the total movement on the seaports in Nicaragua and contributed to the national electrical system with more than 380 MI of kilowatts of renewable energy from sugarcane biomass (CNPA, 2022).

Out of the total Central America, Nicaragua is the country that has the greatest water resources availability (Méndez and Zegarra, 2016) and according to the same authors, around 70% of sugarcane fields are irrigated in this country. Although the sugarcane and irrigation have big importance in the local economy, there is just few information about irrigation, crop growth analysis and water use efficiency available.

The water requirement of sugarcane varies between 900–2500 mm per season (Carr and Knox, 2011; Dingre and Gorantiwar, 2020; Marin et al., 2020; Oliveira et al., 2018; Wiedenfeld, 2000) and irrigation management should be based on recommended allowable water deficit in the soil during each period of the phenological cycle. Magaña et al. (2016), using soil water tension in a vertisol as indicator of the beginning of irrigation, obtained maximum stalk yield of 134.7 and 128.3, 95.8 and 53.4 Mg ha^{-1} for the -15Kpa, -45Kpa and -75Kpa as soil water tension treatments. Silva et al. (2013), using center pivot, reached sugarcane yields of 131.1, 110.2, 100.6, 67.8 and 62.6 Mg ha^{-1} supplying 100 %ET$_0$, 75% ET$_0$, 50% ET$_0$, 25% ET$_0$ and rain-fed respectively. At the same study the water use efficiency was inversely proportional to the sugarcane yield results. Daily sugarcane water consumption in the main producing areas of the country varies from 2 to 6 mm day−1, depending on variety, the stage of crop development, and evapotranspirative demand (Oliveira et al., 2018). In general, sugarcane requires 250 mL of water to form 1 g dry matter while corn requires 500–800 mm of water, depending on climate, for good production in one season (Doorenbos and Kassam, 1979; Oliveira et al., 2018).

Irrigation in sugarcane is present in many countries. About 60% of sugar produced from cane in Australia requires some form of irrigation. In South African, around 40% of the crop depends on irrigation and in some countries cane cannot be grown without irrigation (Swaziland and Sudan, for example) (Inman-Bamber and Smith, 2005). Various irrigation schedules methods have been proposed to optimize irrigation in sugarcane crops. Bhoj and Singh (1960) and Gunasena (1974) recommended irrigation at a fixed time interval while others recommended irrigation at 20% (Singh and Sareon, 1976), 50% (Bose and Thakur, 1977) depletion of available soil moisture from the effective root zone.

Irrigation plays and important whole globally in the food production and it is an important strategy against hunger mitigation (Chichaibelu et al., 2021). Globally, only 17% of croplands are irrigated but this accounts for 40% of total food production (Adu et al., 2018; Dowgert, 2010). Water is a major determinant of biomass production and yields of crops due to its critical role in photosynthesis, nutrient dissolution and uptake, transport and other physiological processes in crop plants (Adu et al., 2018). Therefore, it is important to evaluate the response of sugarcane under different irrigation strategies, in order to maximize the growth variables and yields during the cycle. Several author have shown the decrease in leaf area index, leaf area, stalk weight, stalk diameter, tillering, internode lenght and biomass accumulation in plants under drought stress compared to well-watered treatments (Ecco et al., 2014; Inman-Bamber and Smith, 2005; Misra et al., 2020; Robertson et al., 1999; Silva et al., 2012).

Although the deleterious effects of water stress have evidenced by several authors, its effect can be more or less pronounced when it occurs at a certain crop growth stage. However, it is necessary to evaluate which are the most critical phases of the crop and how the water-soil-plant relationship occurs, due to the compensatory growth phenomenon. This natural endowments, give the sugarcane more resilience over abiotic stresses, which is called compensatory ability.

The lack of information around irrigation is a challenge in Nicaragua and the parameters that guide irrigation on most farms are empirical. Mostly of the sugarcane farmers does not use any equipment to measure soil moisture content or ETc throughout the two steps procedure (ET_0 x Kc) to guide irrigation. The irrigation schedule based on calendar (fixed irrigation interval or frequency) is the principal irrigation schedule used locally, due to its ease, from an operative point of view. This empirical irrigation management may result an over or under depth water application, resulting in elevation of production cost, reducing yields, water use efficiency and or water availability for other crops.

In addressing the lack of information, this study brings valuable information for the sugarcane production. The aim of this study was to evaluate two irrigation management strategies, based on soil moisture and with fixed interval (local management) in order to understand their effect on growth variables, sugarcane yield and water use efficiency in Nicaragua. This knowledge, developed locally, will guide companies, farmers and technicians for a better irrigation management promoting a sustainable irrigated agriculture.

5.3 MATERIAL AND METHODS

5.3.1 Site Characterization

The field experiment was carried out during the crop season 2021 at the Compañía Azucarera del Sur – CASUR sugarcane mill, located in Potosí, Rivas Department (Figure 1) in the south of Nicaragua, Central America (latitude 11,597 north; longitude 85,884 west; altitude 39 m). The experiment was carried out in a second ratoon sugarcane (2nd cut, crop cycle 2021) planted with the variety CP72-2086, genotype from Canal Point – USA but widely planted in Nicaragua and Central America. The experiment and measurements stared on 31st January 2021, after the cutting and last until 13th January of 2022 when the experiment was harvested. The distance between sugarcane rows used for the company is 1.65 m.

Information about climate conditions in the field experiment was obtained using meteorological station, which was located inside the areas from Casur, approximately 3 km distance from the experimental field. This station belongs to INETER (Instituto Nicaraguense de Estudios Territoriales), governmental institution responsible for meteorological monitoring in Nicaragua. The average of annual precipitation in the last 25 years are 1130 mm, which the rainfall concentrated during May until November, which is common the occurrence of hurricanes and tropical storms during this time. The climate classification of Rivas has a tropical savanna climate, which according the Koppen classification is Aw.

The annual mean maximum is 30.9°C in a range between 38.1°C and 21.4°C, and the mean minimum is 24.1°C oscillating between 31.5°C and 11.0°C. The annual mean maximum and minimum relative humidity range from 40% to 100% and 95% to 25%. The annual mean maximum, minimum and average of pan evaporation range from 18.1, 1.1 and 6.4 mm day^{-1}, respectively, while the mean wind speed range from 3.6 to 1.9 m s-^{1}.

Figure 1. Geographical location of the experiment. Highlighter in gray the Rivas Department inside the Nicaragua map.

Source: Author (2022)

Soil analysis was made in the experimental area at the different soil layers, 0-25 and 25-50 cm depth. It was taken four subsamples per layer, randomized in the area that were mixed forming only one sample per layer. In the Table 1 were showed the chemical and physical results. Field capacity, wilting point and porosity was determined using the apparatus plate. The bulk density of the dry soil was taken using a core sample.

Table 1. Physico-chemical characterization of the experimental field.

Variable	Unit	00-25	25-50	Average
		Soil layer depth (cm)		
Chemical Characterization				
Organic Matter	%	1.4	0.75	1.08
pH		7.30	7.40	7.35
Potassium	cmol kg^{-1}	0.17	0.14	0.16
Calcium		19.3	15.93	17.62
Magnesium		1.62	0.96	1.29
Sodium		6.5	8.64	7.57
CEC		27.58	25.66	26.62
Phosphorus	Ppm	18.53	23.58	21.06
Sulfur		45.91	46.43	46.17
Iron		35.07	34.02	34.55
Cupper		8.79	7.68	8.24
Zinc		0.5	0.3	0.40
Manganese		1.62	0.96	1.29
Boron		0.65	0.65	0.65
Physical Characterization				
Clay	%	47.00	53.00	50.00
Loam		37.10	13.10	25.10
Sand		15.90	33.90	24.90
Bulk Density	g cm^{-3}	1.47	1.44	1.46
Field Capacity	g g^{-1}	0.464	0.470	0.467
Wilting Point		0.325	0.322	0.324
Porosity		0.580	0.665	0.623

Source: Author (2022)

The soil of the experimental field is a vertisol, which is characterized by soils usually with high plasticity and stickiness when wet, and crack formation when dry. Soils in the area have generally high levels of calcium, magnesium and in some sites low to high level of sodium. Casur estimate around 70% of its sugarcane fields are cultivated in this type of soil, which include salty areas.

5.3.2 Experimental Design

The effect of irrigation scheduling on the growth variables and yield responses of sugarcane was evaluated on a split plot design with two treatments with five replications. The experimental units considered was ten furrows of 70 m long. The treatments correspondent to different irrigation scheduling was Irrigation based on soil moisture content (ISw) and Irrigation with fixed interval (IFI).

Even with thousands hectares areas under irrigation in Nicaragua, there is such a lack of information in this area and little technical support for farmers. Irrigation with fixed interval should consider variable irrigation depth in order to supply the crop demand without surplus or water deficit. But in Nicaragua the IFI is used due to limited pumping capacity, water availability or the concept of the soil moisture it last long in furrow irrigation because the high irrigation depth. Therefore, IFI treatment was defined as experimental check or as local irrigation practice with 31 days average interval between irrigation events.

Since in Nicaragua there is no free data from meteorological stations, neither a good network of them, the estimation of ET_0 is very difficult. Another difficult of the ET_0 is about its use knowledge, which is not well known locally. In the absence of ET_0 and Kc to calculate ETc, ISw was defined as the second treatment, where irrigation is guide by soil moisture content.

According to the soil moisture monitoring, irrigation management was carried out. The irrigation schedule was defined according to soil moisture content, never allowing more than 45% depletion of the total available water at the root zone. The available water (AW) was determined, according the equation 1.

$$AW = (\theta_{fc} - \theta_{wp}) \times BD \times Z \times 0.45 \qquad (1)$$

Where θfc and θwp is the moisture content at the field capacity and wilting point ($g\ g^{-1}$). BD is the dry soil bulk density ($g\ cm^{-3}$) and Z is the effective root zone. The irrigation system used was furrow irrigation, which is the most used in this region for sugarcane and other crops.

5.3.3 Variables measured

5.3.3.1 Sugarcane yield and growth variables

In order to evaluate sugarcane growth and yield responses under different irrigation management strategies, evaluations were carried out at 60, 90, 150, 210, 270, 300 and 340 days after cutting (DAC), totalizing seven evaluations during the crop cycle.

The growth components evaluated were: TI - Tillering (stalk m^{-2}) measured in 16.5 m^2, by counting the number of stalks in the evaluated area; Di - stalk diameter (mm) measured in the centered internode of the stalk, using digital pachymeter; IN - number of internodes, by counting the number of internodes in each stalk; and H - plant height (m) measured from the bottom until the last visible dewlap (+1 leaf), using measuring tape. The same components were also measured at harvest at 344 DAC on 13th January 2022. On this day each plot of 1,155 m^2

was manually harvested and weighted individually, then after converted for the estimation of CY - cane yield (Mg ha^{-1}). In Nicaragua and Central America, the sugarcane cycle it is between 300 and 360 days after planting or cutting.

Other growth variables measured, related to the plant physiological response measured and calculated were: NGL - Number of green leaves per stalk, measured counting the number of green leaves from the leaf +1 until the last leaf with at least 20% of green area. SLA - Stalk leaf area (cm^2) and LAI - Leaf area index (m^2 m^{-2}), measured according the methodology proposed by Hermann and Camara (1999) and LAR - Leaf area rate (cm^2 g^{-1}), where the LAR is obtained according the equation 2.

$$LAR = SLA \times SD \times DM^{-1} \qquad (2)$$

Where SD, is the stalk density or numbers of stalk per lineal meter and DM is the dry matter of all the plants in one meter long.

For the growth evaluations ten stalks were marked and identified in five plots per treatment, i.e., the same plants were evaluated during the crop cycle. The only data that was not obtained in marked points was the DM. This data was taken by destructive method where, all the plants in one meter long in each plot was cut and weight, obtained the total fresh weight. After that, all the plants per sample was milled and one sample of 500 g was dried in the oven at 110°C until constant weight to obtain the moisture content hence the dry matter.

5.3.3.2 Irrigation water depth

To measure the irrigation water regimes – IWR in each event, was used a Parshall flume at the mean water channel. This equipment measure the water flow – Q (l s^{-1}) and with the area irrigated – S (ha) and the time spent in each irrigation event – t (h) to irrigate the area S was possible to obtain the IWR (Equation 3).

$$IWR = \frac{Q \times 0,36 \times t}{S} \qquad (3)$$

5.3.3.3 Water Use Efficiency

The water use efficiency was calculated considering the sugarcane yield and the total irrigation water applied. Similar studies also calculated the WUE using the same methodology (Ibragimov et al., 2007; Lu et al., 2000; Magaña et al., 2016). To obtain the WUE the following equations 4 and 5 were used:

$$\mathrm{IWUE} = \frac{\mathrm{CY}}{\mathrm{IW}} \tag{4}$$

Where IWUE is the irrigation water use efficiency (Mg ha^{-1} mm^{-1}), CY is the sugarcane yield (Mg ha^{-1}), IW is the total irrigation water applied (mm).

$$\mathrm{TWUE} = \frac{\mathrm{CY}}{\mathrm{TW}} \tag{5}$$

Where TWUE is the total water use efficiency (Mg ha^{-1} mm^{-1}), which is the division by CY and the total water (TW) use by the crop (mm), which is the sum of the total irrigation water applied and rainfall, both in millimeters.

5.3.4 Agronomical practices

The experiment was conducted in a field area in a ratoon sugarcane (2nd cut, crop cycle 2021) planted with the variety CP72-2086, genotype widely planted in Nicaragua and Central America. The past harvest was at 31st January 2021. With 5 days after the mechanical harvesting, the mulch (dry leafs) was aligned letting four rows free of mulch and 1 with. Mechanical cultivation was carried out with discs harrow at 25 days of age, with the aim of killing any weeds and better shaping the furrows for irrigation. At 60 days, the entire field was mechanical fertilized with 410 kg ha^{-1} of the formulation 25-06-06 (NPK), attending the crop nutrient demand. The further weed control happened as needed using the herbicides Terbutrin, Ametrin and 2,4D and was not necessary any use of insecticide either fungicide.

5.3.5 Statistical analysis

The results obtained in this study were statistically analyzed with the software Infostat (2020). The analysis of variance (ANOVA) was performed to evaluate the effects of the irrigation management strategies on sugarcane yield and yield components. Also, differences were considered significant when $p < 0.10$ using Tukey test.

5.4 RESULTS AND DISCUSSION

5.4.1 Irrigation water applied and soil moisture content

During the sugarcane crop cycle the use of irrigation was required in order to allow the crop development. The irrigation was carried out between February and June, during the first 150 DAC. After that, rainfall established and irrigation was no longer necessary. For ISw 9 irrigation events was done, while for IFI 5 events, totalizing 707.1 and 556.4 mm of water from irrigation, respectively (Table 2).

Table 2. Dates of irrigation events with its respective irrigation water regimes (WR) and the total water applied from irrigation in each treatment during the crop cycle 2021.

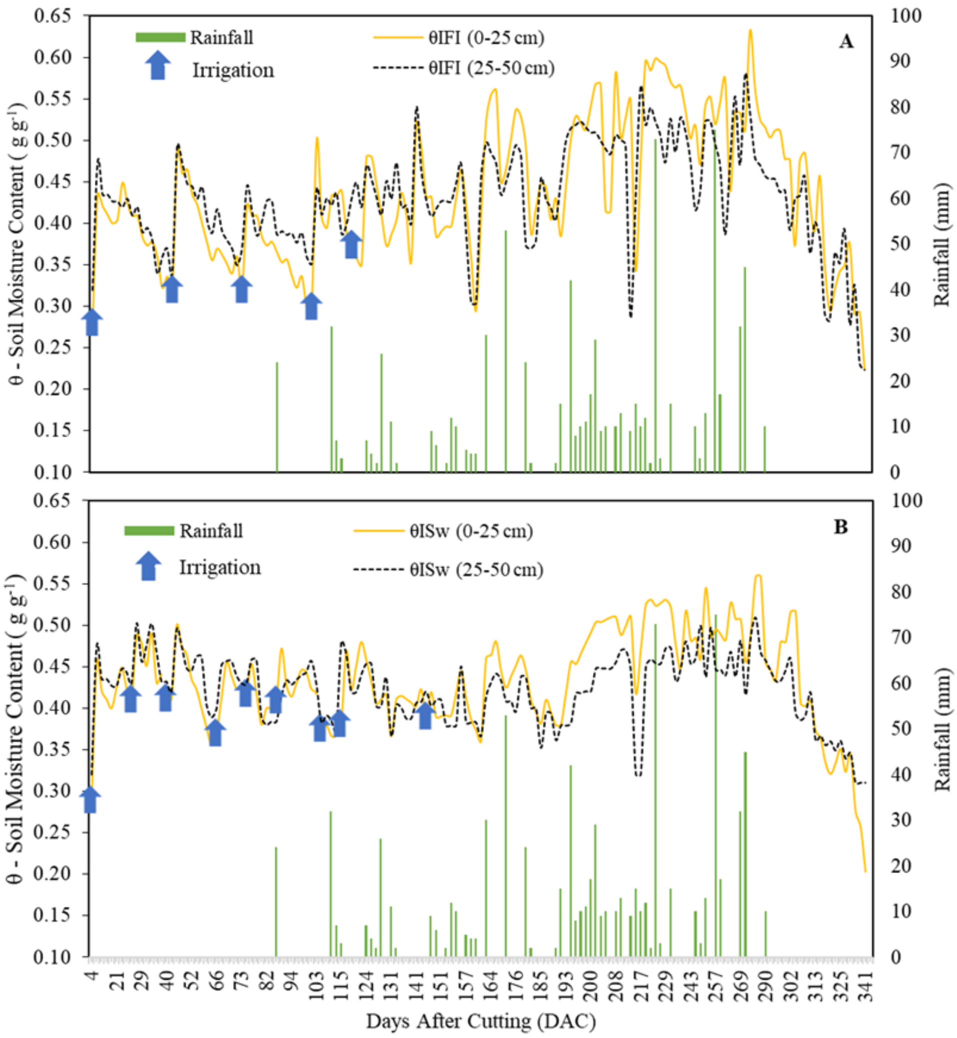
Date	DAC	ISw	IFI
		WR (mm)	
02/12/2021	12	117.0	119.2
02/25/2021	25	76.1	0.0
03/15/2021	43	88.1	116.7
04/07/2021	66	84.7	0.0
04/14/2021	73	61.6	119.0
04/27/2021	86	86.4	0.0
05/12/2021	101	79.4	117.0
05/26/2021	115	56.7	0.0
06/04/2021	124	0.0	84.5
25/6/2021	145	57.2	0.0
Total Irrigation Water		707.1	556.4
Average of WR		78.6	111.3

Source: Author (2022)

Even with 27% more total water consumption, the average of irrigation water regime was 29% less in ISw than IFI. The probable reasons that irrigation depth was higher in IFI was, since the soil was dryer when irrigation stared in IFI, there was less water available hence more water would be necessary to recharge. The other reason, could be due the Vertisol swell-cracking behavior. This type of soil alters its own volume according the soil moisture, expanding or swelling when is moist and cracking when its dry (Coulombe et al., 1996; Kutilek, 1996; Mitchell and Van Genuchten, 1993). With more water depletion in IFI, the soil moisture content reached inferior values than ISw, which caused more cracks in the soil. In furrow irrigation system, water flows from along the furrow from the head until the end by gravity. While the water advance on the surface, infiltration occurs in the soil profile. When the soil is cracked, first the water from irrigation or rain fill up the cracks than advance along the furrow (Fernandez-Gomez et al., 2004; Marlow, 2012), which may cause deep percolation hence more water consumption.

The soil moisture content (SMC) from 0-25 and 25-50 cm soil layer during the sugarcane cycle can be observed in the Figure 2. It is possible to see that the SMC in IFI at 25-50 cm depth, reached lowest values before irrigation and highest after. This may confirm the highest water depletion in the soil in this treatment compared to ISw. This confirms the evidence of deep percolation in this treatment, justifying the highest water irrigation depth in IFI.

Figure 2. Soil moisture content for the layer (0-25 and 25-50 cm) for the irrigation management strategies IFI (A) and ISw (B) and rainfall (mm).



Source: Author (2022)

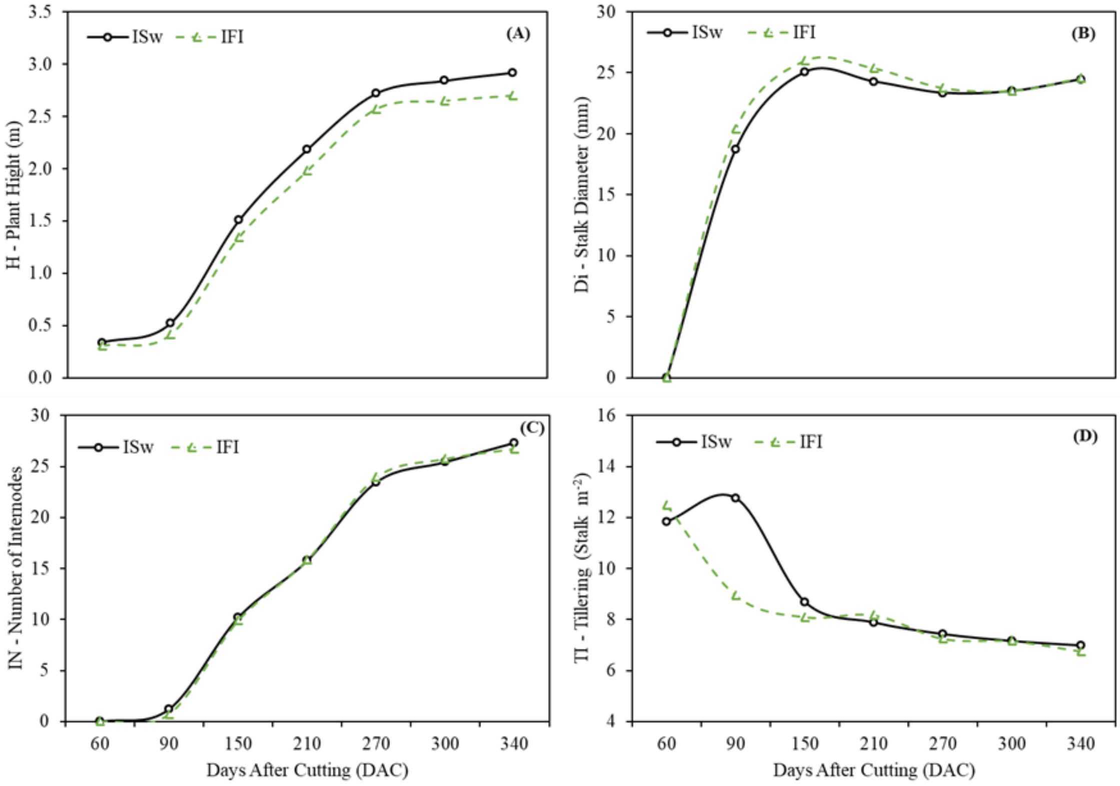
Most significant moisture variations occur at 00-25 cm for both treatments, because of irrigation and rain, and lowest variation take place at 25 – 50 cm (Figure 2). Similar results were found for Magaña et al. (2016) in Mexico, studying the soil moisture tension effect on sugarcane growth and yield. The water depletion was higher in IFI than ISw in both soil profile.

5.4.2 Sugarcane yield responses according irrigation management strategies

The sugarcane yield components response during the crop cycle are shown in Fig. 3. Since early stages, plant height (Figure 3A), in ISw was higher than IFI, and the difference between them increased over time. At 60, 150, 210 and 340 DAC the difference was 2.8, 16.0, 20.5 and 22.2 cm in favor of ISw. In early stages, first 60 days, the difference in stalk elongation was not so higher compared to those on mid stages (60 to 150 DAC). During the first 60 days, the total water applied (TW), irrigation plus rainfall, was 293 and 248 mm for ISw and IFI respectively, which represents only 45 mm of deficit. But on mid stage, the difference increased, reaching 159 at 86 DAC, 178 at 115 DAC and finishing with 151 mm at 145 DAC. This difference in the TW applied cause in IFI water stress which resulted in less plant elongation.

For stalk diameter and number of internodes (Fig. 3B and 3C), was not observed differences at the temporal evolution during the crop cycle. For tillering, the number of tillers per square meter increased at initial stage (90 DAC) for ISw compared to IFI. However, after 150 DAC both irrigation strategies showed the same behavior (Fig. 3D).

Figure 3. Temporal evolution of plant hight (A), stalk dimameter (B), numbers of internodes (C) and tillering (D) for sugarcane during the cycle 2021 in Nicaragua.

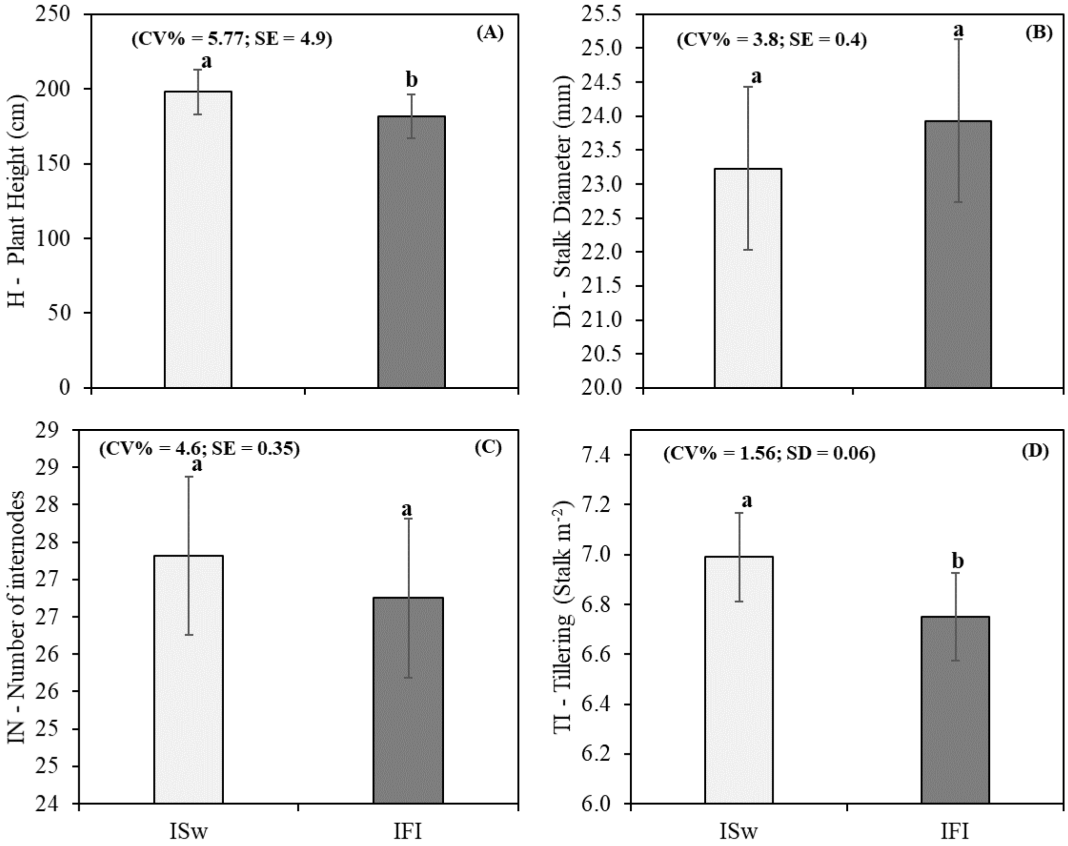


Source: Author (2022)

Sugarcane stalk elongation it was sensitive to water stress and several authors found similar results for this growth variable. In India, sugarcane under drought and waterlogged showed 18.25 and 7.11 % of difference in plant height compared to well irrigated treatment (Misra et al., 2020). Dinh et al. (2018) in Japan, studying the response of sugarcane to different nitrogen application for growth development under well-watered and drought stress condition, found that H reduced significantly under drought stress conditions. At the harvest, there was significant difference, for plant height, between ISw and IFI (Figure 4A).

Water it is essential for the plant turgidity maintenance which is necessary for cell enlargement and growth (Kramer, 1963). Several authors were study the impact of water stress in many other crops (Baher et al., 2002; Bonfim-Silva et al., 2011; Doss et al., 1974; Garcia et al., 2008; Oliveira et al., 2011).

Figure 4. Harvest analysis (344 DAC) for the variables Plant Height (A), Stalk Dimameter (B), Numbers of internodes (C) and Tillering (D). Different letters show significance between treatments at $p<0.10$ by Tukey test.



CV% - Coefficient of variation; SE – Standard Error; The bars represent the least significant difference according of Tukey test ($p<0.10$)

Source: Author (2022)

Plant diameter did not show differences between treatments neither on temporal evolution (Figure 3B) nor at harvest (Figure 4B). Both treatments finished with almost the same diameter, 23.23 and 23.93 mm for IFI and ISw respectively. According to Cesnik and Miocque, (2014), Oliveira et al., (2011) and Silva et al. (2008), stem diameter is a parameter that responses to the plant genetic and is less affected by the environment.

Like DI, number of internodes also did not show differences neither in the temporal evolution (Figure 3C) nor at harvest (Figure 4C) as well. At harvest, ISw was only 2.1% superior to IFI, not statically significant. Although the treatments showed the same number of internodes, IFI presented jointed internodes, due to its exposure to water stress (Figure 5). This happened because during stalk development, each internode operates as an independent unit and while it has a green leaf attached, the internode completes cell elongation, hence internodes generally complete their cycle by the time the attached leaf dies (OECD, 2016). Drought stress contribute to leaf senescence in sugarcane (Inman-Bamber and Smith, 2005; Smit and Singels, 2006) which took place at IFI treatment.

Figure 5. Comparison of internodes length under ISw and IFI conditions at 300 DAC.

Source: Author (2022)

Tillering is a process of underground branching from very short joints on the stem by which number of shoots are produced contribute for the number of millable canes in sugarcane

(Landell and Silva, 2004; Shrivastava et al., 2014; Vasantha et al., 2012). In general, under normal conditions, the shoots starts to germinate after planting or cutting, increasing until the maximum number of tillers when starts to decrease (tiller mortality) until its stabilization. Tiller mortality initiates after the attainment of maximum number of tillers and it varies with varieties, agronomic management, biotic and abiotic stress, climate and nutritional conditions.

ISw and IFI stared with the same number of tiller per square meter (~12.2) at 60 DAC. ISw achieved the maximum tillering at 90 DAC with 12.8 stalk m^{-2}. Afterwards, the stand dropped down until 6.99 stalks at 340 DAC. In the irrigation with fixed interval treatment, the result at initial stages was different. The maximum tillering happened at 60 DAC, with 12.4 and thereafter the field stand dropped down until 6.75 stalk per square meter at 340 DAC (Figure 4D). Final field stand was similar for both treatments, ISw was statistically above IFI (Figure 5D).

Similar results was fund by Zhao et al. (2010), evaluating the sugarcane response of water-deficit-stress and soil type in Florida, USA. They found differences in tillering between soils type but no so for well-watered and water-stressed treatments. In Australia, the number of stalk per square meter was similar but not statically different between treatment well-watered and early-season water stress (Robertson et al., 1999). Other authors was studied the response of sugarcane tillering and another biometric parameters under water-deficit-stress (Albuquerque, 2012; Ecco et al., 2014; Santos et al., 2019; Silva et al., 2008)

We believe that the little variation in TI, although statistically significant, was due the period when the water-deficit-stress happened. They main difference in total water applied (TWA), rainfall plus irrigation, happened in the first 150 DAC (Table 3). In this period, with -57% of TAW in IFI, the tillering just decrease while in ISw had a normal behavior. After that, rainfall was predominant and no irrigation was needed, hence, no variation was observed. Plant shoot formed after 60 to 90 days, due to shading or less radiation interception, are destined to die (Carr and Knox, 2011; Vasantha et al., 2012). Therefore, the tillering after 150 DAC, tended to equalize and ending up in similar values. Probably if the intermittent drought stress had continued in IFI, the TI in this treatment could continue drop down and finish with a field stand more significantly lower.

Table 3. Rainfall water, irrigation water applied and total water (mm), in each crop stage period (DAC) in both treatments and its variation.

DAC	RW	IW		TW		Var.(%)
		ISw	IFI	ISw	IFI	
0-60	12.0	281.1	235.9	293.1	247.9	-15.4
61-90	24.0	232.7	119.0	256.7	143.0	- 44.3
91-150	158.0	193.3	201.5	351.3	359.5	2.3
151-210	331.0	0.0	0.0	331.0	331.0	0.0
211-270	485.0	0.0	0.0	485.0	485.0	0.0
217-300	201.0	0.0	0.0	201.0	201.0	0.0
301 - 340	0.0	0.0	0.0	0.0	0.0	0.0
Total	1,211.0	707.1	556.4	1,918.1	1,767.4	-7.9

DAC – Days after cutting; RW – Rainfall Water; IW – Irrigation Water Applied; TW – Total Water (P + IW); ISw – Irrigation base on soil moisture; IFI – Irrigation with fixed interval (31 days); Var. (%) – TW variation of IFI over ISw.

Source: Author (2022)

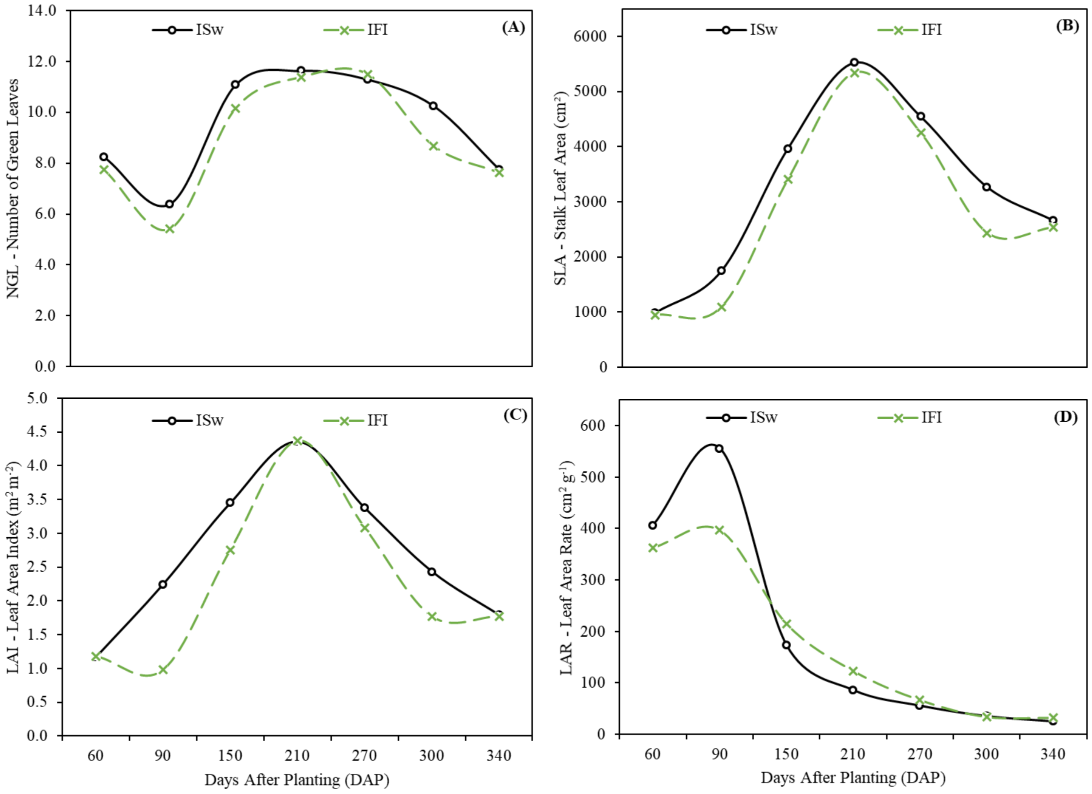
The rainfall and total water applied (irrigation + rainfall) during the crop cycle was 1211, 1918 and 1767 mm for ISw and IFI respectively which may attend the crop requirement according to several author (Carr and Knox, 2011; Dingre and Gorantiwar, 2020; Marin et al., 2020; Oliveira et al., 2018; Wiedenfeld, 2000). Even with enough water to supply the crop demand, the irregular distribution of the rainfall confirm the irrigation necessity in early stages, before 150 days. Thereafter the only the rainfall was enough to supply the crop demand.

5.4.3 Sugarcane growth variables during the crop cycle

Growth variables are parameters that relate external or physical plant structures with internal plant functions. Leaves are the principal plant structure, because is the site where photosynthesis and respiration happens, hence the carbohydrate production.

The number of green leaves per stalk (NGL) in ISw as superior to IFI almost during to whole experiment (Figure 6A). Only between 210 and 270 DAC the NGL was similar in both treatments, with 11.6 and 11.4 and 11.3 and 11.5 NGL, respectively. This indicate that, IFI had more leaves senescence during the irrigation period. Thereafter, the plants showed some degree of compensation in leaf appearance, recovering from the stress period. Similar results were fund by (Robertson et al., 1999). This data contribute to the affirmation where the short internodes was caused by early leaves senescence in the irrigation with fix interval.

Figure 6. Temporal evolution of NGL - number of green leaves per stalk (A), SLA – Stalk Leaf Area (B), LAI - Leaf Area Index - (C) and LAR – Leaf Area Rate (D) for sugarcane during the cycle 2021 in Nicaragua.



Source: Author (2022)

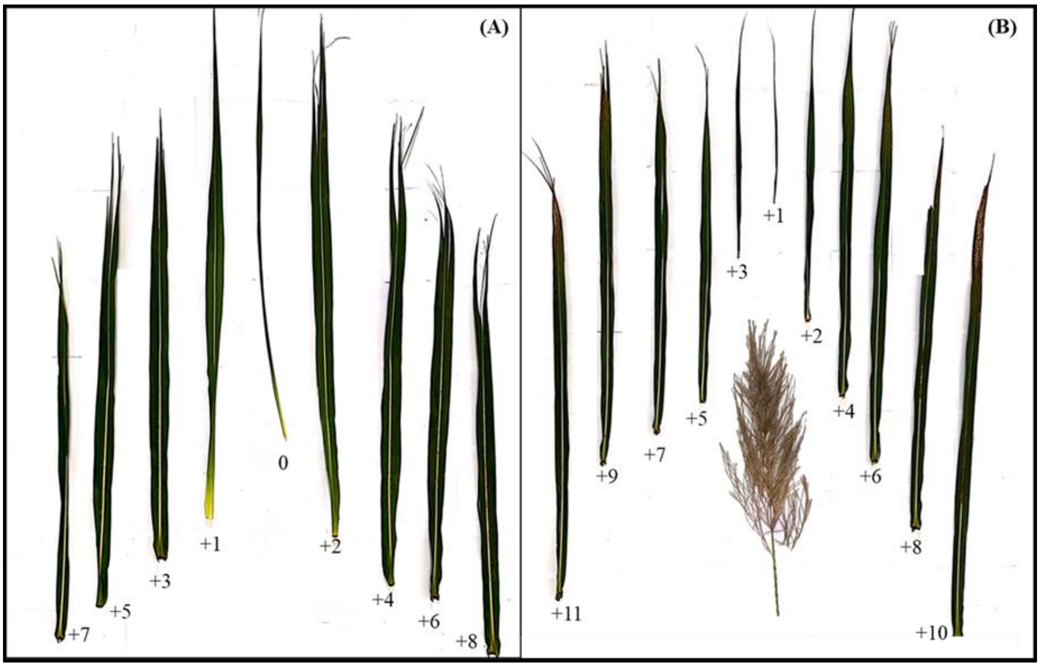
As responsible for the photosynthesis, the understanding about the leaf dimensions has been objective of study in many crops in order to simulate and knowledge growth plant behavior. In the present study, stalk area leaf and leaf area index in the temporal evolution had similar behavior (Figure 6B and 6C). The SLA stared with around 1000 cm2 for both treatments with pick at 270 DAC, with 4543 and 4251 cm2 for ISw and IFI respectively. Finishing at 340 DAC with only 4.6% difference. LAI, with the same tendency for ISw and IFI, with lowest values at 60 DAC, 1.16 and 1.18, and highest values at 210 DAC with 4.36 and 4.37 respectively. For those treatments, the biggest differences within the treatments happened during the 90 and 150 days after planting. The relative variation of IFI over ISw at 90 and 150 DAC was for SLA -37.4 and -14.1 % respectively; and for LAI at the same time interval -56.3 and -20.0%. Since LAI is a relation between NGL and SLA, and NGL present smaller differences between treatments, the variation of SLA according to the irrigation schedule was influenced by the increase or decrease of blade leaf area (Figure 7).

The effect of water deficit on morphological components was described by Cowan and

Innes, (1956) in Jamaica, where the water deficit was linearly related to the leaf elongation. Other authors mentioned the effect of drought stress reducing root growth, may causing the reduction in turgor pressure, the interruption of water flow from the xylem to the surrounding elongation cells, and a slowing down of the growth process, particularly in terms of a decrease in cell elongation and cell volume (Dinh et al., 2018; Nonami, 1998). This explanation is coherent to the effect on reduction of SLA in IFI.

After 210 DAC, both treatments had a sharp decline, especially for SLA and LAI. We believe that the two main reasons responsible for that was sugarcane flowering and the dry-off. CP72-2086 is a sugarcane variety widely planted in Nicaragua and Central America which is susceptible to flowering (Cengicaña, 2017; Oñate et al., 2017). The leaf flag emerged around 230-240 DAC and the flower emergence happened around 270 DAC. Once the panicle emerged the plant growth was stopped, therefore all vegetative development (Araldi et al., 2010). In the figure 7, it is possible to see the difference in all leaves from a stalk without flower (A) and flowered stalk (B). It get evident, the reduction of leaf area, as a result LAI.

Figure 7. Number of full expanded green leaves per plant (NGL) in the ISw treatment for the variety CP72-2086. (A) sugarcane plant without flower and (B) sugarcane plant flowered at 300 DAC.



The number bellow each leaf indicate its morphological position on the stalk according Kuijper system classification (Dillewijn, 1952).

Source: Author (2022)

The last rainfall happened on 20th November 2021 with 20 mm, and the harvest happened 13th January 2022, 54 days after that. Since them, no irrigation was applied in any treatment, which may also contribute for the leaves measurements decline. In order to reduce the soil moisture, the irrigation suppression was necessary. This practice allows the harvest machines traffic on the field without get stuck or damage. In sugarcane, irrigation is often stopped some weeks before harvesting with the aim to reduce soil compaction from harvesting machinery and to enhance sucrose content. This procedure is called “drying off” (Araújo et al., 2016; Inman-Bamber and Smith, 2005). The present study is in accordance to the results found by Inman-Bamber (2004), where he evidenced the drying-off caused rapid leaf senescence, reduction of SLA and LAI as well.

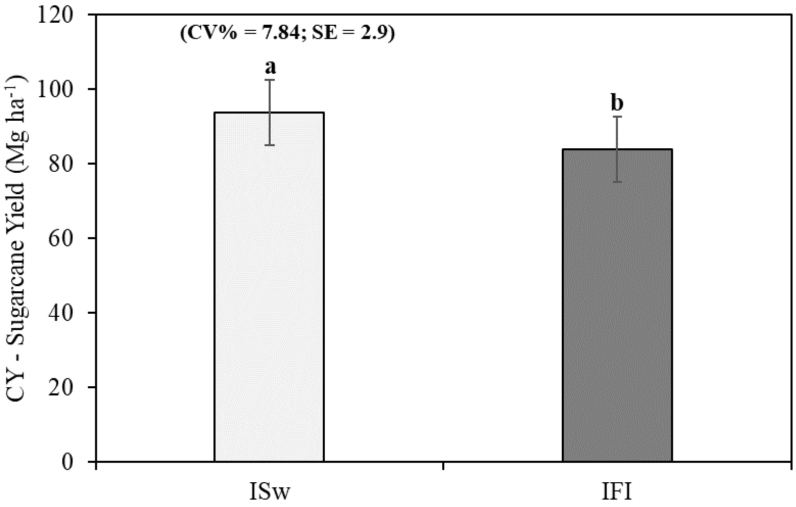
The leaf area rate (LAR) also stared similar in both irrigation schedules at 60 DAC but at 90 DAC ISw showed 555.7 while IFI showed 396.4 g cm^{-2} respectively. Subsequently ISw had a property fall, and the difference at 150 DAC to IFI was only 41.2 g cm^{-2} in favor of IFI, similar difference at 60 DAC. A long the time until harvest, LAR at treatments stared get closer and closer, especially after 210 DAC. According to (Magalhães, 1979) is a measure of the size of the assimilating apparatus, and serves as an appropriate parameter for the assessment of genotypic, climatic and plant community management effects. This parameter expresses the leaf area useful for photosynthesis and it is a morphophysiological component, as it is the ratio between the leaf area (area responsible for the absorption of light and CO_2) and the total dry mass (result of net photosynthesis).

All the growth variables shown the recovering of IFI once the soil moisture content increased, the explanation for this recovery leans on the compensatory growth phenomenon. The compensatory ability or “physiologic compensatory continuum”, is the plant ability to tide over many abiotic stress once this stress ends (Carr and Knox, 2011; Santos et al., 2019; Shrivastava et al., 2017, 2014). The morphological properties of sugarcane such as vast tillering potential, innumerable root primordia, different types of roots and emergence of leaves give the crop this ability to offset the stress once it finish (Shrivastava et al., 2014). Many authors have studied this mechanism underlying crop during post-drought rewatering in cotton, wheat, maize, grasses and sugarcane. Various factors, including photosynthetic rate, stomatal conductance, fertilizer use and anti-aging properties, have been found to play a role (Luo et al., 2016; Sadras, 1995; Shrivastava et al., 2014; Van Staalduinen and Anten, 2005; Wang et al., 2018, 2011).

5.4.4 Sugarcane yield under different irrigation management strategies

At the harvest time, sugarcane yield was significantly different between the irrigation schedules, where ISw and IFI presented 93.9 and 83.8 Mg ha^{-1}, respectively (Figure 8) and the irrigation base on soil moisture was 11.9% superior to IFI. Probably the differences were not bigger due to the time or the crop stage when the water-deficit-stress happened in IFI, in this study early stage. Robertson et al. (1999) found similar results, where drought stress had more deleterious effect compared to well-watered treatments, when the deficit happened in mid-season stages not in early-stages. The same author mentioned that the negative impact of water-deficit-stress is more sever when leaf area index is greater than 2.

Figure 8. Sugarcane yield (Mg ha^{-1}) at 344 DAC for ISw and IFI.

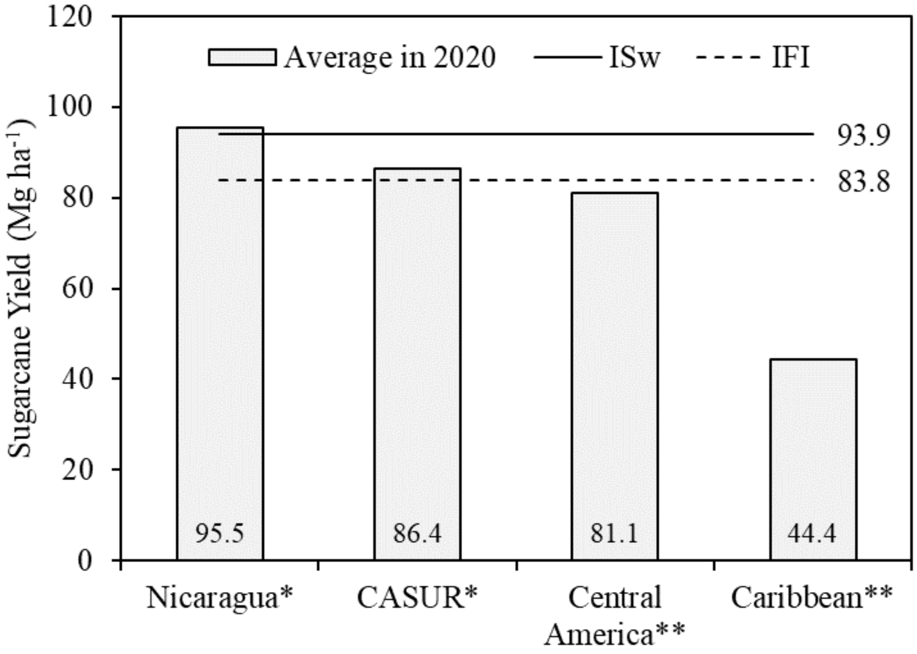


CV% - Coefficient of variation; SE – Standard Error; The bars represent the least significant difference according of Tukey test (*p<0.10*)

Source: Author (2022)

The yield reached in ISw is slightly inferior (-1.6%) than the national sugarcane yield achieved in Nicaragua in 2020 that was 95.5 Mg ha^{-1} reached in 71,516 ha harvested. However was 8.7, 15.75 and 111.7% superior than the yields in CASUR sugarcane mill, Central America and Caribbean respectively (Figure 9). This shows the potential of good irrigation strategy in order to achieve high yield and increase vertically the sugarcane crop production.

Figure 9. Average of sugarcane yield (Mg ha^{-1}) for both irrigation strategies compared with the Nicaragua national average, CASUR sugarcanemill, Central America and Caribbean for the year 2020.



Source: *CNPA (2021) and **FAO (2022).

Therefore, as the water deficit in IFI happened meanly before 150 DAC, once the drought stress finished as result of rainfall the plants probably responded to improved environmental conditions with compensatory growth, resulting in a smaller difference between the irrigation management strategies. Compensatory growth in sugarcane after water-deficit-stress are reported by several authors (Carr and Knox, 2011; Inman-Bamber and Smith, 2005; Nable et al., 1999; Robertson et al., 1999; Rossler et al., 2013; Santos et al., 2019; Shrivastava et al., 2017, 2014).

Even with compensatory growth, the irrigation schedule IFI reached lowest yields than ISw. In seasons when the yearly rainfall gets under the average, growth variables and sugarcane yield could be even higher for ISw. In the context of climate change, which may increase extreme events such as intense and long period of drought, storms, hurricanes, and higher temperatures the adequate use of the water resources became even more important. Best irrigation strategies may bring to the crops more resilience in front of the climate change challenge and allow the crops to achieve higher yield levels, which was obtained with the irrigation base on soil moisture content.

5.4.5 Water use efficiency for sugarcane under different irrigation management strategies

Water use efficiency, from the physiological approach, is the ratio of carbon assimilated as biomass or grain produced to water consumed by the crop (Hatfield et al., 2019; Sinclair et al., 1984). In the present study was evaluated two variables of water efficiency. The first the irrigation water use efficiency (IWUE) which consider only the water from irrigation and the second the total water use efficiency (TWUE), considering the total water applied on the crop, water from irrigation and rainfall. The IWUE for ISw and IFI, was 0.133 and 0.151 Mg ha^{-1} mm^{-1}, respectively (Table 4). Magaña et al. (2016) described studying IWUE in sugarcane under three different soil tensions had for the lowest soil tension treatment (-75 kPa) 0.405 Mg ha^{-1} mm^{-1} and 0.393 Mg ha^{-1} mm^{-1} for higher soil tension (-15 kPa). The treatment that had water-deficit-stress was more efficient in the irrigation water use efficiency, which was similar to the present study. The highest irrigation water use efficiency on IFI may be explained by the fact that the plants subject to water stress tried to maximize the use of available water as much as possible, by increasing their rate of growth in response of the improvement of the environment after drought stress, which is result of the compensatory growth.

Table 4. Cane yield and water relationship parameters under different irrigation schedules treatments.

Treatments	CY	IW	RW	TW	IWUE	TWUE
	(Mg ha^{-1})	(mm)			(Mg ha^{-1} mm^{-1})	
ISw	93.87	707.12	1,211	1,918.12	0.133	0.049
IFI	83.84	556.37	1,211	1,767.37	0.151	0.047

CY – Cane Yield; IW – Irrigation Water; RW – Rainfall Water; TW – Total Water (RW+IW); IWUE – Irrigation Water Use Efficiency; TWUE – Total Irrigation Water Use Efficiency.

Source: Author (2022)

Only 3.2% was the difference of ISw over IFI in the TWUE. This result is directly influenced by the rainfall water which led to a reduced difference between the water consumption between (TW - 8.53%). The results of IWUE and TWUE showed that even with a rise of irrigation water from 27%, the gain of biomass compensated this increase of water from irrigation, which led to a light difference between both treatments.

Values for IWUE and TWUE found in this study for the irrigation treatments are lower than those reported by Magaña et al. (2016) who reported for IWUE and TUWE at -15kPa, -45kPa and -75 kPa as soil tension (0.393, 0.365 and 0.405 Mg ha^{-1} mm^{-1}) and (0.0753, 0.0713 and 0.0569 Mg ha^{-1} mm^{-1}), respectively. Kingston (1994) reported values of TWUE for sugarcane in a range of 0.0837 – 0.2094 Mg ha^{-1} mm^{-1}.

Surface irrigation system it may be one of the main reasons why the lowest IWUE. The method tends to be less efficient than others like drip and sprinkler irrigation. Therefore the lowest irrigation efficiency result in more water consumption (Eldeiry et al., 2005; Varshney, 1995). Several authors have demonstrated the lowest water use efficiency, comparing surface irrigation to drip or sprinkles irrigation, in many crops Ramesh et al. (1994) with sugarcane, Ibragimov et al. (2007) with cotton, El-halim (2013) with maize and Paul et al. (2013) with capsicum.

5.5 CONCLUSION

The irrigation management based on soil moisture content can be an efficient alternative for sugarcane producers in Nicaragua, especially for regions that have limited access to data related to evapotranspiration and crop coefficient.

The sugarcane plants submitted to water-deficit-stress in early stage presented compensatory growth, which permitted the IFI treatment to recover from the drought stress. The growth variables on the temporal analysis confirmed this physiologic behavior.

The irrigation management based on soil moisture content was better than the local practice (irrigation with fixed interval – 28 days) in terms of sugarcane yield. This response can be related to the higher tillering, plant height and leaf area index during the sugarcane cycle.

Considering the water use efficiency of sugarcane produced in Nicaragua, the values for the different irrigation management strategies were similar. These results may be related to the irrigation system used (furrow irrigation), therefore an irrigation system that offers better application efficiency may be the key to achieve higher values of water use efficiency.

5.6 ACKNOWLEDGEMENTS

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5.7 DECLARATION OF COMPETING INTEREST

There is no conflict of interest for this study.

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6. CONCLUSÃO GERAL

A determinação local da evapotranspiração da cultura e do coeficiente da cultura são importantes ferramentas para o manejo adequado dos recursos hídricos na produção de cana-de-açúcar irrigada. Empresas e técnicos poderão usar os dados obtidos neste estudo como guia para uma melhor gestão de irrigação.

Além disso o presente estudo mostrou que, na ausência de dados meteorológicos para cálculo de ETc através do uso de ET_0 e Kc, a irrigação pode ser guiada com base na umidade do solo. Para cana-de-açúcar irrigada com esta estratégia, houve incremento significativo de produtividade sem comprometer a produtividade da água.

Ambos resultados vão ao encontro de uma produção de cana-de-açúcar irrigada sustentável. Tomando em conta critérios técnicos para o manejo consciente dos recursos naturais na produção agrícola de Nicarágua.

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