Path Analysis Technique for Strategic Irrigation Management under Adverse Climatic Conditions

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Abstract

Path analysis is a statistical technique widely used for modeling causation among a set of variables. A path diagram sets out the plausible causal relationships, and the path coefficients estimated by solving the relevant structural equations determine the strength of the relationships. The path diagram can be used to assess the change required in one variable to counteract the effect of another variable or several variables. In particular, a path diagram can be used to determine the timing, duration, and rate of irrigation to a crop to compensate for the effects of unfavourable climatic conditions. However, such an approach would assume other factors like soil fertility, microbial activities, and cultural practices to be time invariant. A path diagram has advantages over crop models in that a crop model cannot account for uncertainty, and the latter is restrictive to the particular field conditions in which it has been developed and has been criticised for its inability to be readily translated into regional parameters where the climatic variables are more stable.

The study area in which such a path analysis technique has been applied is the Fitzroy river catchment in Central Queensland, Australia. The region has a semi-arid climate. The four major crops grown in the area are wheat, barley, cotton, and sunflower. The critical stages for the yield of these four crops, as reported in published literature, are planting time, flowering time, and harvesting time significantly influenced by the minimum, average, and maximum values of rainfall, temperature, and humidity. Water stress in wheat reduces the duration of grain filling. High temperature adversely affects germination and seedling emergence and reduces grain number/spike and grain weight of wheat. High humidity is known to cause stem rust and leaf rust problems in wheat plants.

Climatic requirements for optimal yields of wheat and barley are different. Cotton also requires different climatic conditions for good yield. Cotton is a long-season crop which needs over 160 days with temperatures above 15^0C and adequate sunshine during the growing season. It can tolerate moderate salinity levels, and therefore, can be irrigated by brackish water or return flows. Sunflower production faces major problems with excess rainfall or moisture. Rust infection is a great concern for sunflower production which is favoured by heavy dews, wet weather, and temperatures above 20^0C.

The path analysis technique applied to the Fitzroy region's historic data yielded four different models for the four crops. Each model captures the range of optimal climatic variables and provides coefficients for the degree of adjustment required in the endogenous variable (irrigation supply) due to deviations in the exogenous variable(s). Each model can be used to plan the irrigation management strategy to offset the effects when one or more of the climatic variables deviate from ideal conditions. The climate information is available daily from the Bureau of Meteorology, Queensland.

INTRODUCTION

Prevailing climatic conditions play a very important role in crop yields. Each crop has its own ideal climate for maximum yield. While climatic conditions can be manipulated for a very small scale crop production, such a venture is unimaginable for large scale production or for vast tracts of agricultural land. There are many crop models developed by researchers which capture the crop yields against the backdrop of a set of climatic and soil fertility factors. These are deterministic tools which cannot be applied to large farms or in regional scale because there would be variability in all the factors across a region. A more useful approach to relate climatic factors of a region to its crop production is a statistical model because that would allow taking into consideration the variation within a region. If data on crop yields as well as climatic variables of a region are available for many years, that can be used to develop statistical models as to which values of climatic variables provide maximum yields and how the deviations from those values affect the yields. Once that knowledge is acquired, it may be possible to control some inputs to counter the adverse effects of climatic factors.

Humans have designed irrigation to counter rain deficiency. The same technology can be used to counter other negativities of the climate. For that purpose, we first need to identify what climatic factors do significantly influence crop yields. This evidently would vary from crop to crop and on soil characteristics as well. Second, for a given crop grown in a given region, we need to quantify the degree of relationship between crop yield variation to the deviation in a climatic factor from the ideal condition. Third, given that a quantitative relationship has been established, we need to investigate how irrigation scheduling can be done to counteract the resultant adverse effects of all the climatic variables. The concept of deficit or optimal irrigation has been there for a while and has replaced fixed depth irrigation at set time intervals in many places as water is frequently a scarce resource. Such schemes can easily incorporate the effects of climate. The depiction of quantitative relationship between crop yield and climatic factors can be done through path analysis and that can be done in isolation from the influence of soil characteristics by restricting the study to the same region over time.

The paper is organized such that in the next section path analysis is described. That is followed by a description of the study area. After that, the application of the model and results are presented. The paper is concluded by a discussion section where strategies are suggested.

PATH ANALYSIS

Multiple regression analysis is a common approach in scientific studies to capture relationships amongst variables. However, such an approach lacks interpretation and not necessarily a statement of causal relationship. But, Nagel (1965) draws attention to the fact that we frequently seek causal statements. Path analysis technique can be considered an extension of the regression technique where we attempt to establish causality. To illustrate path analysis in simple terms, consider Figure 1 where Irrigation (Z_1) is an input variable. Maximum Temperature (Z_2) depends on Z_1 and Crop Yield (Z_3) depends on both Z_1 and Z_2. The variable Z_1 is an exogenous variable. Any variable which is not dependent on another variable is called an exogenous variable. The variable Maximum Temperature (Z_2) is an endogenous variable. An endogenous variable is dependent on one or more of the other variables in the model. The direction of the arrow shows the dependency. The direction of the arrow from Z_1 to Z_2 indicates that Z_2 is dependent on Z_1 but the converse is not true. For the converse to be true, a path diagram should have arrows pointing in both directions, which indicates that the dependence is reciprocal. The variable Crop Yield (Z_3) is also an endogenous variable, and the ultimate variable of our interest. All the variables have to be necessarily standardized (Z-score) in order to avoid redundancies due to scales in measurement.

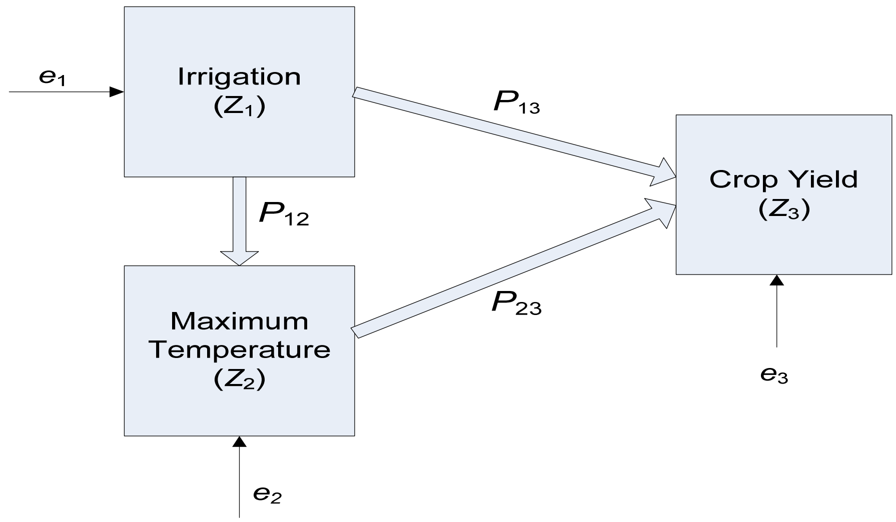

Figure 1. A path diagram of three variables Z_1, Z_2, and Z_3. P_{ij} are path coefficients and e_1, e_2, and e_3 are noise terms.

The path coefficients identified as P_{ij}s in Figure 1 can be estimated by solving the structural equations. The relevant structural equations are:

$$Z_1 = e_1, \quad Z_2 = P_{12}Z_1 + e_2, \text{ and } Z_3 = P_{13}Z_1 + P_{23}Z_2 + e_3 \qquad (1)$$

Applying the covariance operator to these equations and noting that Z-values are standardized scores (therefore, the variance of each variable is 1), we get:

$$\mathrm{Var}\ (Z_1) = \mathrm{Var}\ (e_1) = 1$$

$$\mathrm{Var}(Z_2) = P_{12}\mathrm{Cov}(Z_1,Z_2) + \mathrm{Var}\ (e_2) = 1 \qquad (2)$$

$$\mathrm{Var}(Z_3) = P_{13}\mathrm{Cov}(Z_1,Z_3) + P_{23}\mathrm{Cov}(Z_2,Z_3) + \mathrm{Var}\ (e_3) = 1$$

These are three equations with three unknown P_{ij}s, therefore, they can be solved. Evidently, the covariance terms are the correlations between the variables and the Var (e_i) = 1 - R_i^2, where R_i^2 (coefficient of determination) is the value obtained from the relevant multiple regression equation.

Normally, an elaborate path diagram is constructed first and a final model is determined by trimming the paths which are not significant. The significance is usually determined by the *t*- or *F*-statistic in regression analysis. Some argue (for example, Pedhazur and Kerlinger, 1982) that, with large datasets, significant values can be obtained even with spurious correlations. To avoid these problems, a minimum cutoff value of each regression coefficient has been suggested. This approach has some merit because all the variables are standardized. There are computer software packages available to develop path models – LISREL is one such popular software product.

To construct the elaborate path model of crop yield with respect to climatic variables, we need to know which climatic factors are likely to affect crop production. There is extensive literature available on the topic (for example, see Islam, 1996). From literature survey, it can be concluded that the critical stages of growth of a crop are planting time, flowering/head time, and grain ripening/harvesting time, and the climatic conditions which have significant influence during these critical stages of growth by affecting photosynthesis, evapotranspiration, osmosis, respiration, and phenological development rates are maximum, minimum, and average values of rainfall, temperature, and atmospheric humidity.

STUDY AREA

The area chosen for this study is the Fitzroy river catchment in Central Queensland, Australia. The catchment straddles the Tropic of Capricorn on the east coast of Australia between latitudes 21^0S and 27^0S and longitudes 147^0E and 151^0E. The total area of the catchment is 142,645 km^2, which is the second largest catchment in Australia, and is dominated by agriculture (grazing, dryland cropping and irrigated farming) and mining (coal production of over 100 million tons/year, magnesite and nickel). The area of cropping land is 7,065 km^2 and the area under irrigation is 450 km^2. The catchment gets an average annual rainfall of 750 mm. Russell (1981) has reported from trend analysis of about one hundred years of record that annual rainfalls have declined 2-5 mm per annum.

The catchment lies between two atmospheric pressure systems – south of the usual January position of the monsoon trough and north of the usual position of the subtropical ridge in July. Winds blowing from the east over the warm Coral Sea bring moist air into the catchment in summer. In winter, the monsoon trough and the sub-tropical ridge moves north causing eastward winds to bring much drier air from inland. The atmospheric system is not stable causing occasional occurrence of tropical cyclones and frontal rains. Such events when intense cause soil erosion resulting in soil degradation especially in elevated areas.

Four major soil/vegetation types have been identified in the region – Open Downs, Brigalow, Callide Valley Alluvial, and Eucalypt Woodlands. The agricultural soils are only Open Downs and Brigalow which are of cracking clay type with high water holding capacity and high infiltration rate when dry, but the infiltration rate is very low when wet. The topography of the region is characterised by treeless slopes of 1% to 5% gradient with slope lengths up to 4 km. These soils are shallow, varying in depth from 40 to 90 cm, with shallower sections occurring at the top of the slopes. Garside et al. (1992) report that the soil fertility is on the decline in the region.

Four generic grain farming systems have been identified in the region: all grain, mostly grain (predominantly grain with a small grazing enterprise), grain-cattle, and minor grain. Modern technology is used in the first two categories and the rest use traditional methods. The four major crops grown in the area are wheat, barley, cotton, and sunflower. From crop productions recorded since 1970 on a regional scale, the favourable climatic conditions for satisfactory crop yield are given in Table 1. These are purely empirical values as observed in the field when crop yields were high and has not been correlated with any physical, biological or physiological investigation into the process of plant growth and development. Furthermore, the values given are simply point estimates with the range being anywhere up to 20 percent of the values. Planting, flowering and harvesting times of the crops are given in Table 2. The long time climatic conditions of the region are given in Table 3. They reflect the average values, for example, the value of maximum temperature given is the average of the maximum temperature values observed over many years.

Table 1. Climatic conditions which recorded good crop yield in Fitzroy catchment.

		Wheat			Barley			Cotton			Sunflower		
Climatic Factor		Plant. time	Flower. time	Harv. time	Pla. time	Flo. time	Har. time	Pla. time	Flo. time	Har. Time	Pla. time	Flo. time	Har. time
	Max	200	10	300	110	20	500	100	300	50	300	50	30
Rain	Avg	60	2	50	40	5	110	35	120	10	135	20	8
(mm)	Min	0	0	5	0	0	5	1	40	1	40	0	0
	Max	30	25	35	25	30	35	35	35	30	35	35	30
Temp	Avg	20	15	25	15	15	25	25	25	20	25	23	15
(^{0}C)	Mean	5	4	15	4	8	18	15	20	5	20	10	4
	Max	60	45	40	60	45	48	40	65	45	65	50	40
Humi..	Avg	45	35	30	45	33	33	30	50	40	45	40	30
(%)	Min	35	25	20	35	15	20	20	40	30	30	25	20

Table 2. Planting, flowering and harvesting times of crops in Fitzroy catchment.

Crop	Planting	Flowering/Head	Harvesting
Wheat	April-July	July-September	October, November
Barley	May-August	August,September	October-December
Sunflower	December-February	March-May	June-September
Cotton	October, November	January-April	April-July

Table 3. Climatic variability of Fitzroy catchment as long-term averages.

Climatic Factor		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Max	660	446	447	1107	304	128	170	105	117	172	343	533
Rain (mm)	Avg	106	107	67	49	56	26	31	23	25	51	79	116
	Min	4	4	0	0	0	0	0	0	0	0	0	4
	Max	38	34	31	32	29	26	25	27	32	39	36	38
Temperature	Avg	27	28	25	22	25	16	15	16	20	24	26	27
(^{0}C)	Min	19	18	16	11	7	2	1	3	8	10	15	17
	Max	76	72	65	63	75	58	61	54	53	63	55	59
Humidity	Avg	43	49	43	41	43	41	39	34	31	34	36	38
(%)	Min	27	27	28	28	25	25	21	16	15	16	20	22

MODEL DEVELOPMENT AND RESULTS

The basis of path analysis is the assumption that there is a causal relationship among the variables. Frequently, there is a hierarchy of relationship. For example, we assume that temperature affects rainfall by influencing atmospheric pressure distribution which in turn is responsible for atmospheric circulation. Temperature also affects humidity and crop yield. Rainfall affects humidity and crop yield, and humidity affects crop yield. Some relationships are constituted partly of direct relationship and partly of indirect relationship. For instance, in Figure 1, path P_{13} gives the component of direct relationship between Irrigation and Crop Yield and paths P_{12} and P_{23} gives the indirect relationship via Z_2. Following the same procedure described in Equations (1) and (2), and 27 climatic factors mentioned in Table 1 (nine climatic factors for each of planting time, flowering time, and harvesting time) for each crop, path analysis was done and only those significant relationships were retained as has been suggested by Garside et al. The path diagrams for the four crops obtained from such analyses are presented in Figures 2 to 5.

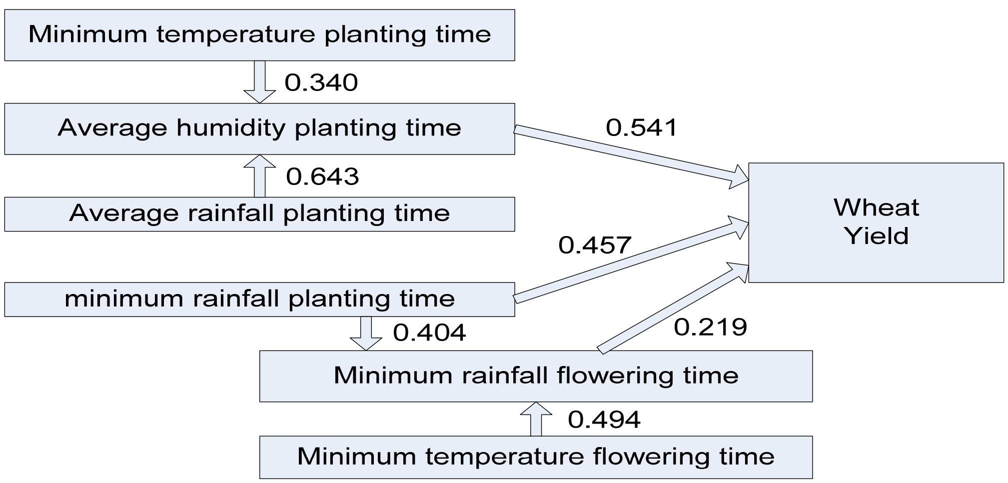

Figure 2. Path diagram for wheat yield.

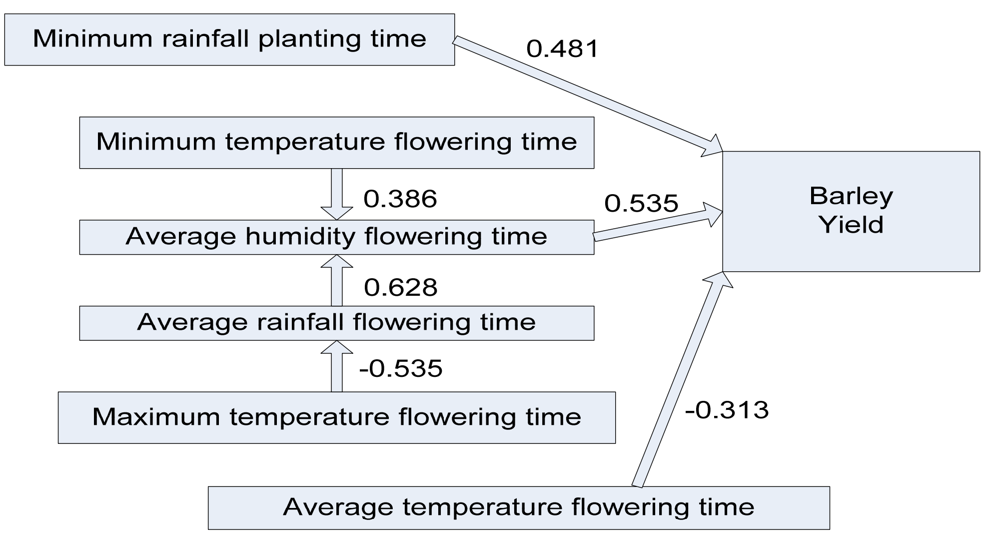

Figure 3. Path diagram for barley yield.

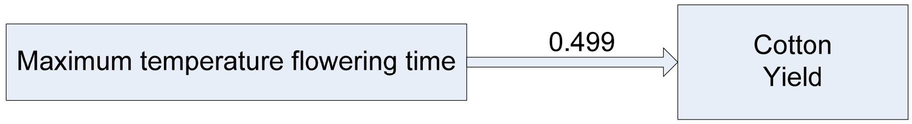

Figure 4. Path diagram for cotton yield.

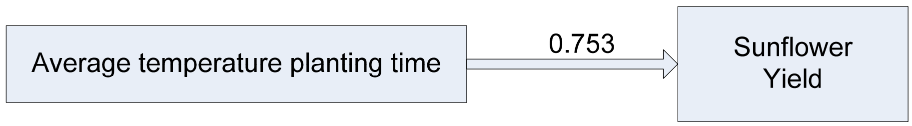

Figure 5. Path diagram for sunflower yield.

DISCUSSION

The path diagram gives a quantitative understanding of the influence of a climatic variable on crop yield. If maximum temperature, for example, adversely affects crop production, its effect can be reduced either by providing more water at the plant root zone during its occurrence or by sprinkler irrigation during the hottest part of the day. In both cases, higher evapotranspiration rates would cool the plant, but there would be more evaporation and water loss with sprinkler irrigation causing greater cooling than by drip irrigation. It has been recorded that over-tree irrigation can reduce the leaf temperature by 6^0C, is effective in keeping chlorophyll levels significantly higher, and can increase photosynthetic activity. At field level, control of canopy temperature, measured remotely with infrared thermometry, through irrigation has been reported to provide better yields. By contrast, if maximum temperature has positive effect on yield, it should be allowed to prevail during the day, and if irrigation is required, it should be done at minimum level in the afternoon and not in the morning. Figure 4 shows that cotton yield is favoured with maximum temperature at flowering time. In fact, Karam et al. (2006) have demonstrated that the cotton yield is the maximum when irrigation is stopped altogether at first open boll.

The availability of weather forecasts with lead time of several days in modern times makes it possible to plan irrigation contingent on such forecasts as well as on soil moisture conditions. The push for such an approach is likely to gain momentum because water is getting more and more to be a scare resource. We can seldom afford full irrigation and deficit irrigation has become a reality. Already positive findings have been reported to reduce irrigation level but maintain same level of yield by altering fertilizer application regime (see for example, Mandal et al., 2006).

The path analysis such as those of Figures 2 to 5 is the first step to incorporating climatic conditions to irrigation management at regional scale. As a next step, further research is needed as to how effective irrigation management could be to counter all the adverse effects of climate. Water can take a lot of heat out from a system by evaporation. It also has a very high heat storage capacity – it is cooler during the day and warmer during the night than soil and plants.

There are other important considerations, which unfortunately, make such studies quite complex. Irrigation is likely to raise the level of humidity. High humidity is known to cause stem rust and leaf rust problems in wheat plants. Sunflower production faces major problems with excess rainfall or moisture. Rust infection is a great concern for sunflower production which is favoured by heavy dews, wet weather, and temperatures above 20^0C. Cotton is a long season crop that can tolerate moderate salinity levels, and therefore, can be irrigated by brackish water or return flows.

Many past studies have focussed at the field level. It is perhaps the time that we take a regional approach.

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REFERENCES

Garside, A.L., Agnew, J., Chamberlain, H.J., Huff, S. and Turnour, J. (1992), "Yield and protein content of grain sorghum crops in Central Queensland 1990-1991. Results and implications from a survey of commercial crops." *Proceedings Second Australian Sorghum Conference*, Gatton, Queensland. Feb. 2-4, pp. 311-315.

Islam, F.M.A. (1996), "The macro-scale influence of climate on crop production in the Fitzroy catchment of Central Queensland." M.Sc. thesis. Faculty of Business and Informatics, Central Queensland University, Rockhampton.

Karam, F., Lahoud, R., Masaad, R., Daccache, A., Mounzer, O., and Rouphael, Y. (2006), "Water use and lint yield response of drip irrigated cotton to the length of irrigation season." *Agricultural Water Management*. Vol. 85, Issue 3, pp. 287-295.

Mandal, K.G., Hati, K.M., Misra, A.K., and Bandyopadhyay, K.K. (2006), "Assessment of irrigation and nutrient effects on growth, yield and water use efficiency of Indian mustard (Brassica juncea) in central India." *Agricultural Water Management*. Vol. 85, Issue 3, pp.279-286.

Nagel, E. (1965), "Types of causal explanation in science." In D. Lenner (Ed.) *Cause and Effect*. Free Press, New York.

Pedhazur, E.J. and Kerlinger, F.N. (1982), *Multiple Regression in Behavioral Rresearch*. (2nd ed.). Holt, Rinehart, and Winston. New York.

Russell, J.S. (1981), "Geographic variation in seasonal rainfall in Australia – An Analysis of the 80 year period 1895-1974." *Journal of Australian Institute of Agricultural Science*. Vol. 47, pp.59-66.