DRAINMOD Simulated Impact of Future Climate Change on Agriculture Drainage Systems

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***Abstract-* Agriculture drainage systems are designed to work for a long period. In the future, these systems will work in different climate conditions. A simulation study has been conducted using the widely used hydrological model DRAINMOD and nitrogen model DRAINMOD-NII to assess the potential impacts of future climate change on drained lands in Sweden. Two sets of 49-years climate data were used: measured historic period 1961-2009 and predicted period 2011-2059. Climate models predicted an increase in annual temperature by 1.9ºC and a 9% increase in annual precipitation. In response, DRAINMOD predicted a moderate increase in annual evapotranspiration (approximately 10%) and a slight increase in average annual drainage (less than 4%). Over the future 49-years, a 3% reduction in soil organic carbon was predicted because of faster decomposition during warmer winter and spring. The increase in predicted drainage and mineralization of organic nitrogen caused an increase in predicted N drainage losses. The predicted increase in denitrification during the warmer winter and spring improved the performance of controlled drainage for reducing N drainage losses. The model predicted a slight increase in crop yields of winter wheat and spring barley (less than 3%) and 7% reduction in the sugar beet yield.**

***Index Term* - Climate change, drainage, DRAINMOD, DRAINMOD-N II, carbon, nitrogen, water quality, crop yield.**

I. INTRODUCTION

Several studies have been conducted to predict the impact of future climate change on hydrology and crop production. In United States, Tubiello et al. [1] studied the impact of climate change in the 60 years period (2030-2090) on the yield of several crops (i.e. winter wheat, spring wheat, maize, potato, and citrus). The study showed that the increase in crop production depends mainly on the increase in precipitation. California’s Central Valley, Lee et al. predicted cotton, sunflower, and wheat yields decreased by approximately 2% to 9% by 2050 compared to the 2009 average yields [2]. While, other crops (e.g. alfalfa, maize, tomato, and rice), showed apparently no decreases in yield for the period 2010–2050.

In West Africa, Sonneveld et al. [3] showed that under average climate change conditions the current low yields are not reduced in the Oueme River Basin, Benin. In Iran, the impact of future climate change of the period (2015-2044) on four crops (wheat, barley, rice, and corn) has been studied [4]. Out of the four studied crops, rice and corn are more vulnerable to climate change due to their high irrigation water demand. So, their continued production can be compromised under climate change.

Models predicted that future climate change will bring about a rise in temperature and a change in precipitation regimes, which will affect the water, carbon, and nitrogen cycles (e.g. According to climate scenarios from SWECLIM model [5] the yearly mean temperature in Sweden will raise more than the global average). The predictions indicated that precipitation pattern will change in a warmer climate, with consequences for water availability, and the problems that too much or too little water will bring on [6]. Earlier studies showed that a rapid, even crop establishment are the basis for a high yield. Before and after growing season, drainage dries up farmland allowing for timely planting and harvesting. During growing season, drainage gets rid of excess water in the plant root zone, which eliminates or reduces excess water stresses and improves crop yield. The optimum design of Drainage systems should increase yields, reduce production costs, and minimize nutrient losses from drained farmlands to ground and surface waters. Over-draining farmlands could lead to yield losses because of the potential increase in dry stresses. On the other hand, Over-designed drainage systems also increase the potential for leaching losses of applied N fertilizers, which increase production costs and contaminates ground and surface waters. Drainage systems are designed to improve drainage characteristics for a specific soil type to meet the demands of a specific cropping system for specific climatic conditions. Drainage systems usually have a useful life of more than thirty years. As such, these systems are considered a long term investment. Thus, it is important to study the impacts of predicted climate change on the performance of agricultural drainage. Understanding the influence of predicted climate change on the water, carbon, and nitrogen cycles in drained lands will enable us to design drainage systems that improve crop productivity and environmental quality under the future climatic conditions. Models are the only tool that can be used to predict the implications of climate change on crop production. The latest version of the widely used drainage model, DRAINMOD [7], which incorporates the carbon and nitrogen model DRAINMOD-N II [8] has been calibrated and validated for a crop production system on a drained site in south eastern Sweden [9].

The objective of this research was to conduct a simulation study to assess the potential impacts of climate change on hydrology, nitrogen, and crop production for drained land in Sweden. The SWECLIM model was used to predict climate data for the future period. The DRAINMOD and DRAINMOD NII models were used to simulate the water, carbon, and nitrogen dynamics in Swedish drained crop lands under different climatic conditions.

II. MATERIALS AND METHODS

A. *Brief description of the DRAINMOD model.*

DRAINMOD [7, 8] is a field scale water management model developed to simulate the performance of drainage and water table management systems for shallow water table soils, and it has been widely used in the United States and worldwide over the last three decades. It conducts a water balance for soil column midway between two adjacent drains or ditches on a day-by-day, hour-by-hour basis and calculates infiltration, evapotranspiration (ET), subsurface drainage, surface runoff, deep seepage, water table depth on daily, monthly and yearly basis and crop yield on yearly basis. DRAINMOD simulates different drainage management systems including conventional drainage, controlled drainage, subirrigation, and combined controlled drainage/subirrigation systems. The model has different types of inputs including soil input parameters (saturated hydraulic conductivity (K_{sat}), Soil Water Characteristic Curve (SWCC), climatic input parameters (e.g. rainfall, temperature, and evapotranspiration), and cropping system parameters (e.g. planting and harvesting dates, root depths). In the last three decades, the model has extensively been tested for different climatic conditions, soil types, and farming practices [10-14]. In these studies, the model was calibrated and validated against field measured water table and subsurface drain flow data. DRAINMOD has graphical user interface software which is easy to use and available online with full description at the model home page (www.bae.ncsu.edu/soil_water/drainmod/).

B. *Climate Change Modeling*

There are alternative approaches for assessing hydrological impacts of climate changes scenarios (Fig. 1). Global climate models (GCMs) predicts climate changes for different hypothetical scenarios of greenhouse gas emissions. Hydrological models simulates the water, carbon, and nitrogen cycles for climate data predicted by the GCMs. An intermediate step to increase the resolution of GCM results over limited regions is the use of regional climate models (RCMs), which typically have horizontal resolutions of 50 km or less. Direct use of either GCM or RCM simulations in hydrological impact models is uncommon. Instead an aid worker called “Delta change” is used to transform climate data before using it in hydrological models. Climate change is caused by changes in atmospheric composition. Because it is not sure how emissions will be in the future, predicted climate data are based on different possible scenarios [16]. In this study, Rossby Center regional Atmospheric model, RCA3 [17], linked to the results from a global model, ECHAM4/OPYC3 [18], with an emission scenario called B2, produced the climate data used in the simulations. RCA3 includes a description of the atmosphere and its interaction with the land surface by the incorporated land surface and lake model, PROBE [19].

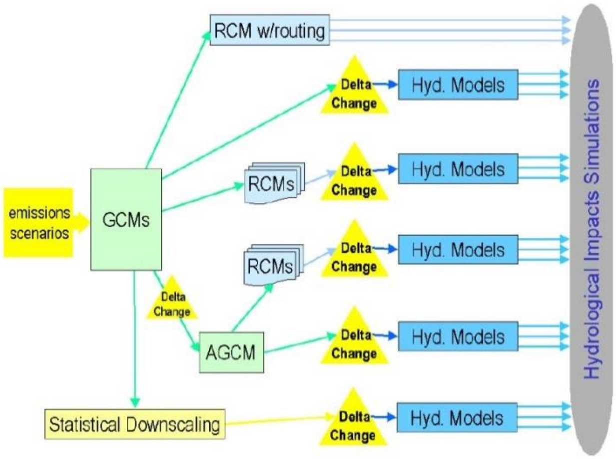

Fig. 1. Alternative approaches for assessing hydrological impacts from climate change scenarios [15].

The output from the RCA3 model was used as input data in DRAINMOD without further modifications. The climate data used in this study consisted of two thirty-year periods, one historical period including the years 1961-1990 and future period including the years 2011-2040, being compared and analyzed. Historical climate data were measured at Kristianstad meteorological network station provided from the SMHI [6]. The potential evapotranspiration was calculated from this data according to Penman-Monteith equation. The future period climate data were produced by calculations from RCA3.

C. *Site description.*

Figure 2 represents the location of the Gards Kopinge experimental site in south-east Sweden and field layout. The study area has a semi-humid climate with a mean annual air temperature of 7.6 0C (using 1961–1990 data from a meteorological network station at Kristianstad). Two months (January and February) have a mean air temperature below zero degrees [20]. The mean annual precipitation is 562 mm.

The topsoil (0–40 cm) at the site is weekly structured loamy sand with an organic matter content of 5%. The subsoil (40–100 cm) is sand with low organic matter content, which restricts the main microbiological activity to the topsoil. The root depth is limited by the soil texture in the subsoil [21]. Below 1 m depth there is a clay layer, which effectively restricts downward seepage. Soil physical properties are listed in Table 1. The experimental site was divided into four plots (Figure 2). The plot size was 36 m x 40 m. Each plot was drained separately by four parallel lateral drains spaced 9 m apart. Average drain depth was 0.9 m. The plots were isolated by plastic sheeting to a depth of 1.6 m to prevent lateral leakage and subsurface interactions. The outlets were connected to a weir allowing the groundwater to potentially rise to a pre-selected maximum height, after which outflow occurred. Two plots (P1, P3) were drained with conventional subsurface drainage (water table at 1 m depth) and the other two fields (P2, P4) were drained with controlled drainage (water table at 0.5 m depth) at the site.

Table 1. Measured soil physical properties at the experimental site in south-east Sweden

Soil properties	Soil depth (cm)		
	0-40	40-100	100-130
Clay (%)	9	2	56
Silt (%)	10	3	36
Sand (%)	81	95	8
Bulk density (Mg m^{-3})	1.3	1.6	1.5
Organic matter (%)	5.2	0.5	-
Soil pH	7.5	7.5	-
Soil water retention (cm^3 cm^{-3})			
Θ0.5 kPa	0.46	0.36	0.46
Θ10 kPa	0.27	0.12	0.45
Θ60 kPa	0.20	0.08	0.43
Θ1500 kPa	0.09	0.02	0.31
Ks (cm h^{-1})	9.70	14.07	0.00

All plots were treated equally for the times of planting and harvesting and the amount of fertilizer. The plots were incorporated into an ordinary Swedish conventional farming system with potato, cereals, sugar beets and catch crops included in the crop rotation. The farmer carried out all farming operations except the harvesting.

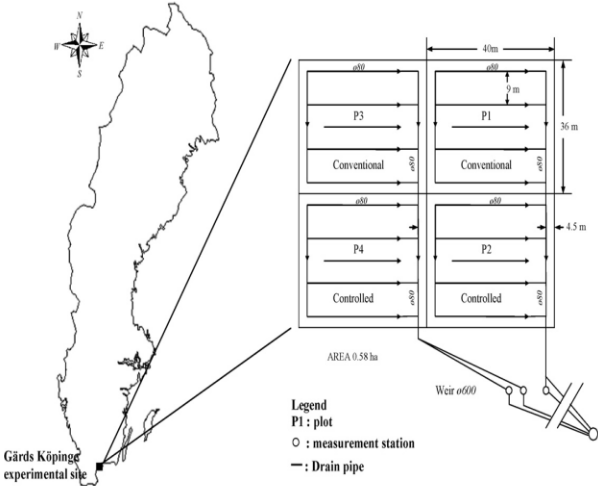

Fig. 2. Location of the Gards Kopinge experimental site in south-east Sweden and field layout [21]

D. Measurements

Climatic parameters were measured hourly (air temperature, soil temperature and precipitation) and daily (potential evapotranspiration) at the experimental field. Snow depth was obtained from meteorological network stations (SMHI). The groundwater levels in the plots (three replicates per plot) and the water levels in the weirs were monitored hourly. The drain outflow from each plot was measured hourly by flow meters. A water balance for each plot was calculated.

Mineral nitrogen contents in the soil profile (total N, NO3-N and NH4-N) and total C were measured three times a year; in early spring, at harvest and in late autumn. Soil sampling depths were 0-30 cm, 30-60 cm and 60-90 cm. The C/N ratio was determined. Samples of drainage water were collected by a flow controlled water sampler device. The water was analysed for total N, NO3-N, NH4-N, orthophosphate and total phosphorous.

E. DRAINMOD inputs

Input data and model parameters required in DRAINMOD including soil properties, parameters characterizing the crop, drainage parameters and climate data. Nitrogen-related parameters required in DRAINMOD NII include soil and crop management, N transport and transformation, and organic matter parameters. The option was selected for DRAINMOD NII to consider ammoniacal-N. In this study, simulations were conducted using data from a previously published study in which the model was calibrated sequentially for the hydrological and N components [22]. In model calibration/validation, monthly observed and simulated drainage outflows and NO3-N losses in subsurface drains (36 months) were compared by calculating mean absolute error (MAE), modelling efficiency (E) and index of agreement (d). Observed and predicted NO3-N losses in subsurface drains were in satisfactory agreement and the results showed that DRAINMOD is applicable for predicting NO3-N losses from drained soil under cold conditions in south-east Sweden.

F. DRAINMOD simulations

In this study, DRAINMOD simulations were conducted for the historic and future periods with the same soil conditions and cropping systems of the Gards Kopinge experimental site in south-east Sweden. Artificial subsurface drains were simulated at a depth of 100 cm with a spacing of 1000, 2000 cm. For simulations of drainage water management (DWM), the head gate was lowered to the drain depth of 100 cm three weeks prior to planting. Two weeks after planting, the gate was raised to a depth of 50 cm for the duration of the growing season. In preparation for harvest, the gates were again lowered to the 100 cm drain depth two weeks before the harvest date. One week after harvest, the gates were raised to 30 cm for the duration of the fall and winter seasons. To simulate conventional drainage, the head gate was set at the drain depth of 100 cm for the entire simulation period.

III. RESULT AND DISCUSSION

A. Comparison between historic and future weather

Table 2 shows the measured precipitation for the historic period. Also, the climate model was used to predict the precipitation for both the historic and future periods. The results showed very high precipitation for the future period (2011-2059), which is more than the measured historic precipitation by 75%. To judge the reliability of the climatic model predictions, the model was used to predict the daily precipitation for the historic period (1961-2009) based on the measured data and comparing these predictions with the actual measured daily precipitation. The results showed overestimated precipitation by 62%, which indicate the unreliability of the climate model predictions. The model performed the same with the predictions of the ET for the historic period, which is totally deviated from the measured values in the same period. To get more accurate predictions for the future precipitations, another precipitation values were adjusted for the future period based on the measured historic precipitation (Table 3).

Table 2. Comparison between measured and predicted historic and future precipitation (mm)

Month	Measured Historic Precipitation	Predicted Historic Precipitation	Predicted Future Precipitation
1	48.32	75.7	92.5
2	42.10	55.7	74.9
3	45.82	60.0	65.2
4	44.73	54.9	65.4
5	45.73	69.8	75.3
6	48.03	73.5	76.4
7	50.71	78.1	75.0
8	46.25	85.6	84.3
9	46.96	88.9	92.1
10	45.68	91.2	98.3
11	48.53	82.3	88.2
12	52.08	82.2	101
Annual	564.93	916	988

Table 3. Comparison between measured historic weather with future temperature and modified future precipitation

Month	Historic		Future	
	Temp. (C^0)	Rain (mm)	Temp. (C^0)	Rain (mm)
1	1.37	48.32	3.64	56.3
2	0.86	42.10	3.90	53.8
3	2.26	45.82	5.17	49.3
4	6.24	44.73	7.97	53.1
5	10.67	45.73	11.56	50.1
6	13.92	48.03	15.39	48.1
7	15.53	50.71	16.74	48.7
8	14.83	46.25	16.45	44.6
9	12.56	46.96	13.91	48.2
10	8.38	45.68	10.06	50.2
11	4.38	48.53	6.06	50.9
12	2.40	52.08	4.79	62.8
Annual	7.78	564.9	9.64	616.2

The new adjusted future precipitation was predicted to maintain the same monthly ratios between the predicted historic and future precipitation with the monthly measured precipitation. The ET predictions of the climatic model were not used in the DRAINMOD simulation. A temperature based method (Thornthwaite method) was used to predict the ET for DRAINMOD. The future precipitation showed average annual increase by 9% over the measured precipitation. This increase in the precipitation is due to the increase of the average future temperature ($9.64C^0$) from the average historic temperature ($7.78C^0$). This increase is mainly occurred in the winter and the early spring months which have the most increases in the temperature. The future precipitation is very similar to the historic precipitation in the summer months due to the similarity of the air temperature in these months.

B. *Effect of future climate change on hydrology*

The results of DRAINMOD simulations for both the historic and future periods at 10 m drain spacing are shown in Table 4. The results showed increase in the future evapotranspiration by 10.33% for the 10 drain spacing and 10.66% for the 20 m drain spacing (data not presented). The subsurface drainage will be almost the same for the future period. The increase in the precipitation produce corresponding increase in the evapotranspiration in the winter and early spring months due to the increase in the temperature in these months. Simulations of the hydrologic balance demonstrated that the ET has the greatest response to the change in the air temperature and this could be because ET was predicted using thornthwaite method which is a temperature based method. In this study, the DWM has a little affect on the subsurface drainage (i.e. the subsurface drainage outflows were reduced by less than 15% for the historic and future periods).

Table 4. Subsurface drainage and evapotranspiration (cm/month) predicted using historic and future weather data at 10m drain spacing

Month	Historic				Future			
	Conv.		Ctrl.		Conv.		Ctrl.	
	ET	DRN	ET	DRN	ET	DRN	ET	DRN
1	1.05	1.84	1.05	0.10	2.46	2.39	2.46	0.44
2	1.04	1.60	1.04	0.08	2.65	2.55	2.65	0.78
3	1.56	2.88	1.56	6.57	2.93	2.51	2.92	6.36
4	4.60	1.91	4.60	2.46	5.55	1.18	5.56	1.72
5	8.36	0.24	8.38	0.00	8.29	0.18	8.39	-0.01
6	9.38	0.00	9.43	0.00	9.45	0.00	9.48	0.00
7	9.10	0.11	9.20	0.11	8.91	0.00	8.99	0.00
8	3.80	0.00	4.01	0.00	2.89	0.00	3.19	0.00
9	2.19	0.00	2.43	0.00	1.50	0.00	1.78	0.00
10	2.66	0.11	2.76	0.00	2.55	0.09	2.72	0.00
11	1.78	0.40	1.78	-0.01	2.12	0.43	2.14	0.01
12	0.96	1.26	0.96	0.08	1.94	1.45	1.94	0.11
Annual	46.46	10.36	47.19	9.38	51.26	10.76	52.22	9.41

C. Effect of future climate change on crop yield

Table 5 shows the long term values of the relative crop yield for the historic and future periods for two water management practices. The results indicated that the climate change will not have significant affect on the crop production except for the second crop (Sugar beet), which will decrease by 13.4% due o the excess dry stresses expected in the future. Production of some other crops (Barley) will increase in the future by 2.6%.

Table 5. Relative crop yield predicted using historic and future weather data at 10m drain spacing

	Historic		Future	
Crop	Conv.	Ctrl.	Conv.	Ctrl.
1 winter wheat	92.2	92.5	91.8	92.0
2 sugar beet	74.5	75.5	64.5	65.6
3 spring barley	96.0	96.0	98.4	98.4
4spring barley	94.5	94.5	95.8	95.9
Avg.	89.3	89.6	87.6	88.0
STDEV	10.0	9.5	15.7	15.1

D. Effect of future climate change on OC dynamics

DRAINMOD was used to simulate the organic carbon (OC) dynamics in the soil for the historic and future periods. Results are presented in figure 3. The concentration of the organic carbon in the top 20cm layer was effected by the weather condition and by the water management practices while the first has the great impact. The organic carbon content will be reduced as a result of the future climate change. The reduction in the organic carbon content is about 3% due to the change in the weather condition and this could be due to the increase in the decomposition of the organic materials due to the increase in the temperature in the future period.

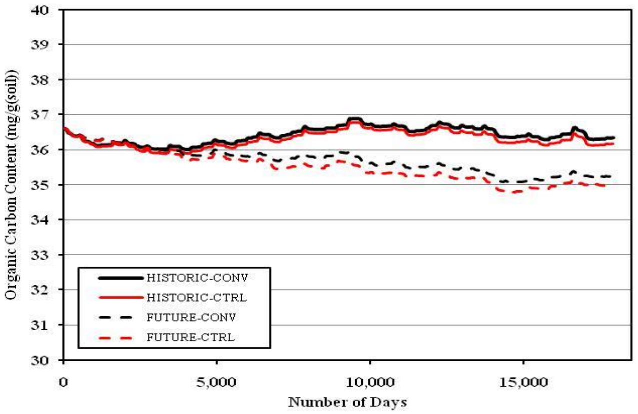

Fig.3. Change of organic carbon content of the top 20cm layer in the historic and future periods for 10m drain spacing

E. Effect of future climate change on nitrogen cycle

The results of DRAINMOD nitrogen simulations for the historic and future periods are presented in Table 6. The results demonstrated that the increase in the future temperature will increase the nitrogen losses in the subsurface drainage in the case of conventional drainage by 2.55 kg N ha^{-1} yr^{-1} across the region, which corresponded to a 10% increase. In the case of controlled drainage, the changes in the nitrogen losses will still the same in the future with small reduction. Also, the DWM has the greatest impact on the NO3 losses in the drainage outflows. Drainage water management reduced NO3 in subsurface drainage by an average of 4.42 kg N ha^{-1} yr^{-1} in the historic period, which corresponding to 17.25% and by 7.25 kg N ha^{-1} yr^{-1} in the future period, which corresponding to 25.75%. The denitrification process will increase in the future period as a result of the increase temperature.

Table 6. DRAINMOD simulated nitrogen components (Kg N ha^{-1} yr^{-1}) in the soil profile in the historic and future period for 10m drain spacing

			FA	RD	NM.	PU	DL	RL	DF
Historic	Conv.	Avg.	128.5	5.68	66.11	147.6	25.60	0.45	25.44
		Stdev.	36.95	1.35	38.10	40.57	26.56	1.46	14.20
	Ctrl.	Avg.	128.5	5.68	66.06	149.4	21.18	0.52	27.50
		Stdev.	36.95	1.35	36.27	42.26	23.03	1.47	17.56
Future	Conv.	Avg.	128.5	6.19	67.38	144.7	28.15	0.00	28.53
		Stdev.	30.81	1.54	32.39	36.32	31.98	0.02	17.02
	Ctrl.	Avg.	128.5	6.19	66.91	145.7	20.90	0.04	33.36
		Stdev.	30.81	1.54	32.58	37.17	24.85	0.12	24.44

FA, Fertilizer Application; RD, Rain Decomposition; NM, Net Mineralization; PU, Plant Uptake; DL, Drainage Losses; DF, Denitrification

IV. CONCLUSIONS

The effect of the future climate change in temperature and precipitation on the drainage system of the artificially drained land was studied. Two periods of forty nine-years: one historical period including the years 1961-2009 and future period including the years 2011-2059 for a study site in south-east Sweden were used to feed the hydrological model DRAINMOD. The model was used to simulate the hydrology, crop yield, carbon and nitrogen cycle. The climate data demonstrate a change in the future weather by increasing in the temperature and amount of precipitation. This change in the future weather will reflect on the drainage system in the future. The increase of the future precipitation will produce the same increase in the amount of the evapotranspiration and this could be because of the increase in temperature. The subsurface outflow will not have a significant change because the change in the precipitation will go directly as a change in the ET. The relative crop yields will still the same for the four crops in the crop rotation except for one crop, which will be decreased. The organic carbon content will be decreased by 3% for the top layer as a result of the increase of the temperature. Also, the NO3 losses in the drainage water will be increased in the case of conventional drainage by 2.55 kg N ha^{-1} yr^{-1} across the region, which corresponded to a 10% increase.

ACKNOWLEDGMENT

The author would like to thank **Dr. Mohamed Youssef**, the developer of DRAINMOD model from the department of biological and agriculture engineering, NCSU, USA for his help in model simulations and providing the required inputs of the model. Also, would like to thank **Dr. Ingrid Wesström** from Department of Soil and Environment, Swedish University of Agricultural Sciences for providing the climate date used in the analysis.

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