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Analysis of Indirect Effects in a Hydrologic Model for Use in Determining Potential Primary Productivity

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Contents

Abstract

A current program of the Land-Use and Land-Cover Change (LUC) group at the International Institute of Applied Systems Analysis is to determine the potential primary productivity of agricultural crops for parts of China, the former Soviet Union, and Mongolia. The work in this paper, supported by the Dynamic Systems group, is in collaboration with that LUC program. The main goal is to provide a methodology for investigating some of the indirect processes and pathways which affect primary productivity of crop production and to introduce a different modeling approach in estimating the potential productivity. The three main objectives of this research are the following: 1. Use network analysis to identify and quantify the indirect processes that affect the primary production of crop growth, 2. Develop a flow-storage compartment model to be used in the network analysis, 3. Quantify the flow-storage model using a dynamical simulation model. Although many factors control the primary productivity of a region, a main one is the availability of water, so the simulation model used here is based on the hydrologic budget of the study region. A four-compartment hydrologic model is developed which includes the within-system transfers between ground water, surface water, atmosphere, and vegetation, along with the external water transfers with the environment. When available, on-site climatic data are used to evaluate the model's parameters. The model is applied to a homogeneous region with a single cover type. Specifically, the model is calibrated using data from the Kursk region of Russia and the crop barley. This research shows that the atmosphere and soil moisture content both contribute important direct and indirect pathways for the water to reach the vegetation and subsequently affect primary production. Also, based on this model, the primary productivity is most sensitive to the vegetation growth rate and the rate of evapotranspiration. The model rationale and results are discussed herein.

Acknowledgments

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About the Author

This paper was written at the International Institute of Applied Systems Analysis, Laxenburg, Austria, where the author participated in the Young Summer Scientists Program 1997. Brian D. Fath comes from the Institute of Ecology, University of Georgia, Athens, Georgia, 30602, USA.

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INTRODUCTION

The main goal of this project is to provide a methodology for investigating some of the indirect processes and pathways which affect primary productivity of crop production. The methodology suggested for this project is network analysis. This approach allows for the identification and quantification of the direct and indirect pathways and contributions of flow along these pathways for a flow-storage network. The network analysis is the third of three distinct stages to be accomplished in this project. Each of the three stages builds on the previous one, and therefore, the tasks must be completed in reverse order.

The first step in implementing this methodology is to develop a flow-storage conceptual model of the study area which gives information relevant to primary production. Box (1981) suggests that a model based on macroclimate data is most suitable for assessing the primary productivity of a region. Macroclimate data such as temperature, precipitation, solar radiation, vapor pressure, and wind speed is generally reliable and available. However, these types of data do not represent physical flows, but rather are the parameters that act as controls on the system flows. A flow model is based on the movement of energy or matter through the system. Since plant growth processes interact with soil water and soil minerals to produce grain yield (Doraiswamy, *et al*. 1979), we could use either water or minerals as the model's conservative tracer. If we assume that the plant is not nutrient limited, then primary productivity is largely controlled by the amount of available water. The main assumption of this model is that crop yield can be expressed as a function of the amount of total water stored in the vegetation at the time of harvest. Therefore, a hydrologic model is developed and the physical quantity passing through the flow-storage network is water.

This conceptual model is realized using a dynamical simulation software package, STELLA (© High Performance Systems). In this way, the specific flows and compartments are identified. A system of differential equations can be derived from the model. By and large, the equations are linear donor controlled with time-varying parameters, but some flows are dependent completely on climate data. It is not practical, and probably not possible, to solve this set of differential equations analytically; however, using STELLA a numerical solution can be obtained. In this way, the direct flows are quantified and the model calibrated. These flow measurements are used in the network analysis.

The third stage of this project is the network analysis. Network analysis is an environmental application of input-ouput (I/O) analysis. I/O analysis was first developed by Leontief (1966) to analyze the interdependence of industries in an economy (Miller & Blair 1985). Hannon (1973) used I/O analysis to analyze the interdependence of organisms in an ecosystem. This technique has been modified and extended considerably since then (see Barber 1978, 1979, Finn 1976, Hannon 1979, 1986, Higashi and Patten 1989, Patten 1978, 1985, 1991, 1992, Ulanowicz 1986, 1997) and is the basis for the field of ecological network analysis. The main advantage of network analysis is that it allows for the investigation of the relationships between components of a system without removing them from the system. The reductionist trap of isolating two parts from an integrated whole is avoided. All direct and indirect effects are accounted for and the result is a holistic interpretation of system structure and function.

CONCEPTUAL MODEL

As stated above, the first step is to develop a conceptual model based on physical flows of energy or matter in the system which gives useful information regarding the primary productivity. There are many important factors to consider which influence potential primary productivity, and several are listed in Table 1. The data for many of these factors are readily available for the study area. The fourth category in Table 1, culture, can be very important locally in determining the overall crop yield of a region. However, cultural factors do not alter the primary productivity of this model because they are known and constant. Therefore, they are not explicitly incorporated into the model. The other factors in Table 1 are all included in the model.

Table 1. Main Factors Influencing Primary Productivity

1. Climate	a. Temperature b. Precipitation c. Wind Speed d. Vapor Pressure e. Irradiation
2. Vegetation	a. Growth Rate b. Date of Emergence c. Date of Maturity d. Maximum Root Length
3. Soil	a. Soil Moisture Content b. Water Table Level c. Hydraulic d. Conductivity e. Infiltration Rate
4. Culture	a. Crop Selection b. Time of Planting

Along with determining which data we need to analyze, it is necessary to choose an appropriate type of model for this research. Doraisway, *et al*. (1979)

identified three main types of models: statistical, realistic physiological, and general physiological, for use in estimating primary productivity (Table 2). Statistical models use least squares or regression to choose variables and identify significant interactions. This approach often has strong predictive power, but is less useful in adding understanding of the physical and biological processes. Realistic physiological models use a detailed simulation of main plant processes. These models are strong in understanding, but the complexity and detail makes them difficult to implement without a great deal of expert knowledge of the plant physiology. General physiological models simulate a few plant processes using a limited number of variables based on physiological principles, theories, and experimental data. Given the amount and type of data available, as well as the expected application, the third model type was deemed most appropriate for this study. A general physiological model, which captures the basic climate, vegetation, and soil factors listed in Table 1, was selected for this project.

Table 2. Three common types of models used to estimate primary productivity

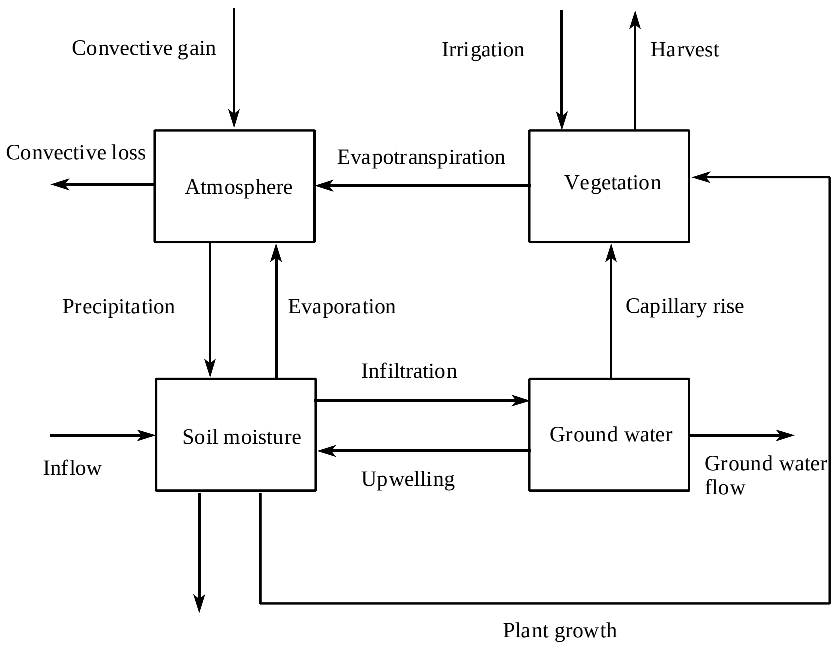
1. Statistical Models	Use least squares or regression to choose variables and significant interactions
2. Realistic Physiological Models	Use detailed simulation of many plant processes
3. General Physiological Models	Use simulation of a few plant processes from a few variables based on physiological principles, theories and experimental data

MODEL

Based on the above considerations, a four-compartment hydrologic model is developed for this project. The goal of the model is to trace the hydrologic budget through the main components of the system. The total amount of primary productivity is related to the gross amount of water present in the vegetation at the time of harvest. Of the gross biomass of the vegetation, a certain percentage is water, some usable grain, and some unusable biomass. Therefore, having information regarding the total amount of water in the vegetation allows for an estimation of the total grain yield of that region.

The model represents a point in space of an agricultural field in the Kursk region of Russia in which the grain crop barley is produced. Numerically, the values in the model represent mm of water over one square meter per month. Therefore, the values are equivalent to liters of water (which equals one kg) per month. The conceptual model which was developed using the STELLA software is shown in Figure 1.

Figure 1. Conceptual Hydrological Model



STATE VARIABLES

The four compartments in the model are atmosphere, vegetation, soil moisture, and ground water. The specific form of water is not important, and therefore, is not specified in the model. The atmosphere contains a considerable amount of water vapor. This value can be obtained from the saturation vapor pressure and the relative humidity. It is assumed that the starting value in the model is 100 mm/m^2. During the growing season the vegetation acts as a pump taking water from the soil and transferring it to the atmosphere. A certain percentage of this water is necessary for the plant growth and metabolism and some is retained in the plant structure. Growth and water uptake into vegetation occur only during the growing season. When there is no vegetation, such as at the beginning of the year, there is no water present in this state variable, therefore, the initial value for the vegetation compartment is zero. The soil also contains a certain amount of water which is represented by the soil moisture compartment. The starting value for the soil moisture is assumed to be 20 mm/m^2. Finally, ground water can also play a role in the flow of water through the vegetation. The value of standing stock initially present in this compartment is difficult to estimate, and is initially assumed to be zero. This does not adversely affect the model because the interactions between the ground water and vegetation are minimal for the specific data used in this model. We have identified seven possible internal flows through which water can pass among these four state variables. These internal flows (connections) are depicted in the following adjacency matrix.

$$A = \begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad (1)$$

The adjacency matrix, A, is the connection matrix of the model. The flows are from columns to rows and correspond to the following compartments respectively: x_1=atmosphere, x_2=vegetation, x_3=soil moisture, and x_4=ground water. A general flow matrix for this system is given by:

$$F = \begin{bmatrix} 0 & f_{12} & f_{13} & 0 \\ 0 & 0 & f_{23} & f_{24} \\ f_{31} & 0 & 0 & f_{34} \\ 0 & 0 & f_{43} & 0 \end{bmatrix} \quad (2)$$

The seven flows are the following: f_{12}=evapotranspiration, f_{13}=evaporation, f_{23}=plant growth, f_{24}=capillary rise, f_{31}=precipitation, f_{34}=upwelling, and f_{43}=infiltration. Each flow is described in detail below (Table 3).

Table 3. Summary of flows and controls where A - Atmosphere, V - Vegetation, SW - Soil moisture, and GW - Ground water

Pathway	**Process**	**Controls**
V→A (f_{12})	Evapotranspiration	Growth Season
SW→A (f_{13})	Evaporation	Temperature, Humidity, Wind Speed, Irradiation
SW→V (f_{23})	Plant Growth	Crop Growth Rate, Soil Moisture
GW→V (f_{24})	Capillary Rise	Root Length, Water Table
A→SW (f_{31})	Precipitation	Climate
GW→SW (f_{34})	Upwelling	Water Table, Hydraulic Head
SW→GW (f_{43})	Infiltration Rate	Hydraulic Conductivity, Water Table, Climate

FLOWS

Evapotranspiration

The evapotranspiration pathway, f_{12}, captures the flow of water from the plant directly to the atmosphere. During the growing season, vegetation acts as a pump to move the water from the soil to the atmosphere. The amount of water along this pathway is dependent on the quantity of water stored in the plant compartment and the rate at which the evapotranspiration process occurs. The flow equation used in the model is given by: $f_{12}=c_{12}*x_2$, where c_{12} is the evapotranspiration rate. During one month's time, most of the water entering the plant will be lost so the value for this coefficient is high. This rate is held constant during the simulation process and was assumed to be 0.98.

Evaporation

The flow, f_{13}, from soil moisture to atmosphere is obtained by the onsite climatic data. This flow was the most complicated to calculate. Evaporation, E, was calculated using a modified form (Raudkivi, 1979) of the Penman equation (1948) (Eq. 3). Many of the climatic and soil parameter values were available from the field data and others had to be estimated. Breaking down Eq. 3 term by term we see that L, γ, and Δ are constants, which can be calculated from the ambient air temperature. R_n is the amount of incident solar radiation. The factor B affects the air drying process and is based on the surface roughness and wind profile, and e_{2s}-e_2 is the vapor pressure deficit. Calculation of the evaporation is done in the sub-model in Figure 1. Equations 3-8 are all taken from Raudkivi, 1979.

$$\mathrm{Evap} = \frac{\left(\Delta / L\gamma\right) R_n + B\left(e_{2s} - e_2\right)}{1 + \Delta / \gamma} \qquad (3)$$

The coefficients in Eq. (3) can all be derived from basic physical and climate data and are described below in further detail.

L, γ, and Δ are calculated from the average ambient air temperature. The average temperature is calculated using data for the minimum and maximum air temperature in the region, (Figure 2).

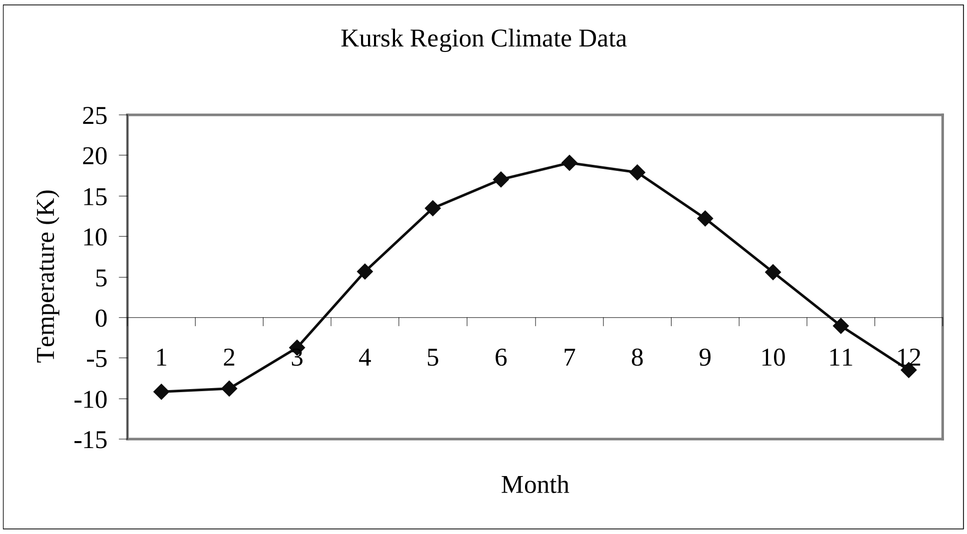


Figure 2. Average monthly air temperatures (C) for the Kursk Region.

These average temperature, T, values were used to calculate the parameters in equations 4, 5, and 6.

$$L \approx 2500.78 - 2.37(\overline{T} - 273)\, {}^{kJ}\!/\!_{kg} \tag{4}$$

$$\gamma = 0.000660(1 + 0.00115\overline{T_s})p \tag{5}$$

$$\Delta = \frac{e_s}{T^2}(6790.5 - 5.02808T + 4916.8 * 10^{-0.304T} T^2 + 174209 * 10^{-1302.88/T}) \tag{6}$$

For simplicity, the net radiation, R_n, was assumed to have a constant value (200 W/m^2). The coefficient B is dependent on several factors such as air density (ρ), air pressure (p), wind speed (u_2), relative humidity (z_2), and surface roughness (k) (Eq. 7).

$$B = \left(0.01\frac{\rho}{p}\right)\frac{u_2}{\ell n^2 z_2 / k} \tag{7}$$

The air density was assumed to be constant and equal to 1.0. The air pressure is also assumed to be constant and equal to 1000 mb. Even if these parameters varied it would have little or no impact on the overall estimation. However, both these terms are explicitly represented in the model and can be directly entered if data are available. The wind speed, u_2, is taken from field data and measured in m/s (Figure 3).

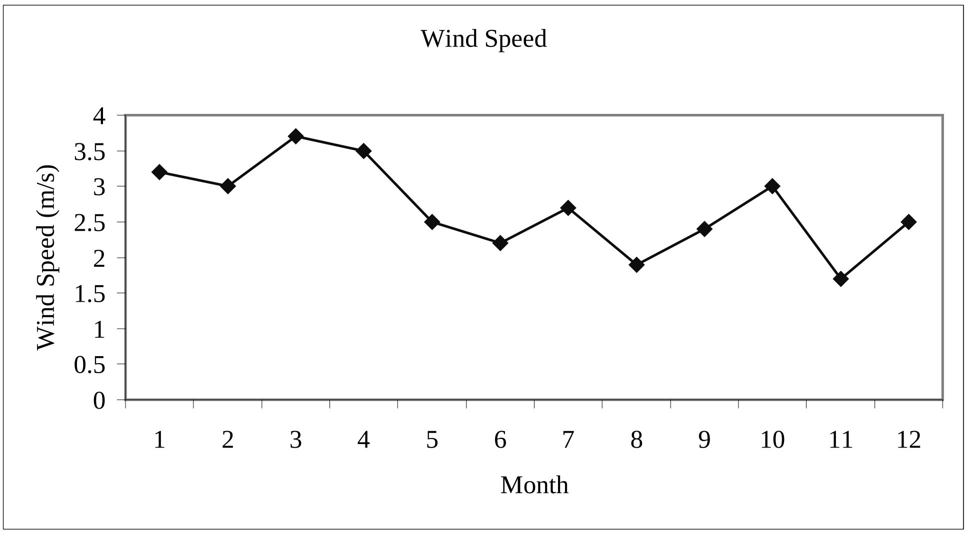


Figure 3. Average monthly wind speed (m/s) for the Kursk Region.

In an agricultural field, the terrain is relatively uniform, and the surface roughness depends on the crop height. Several authors (Deacon 1953, Tanner and Pelton 1960, Penman and Long 1960, Wright and Lemon 1962) have estimated the surface roughness coefficient for different crops (grass, alfalfa, wheat, and corn). Based on these estimates and the expected height of the crop during different stages of the growing season, the roughness height for barley is given in Figure 4. These parameters combine together to give an estimate of the coefficient B. The magnitude of this coefficient is generally very small for these simulations.

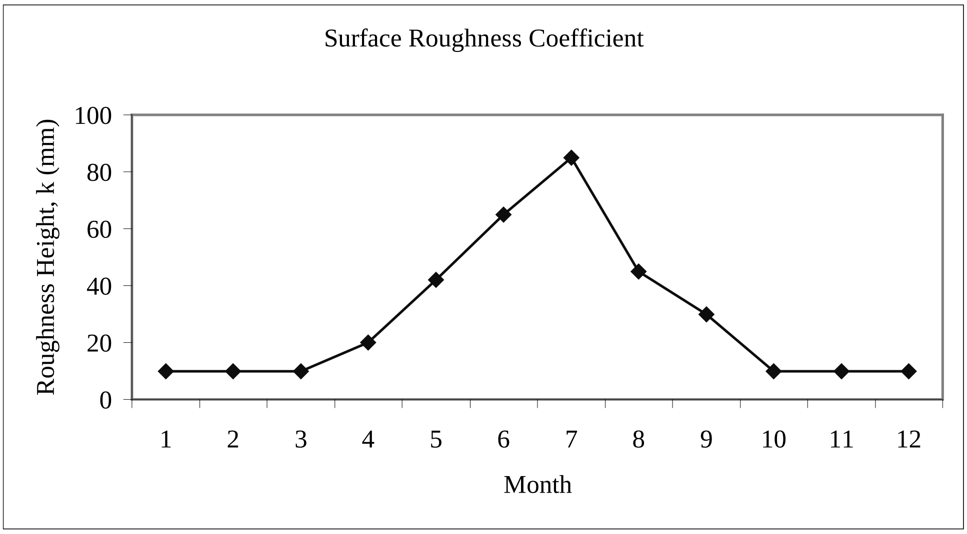


Figure 4. Monthly estimate for the surface roughness (mm) for barley in the Kursk Region.

The vapor pressure deficit, (e_{2s}-e_2) is the difference between saturation and actual vapor pressure. The saturation vapor pressure is also dependent on the average air temperature. In Equation 8, the temperature is expressed in °C rather than K. For –40 °C < T < 40 °C saturation vapor pressure can be expressed as:

$$e_s = 6.11 * 10^{7.5T/(T+137.3)} \quad (8)$$

The vapor pressure deficit, e_{2s}-e_2, is calculated using the saturation vapor pressure minus the actual vapor pressure. Data for the relative humidity at the site are used along with the calculated saturation vapor pressure (Eq. 8) to estimate the actual vapor pressure.

All these parameters control the amount of evaporation occurring in the system. The evaporation is calculated in Eq. 3 in units of mm/s over the unit square meter. The value is converted to liters per month for a point of the model. Here, the evaporation value is dependent entirely on climatic and estimated parameters, but not on the amount of water in the soil (or atmosphere). This flow is not donor (or recipient) controlled. We will show later how this affects the results.

Plant Growth

The uptake of water by the barley crop, f_{23}, is dependent on the growth rate of the crop. Water uptake only occurs during the growing season. An If-Then switch is used in the model to allow growth only during the appropriate months. Barley is planted in this region in April and harvested by August. The barley growth rate was assumed to be 0.25. This indicates that the plant took up 25% of the available soil moisture during the growing season and none the rest of the year. If the soil moisture is limited, then the amount of uptake by the plant is also limited. The flow equation is given by: $f_{23}=c_{23}*x_3$, where $c_{23} = 0.25$.

Capillary Rise

Capillary rise, f_{24}, is the process by which the plant roots take up water directly from the ground water. This occurs if the root depth and the water table levels coincide closely enough. The flow is represented in the model by an If-Then statement comparing the water table and the root depth. For this particular region and crop, the water table level is on average 5 m below the surface and the maximum root depth is only 1.2m. Therefore, the capillary rise flow is zero. The flow equation describing capillary rise is given by: $f_{24}=c_{24}*x_4$, where $c_{24} = 0$.

Precipitation

The amount of flow from the atmosphere to the soil moisture, f_{31}, is taken directly from the precipitation field data available for the region. The values for a monthly rainfall, in mm per month, are averaged over several years (Figure 5). The precipitation flow equation is given by: $f_{24}=c_{24}(t)$, where $c_{24}(t)$ is a time varying coefficient based on Figure 5. This flow is also completely determined by climatic data and is neither donor nor recipient controlled.

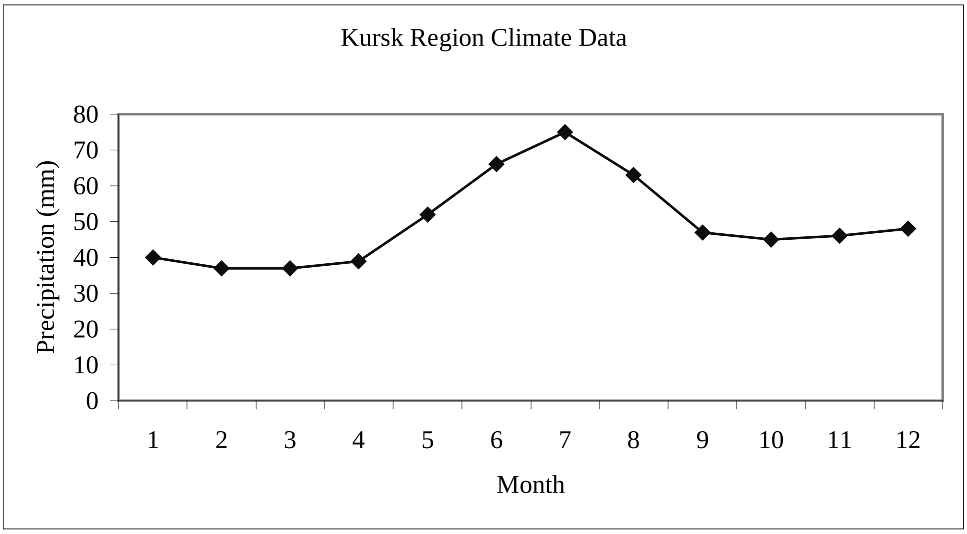


Figure 5. Average monthly precipitation (mm/month) for the Kursk Region.

Upwelling

Upwelling, f_{34}, occurs in areas in which ground water directly recharges the surface water. Because of the depth of the water table this flow was assumed to be zero for this region. The upwelling flow equation is given by: $f_{34}=c_{34}*x_4$, where $c_{34} = 0$.

Infiltration

There are several pathways available for the water held in the soil. It can be removed to the atmosphere through evaporation, be taken up by vegetation, leave the area by overland runoff, remain in the soil as storage, or infiltrate directly into the ground water. Infiltration, f_{43}, is the surface water that seeps into the ground water. The flow equation describing infiltration is given by: $f_{43}=c_{43}*x_3$, where $c_{43} = 0.20$.

INFLOWS AND OUTFLOWS

In addition to the internal flows, each compartment has outflow to the external environment and all but ground water receive external import into the system. Flows from and to the environment are notated using a zero subscript, f_{10} and f_{01} respectively. The ground water compartment may receive input but it does not have an effect on the flow model and so was excluded. The inflow into the atmosphere comes from the convection currents due to natural weather patterns. This value was assumed to be constant throughout the study period, $f_{10} = 50$. The outflow of moisture from the atmosphere is also primarily due to wind currents. It was assumed that half of the water vapor in the atmosphere state compartment is removed by convection processes, $f_{01}=c_{01}*x_1$ where $c_{01}=0.50$. The inflow to the soil moisture compartment comes in the spring months in the form of a winter snow melt. The input due to snow melt is given in Figure 6. Excess water runs off the surface as overland flow. It was assumed that 20% of the water in the soil moisture compartment would exit as overland flow, so $f_{03}=c_{03}*x_3$ where $c_{03}=0.20$. Inflow to the vegetation is in the form of irrigation. This option is available in the model but was assumed to be zero. Outflow from the vegetation compartment occurs during the fall harvest when the plant biomass is removed.

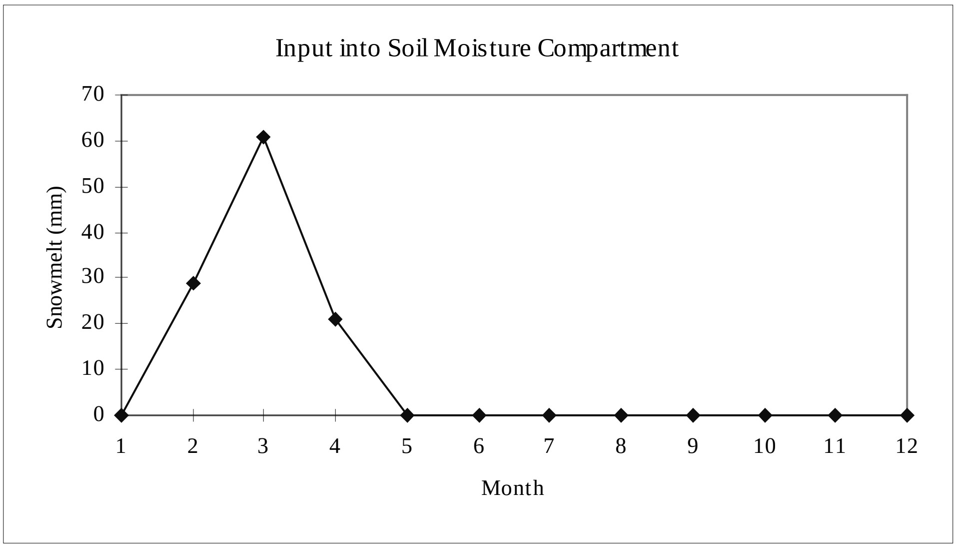


Figure 6. Input of water to soil moisture compartment from seasonal snow melt.

STATE EQUATIONS

Putting all the flow equations together we get the following set of state equations:

$$
\begin{aligned}
\frac{dx_1}{dt} &= f_{10} + f_{12} + f_{13} - f_{31} - f_{01} \\
\frac{dx_2}{dt} &= f_{20} + f_{23} + f_{24} - f_{12} - f_{02} \\
\frac{dx_3}{dt} &= f_{30} + f_{31} + f_{34} - f_{13} - f_{23} - f_{24} - f_{03} \\
\frac{dx_4}{dt} &= f_{40} + f_{43} - f_{24} - f_{34} - f_{04}
\end{aligned}
\qquad (9)
$$

This set of differential equations is solved numerically using a Runge Kutta method with a time step of 0.25 months for a period of 4 years.

MODEL RESULTS

The model was run for a four year period. At the end of the four years, the seasonal dynamics had settled into a repeating pattern (Figure 7). By assuming constant weather, the model

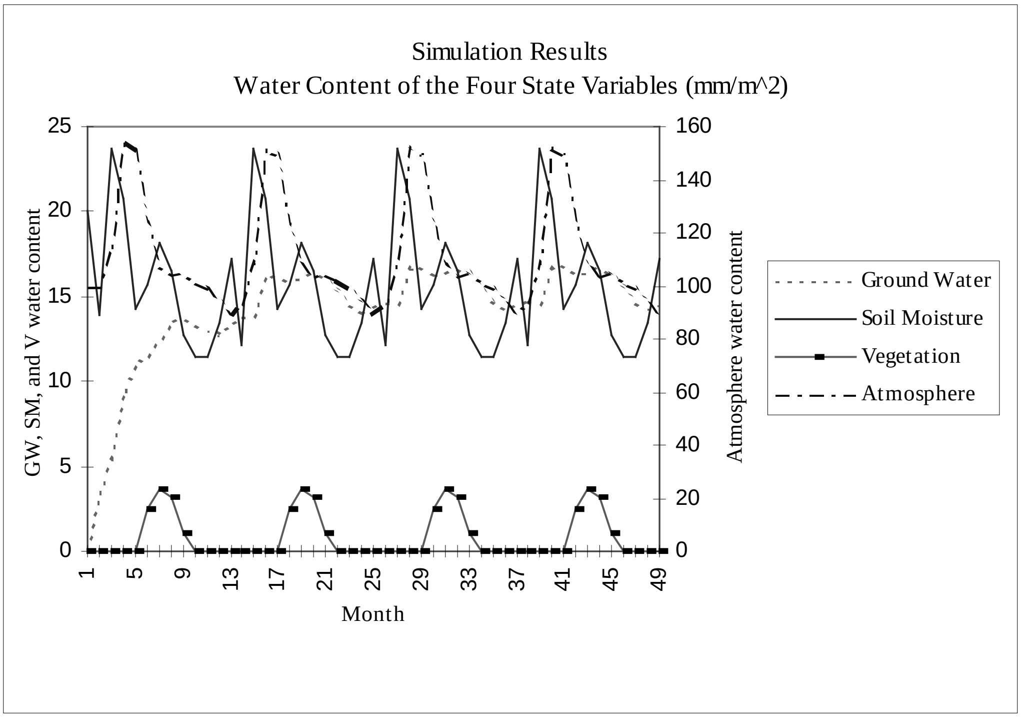


Figure 7. Seasonal variation of water content in the four model state variables: ground water, soil moisture, vegetation, and atmosphere.

reaches a periodic steady state necessary for the network analysis. Fluctuating weather data could easily be introduced by allowing the key parameters randomly varying between a given range. The model shows that at the end of four years there are 0.79 liters of water in the vegetation compartment during the time of harvest. This is equivalent to 0.79 kg of water over the one square meter of space represented by the model. If we assume that the ratio of water to grain production is 2:1, then the model estimates that a yield of .395 kg per square meter of agricultural land. Converting, this gives an estimated yield of 3950 kg per hectare. This value is almost a factor of 2 too high compared with the results from the WOFOST model for a primary productivity of the same region (Savin and Novikova, 1997). Of course this estimate is highly dependent on the accuracy of the ratio of water to grain in the vegetation at the time of harvest. Although the 2:1 ratio may be a guesstimate, it shows that this methodology can achieve results similar to the WOFOST model.

In order to look more closely at the relationship between model variables and yield estimation, a sensitivity analysis was performed in which the initial conditions and flow parameters were systematically changed and the subsequent effect on the yield noted. The results of this sensitivity analysis showed that the model was highly robust to changes in many of the parameters. Changing the initial conditions of any of the four compartments had no effect on the final output. Also increasing or decreasing many of the flow parameters by 10 percent had no effect on the yield. The model was most sensitive to growth rate, evapotranspiration rate, and precipitation. Figure 8 shows the results of changing the two most important variables for a series of simulations. As mentioned above, the water-to-grain ratio will also significantly alter the final crop yield.

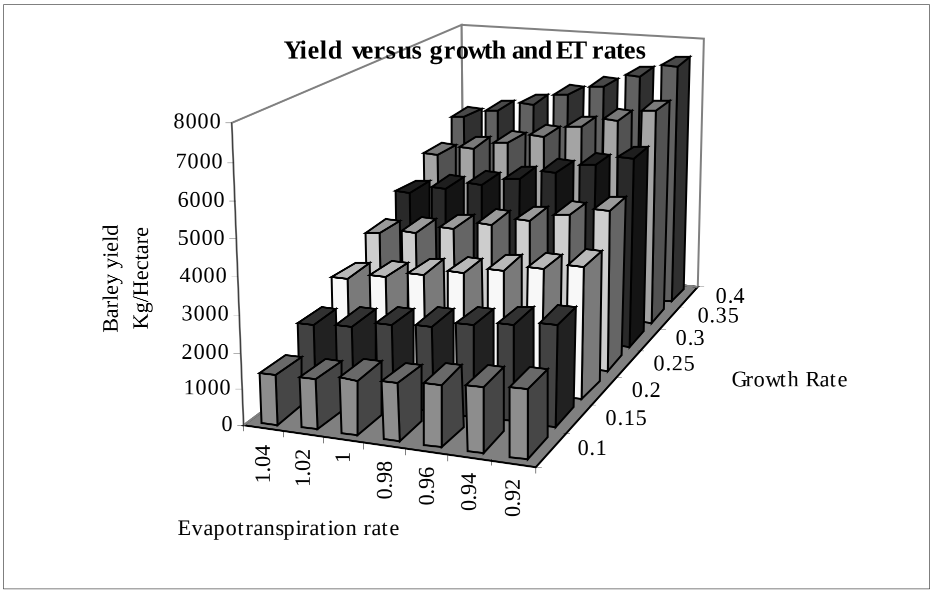


Figure 8. Sensitivity analysis of grain yield for various values of growth rate and evapotranspiration.

NETWORK ANALYSIS

PATH ANALYSIS

Network analysis gives several insights into the understanding of model structure and function. One of its most important aspects is its application in determining the indirect effects. The system is conceptualized so that the major nodes and pathways are identified. In a network with flow between two nodes. Indirect processes are those in which the flow between transmitting and receiving nodes is separated in either time or space. For example, to demonstrate the occurrence of indirect processes, we look at the simplified network given by the adjacency matrix in Eq. 10. The elements of the adjacency matrix, a_{ij}, give the total number of direct paths from j to i.

$$A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \tag{10}$$

Matrix multiplication gives the number of pathways from j to i in which the path length is equal to the matrix power. Whereas the pathways in A correspond to the direct flows, the matrices A^k, where k=2,3,…, are associated with the indirect pathways.

$$A^2 = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix} \qquad A^3 = \begin{bmatrix} 3 & 2 \\ 2 & 1 \end{bmatrix} \qquad A^4 = \begin{bmatrix} 5 & 3 \\ 3 & 2 \end{bmatrix} \tag{11}$$

If we look just at the number of paths to go from node x_1 to node x_2 (the (1,2) element in each matrix) there is exactly one path of length two: 1-1-2; two paths of length three: 1-2-1-2, 1-1-1-2; and three paths of length four: 1-1-1-1-2, 1-1-2-1-2, 1-2-1-1-2. These are the only possible paths to get from one node to another in the given number of steps. In this way, the direct and indirect pathways are explicitly counted. In a simple model such as this all the paths can be identified. Identifying the individual paths for longer path lengths and larger models is a very difficult task (Whipple, 1995). Yet, each of these paths is unique and flow along each one contributes to the overall effect of j on i.

FLOW ANALYSIS

The same basic principle which is used in the path analysis applies to flow analysis. Here however, the matrix multiplication is applied to a transition probability matrix. Now, the higher powered matrices give not the number of paths, but the probability of flow from j to i along all paths equal in length to the matrix power. The flow matrix is converted to a transition probability matrix by dividing its elements by the total throughflow at each compartment. The steady-state throughflow vector is calculated by summing the inflows or outflows to each compartment, $T_i = \sum_{j=0}^{n} f_{ij} = \sum_{j=0}^{n} f_{ji}$.

A limitation of flow analysis is that it can only (as presently formulated, see Matis and Patten, 1981 and Hippie for non-steady state examples) be applied to a system which is in steady state. The state variables in the hydrologic model clearly are not at steady state as they display seasonal fluctuations (Figure 6). However, after a significantly long run time (four years in this case) the seasonal variation is repeated year after year as a dynamic steady-state. For this region and this set of climatic conditions, one would expect the same flows for all subsequent years. Fourth year data are used as the baseline case for the analysis. The system is not in steady state at a particular instant in time, but over the course of a year the inflows and outflows are balanced. Therefore, the flow matrix, based on these 12 month averages, including the external flows, is at steady state. This balanced flow matrix is used in the flow analysis.

The annual average flow and storage values for the fourth year of simulation are used to determine the system flow matrix. In the flow matrix, F, the fifth column represents the inflow from the environment to each compartment and the fifth row is the outflow from each compartment to the external environment (Eq. 12).

$$F = \begin{bmatrix} 0 & 0.8608 & 53.9242 & 0 & 50.0000 \\ 0 & 0 & 0.9258 & 0 & 0 \\ 49.5783 & 0 & 0 & 0 & 9.2342 \\ 0 & 0 & 3.1275 & 0 & 0 \\ 55.2017 & 0.0658 & 0.8383 & 3.1275 & 0 \end{bmatrix} \qquad (12)$$

The nondimensional transition matrix, G, is calculated by dividing the flows by the total system throughflow (Eq. 13).

$$g_{ij} = \frac{f_{ij}}{T_j} \qquad (13)$$

Here we are interested only in the within system transfers so the 5th row and column are eliminated in the final transition matrix:

$$G = \begin{bmatrix} 0 & 0.9290 & 0.9168 & 0 \\ 0 & 0 & 0.0157 & 0 \\ 0.4732 & 0 & 0 & 0 \\ 0 & 0 & 0.0532 & 0 \end{bmatrix} \qquad (14)$$

Network flow analysis is based on the transitive closure matrix of the nondimensional transfer matrix (Kemeny and Snell 1960). As stated earlier the indirect pathways are captured in the matrices with powers greater than 1. To see the effect of all the direct and indirect processes, the sum of all powers is taken. This infinite series converges as long as the eigenvalues of the characteristic equation are less than one. Because of the openness assumption this criterion is always met. Therefore, the transitive closure matrix can be expressed as:

$$N = \sum_{k=0}^{\infty} G^k = (I - G)^{-1} \tag{15}$$

For the nondimensional flow matrix in Eq. 14, we get the following transitive closure matrix:

$$N = \begin{bmatrix} 1.7881 & 1.6610 & 1.6655 & 0 \\ 0.0133 & 1.0124 & 0.0281 & 0 \\ 0.8460 & 0.7859 & 1.7881 & 0 \\ 0.0450 & 0.0418 & 0.0951 & 1.0000 \end{bmatrix} \tag{16}$$

Looking at N, we see that elements, n_{ij}, that are greater than one have very strong indirect effects. In this model the indirect effects are strongest, not including the diagonal terms, along the flows from vegetation and soil moisture back to atmosphere. These flows play the biggest role in the overall hydrologic cycle.

Other key parameters which can be calculated using network analysis are total system throughflow, indirect-direct ratio, cycling, and utility benefit-cost ratio. The total system throughflow (TST) gives a measure of the total matter which is pulsing through the system. In an energy flow model this would be equivalent to the power, or work per unit time. Here it measures the total water flowing through the system. TST is calculated as the sum of the throughflows at each compartment:

$$TST = \sum_{i=1}^{n} T_i. \tag{17}$$

The direct transition probabilities in the system are represented in **G** and the integral flows nondimensionally in **N**. Therefore, the total indirect flow in the system is equal to the integral flow minus the direct flow and initial condition (indirect = **N–G–I**). An indirect to direct (i/d) flow parameter is found by taking a ratio of the sum all the elements of **N–G–I** and all the elements of **G**:

$$\frac{i}{d} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}(n_{ij} - g_{ij} - i_{ij})}{\sum_{i=1}^{n}\sum_{j=1}^{n} g_{ij}}. \tag{18}$$

The indirect/direct ratio is a measure of strength of the indirect effects in the network. For this model the ratio of indirect to direct effects is 1.756. Values greater than 1 indicate that indirect effects are dominant in the system.

The integral flow matrix, **N**, can also be used to calculate cycling in a system. Diagonal elements of **N** which are greater than 1 represent the fraction of throughflow at each component that cycles. Cycled total system throughflow (TST_c) is:

$$TST_c = \sum_{i=1}^{n}\left(\frac{n_{ii} - 1}{n_{ii}}\right)T_i, \tag{19}$$

and its ratio to TST is the cycling index (Finn 1976):

$$CI = \frac{TST_c}{TST}. \tag{20}$$

The cycling index gives a measure of the amount of material which cycles through the system. For this model, CI=0.42. This signifies that there is a great amount of water cycling in the model.

The utility analysis is given by the nondimensional net flow between system components (for more detail see Patten 1991, 1992, Fath and Patten in press). This analysis uses a benefit-cost ratio metric which gives a comparison of the strength of the positive interactions in the direct matrix and compares it with the strength of the positive interactions in the transitive closure matrix. If the b/c ratio is greater than one then the integral system has more positive interactions than the direct system. For this model, b/c=21.36. Numbers much greater than one, like in this case, indicate that synergism is strong, and underscore the above observations. that indirect processes dominate the system. Table 5 gives a summary of the key network analysis parameters.

Table 5. Key parameters derived from network analysis

Parameter	**Value**
Total System Throughflow	222.38
Cycling Index	0.42
Indirect-Direct Ratio	1.76
Benefit-Cost Ratio	21.36

DISCUSSION AND SUGGESTIONS FOR FURTHER RESEARCH

There are several places where this model could be improved and made more realistic given more time and data. The most pressing need for improvement is with the linkages between evaporation and the soil moisture compartment. The evaporation flow should be directly linked to the amount of water in the soil (and possibly also to the amount of water in the atmosphere). This will provide a direct feedback between the flow and state variable. Currently, without the feedback, the evaporation flow has little or no impact on the final primary productivity because it is constant based on the prevailing climatic data. Another addition may be to make the plant growth rate a function of temperature. This would also more closely link the growth rate parameter to the climatic data. Also, as mentioned above, some stochasticity could be introduced to precipitation or temperature data to more accurately reflect the changing climatic conditions. In other agricultural regions, the ground water may play a more important role in the transfer of water to the vegetation compartment. However, given the data for the Kursk region, the ground water had minimal impact on the vegetation growth. The model could be tested in regions which have a higher ground water table.

Finally, a more comprehensive and long-term research project could include linking together many point models to make a spatially explicit representation of the region (see Costanza and Maxwell 1991, Sklar *et al*. 1985, and Turner *et al*. 1989). Dynamic simulations could then be run for the entire landscape. The model could be designed to give both dynamic and spatially explicit indication of crop yield. This type of model takes many years to develop and a considerable amount of data.

CONCLUSIONS

The goal of this paper was to provide the LUC group another possible methodology for estimating the primary productivity of agricultural yield. I have shown that by using a simple hydrologic model a reasonable estimate can be made. Although overly detailed models are not recommended, because their inherent complexity often overwhelms the user's understanding and interpretation, this model could benefit from more time and attention to detail. The model did show, intuitively, that yield is most sensitive to the plant growth rate, evapotranspiration rate, and precipitation, in that order. In addition, the major benefit of using a hydrologic model is that it is a flow model in which the results can be used in network analysis. Network analysis has shown that the vegetation compartment is heavily dependent on indirect effects from both the atmosphere and soil moisture content. The amount of cycling in this system is high because the vegetation acts as a pump moving water from the soil to the atmosphere. The influence of the entire hydrologic cycle impacts the final production yield.

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