Five Decades of Research in Statistical Modelling: An Overview

Prajneshu and Himadri Ghosh

1. Introduction

Statistical modelling plays a very important role in comprehending underlying relationships among crucial variables in an agricultural system. Some examples are: Length-weight relationship, Input-output relationship, Computation of compound growth rate, and Path of adoption of high yielding varieties. A statistical model can be either 'Linear' or 'Nonlinear'. In a linear model, all the parameters appear linearly, whereas in a nonlinear model, at least one of the parameters appears nonlinearly. Those nonlinear models, which can be transformed to a linear model by means of some transformation, are called 'Intrinsically linear'. Before 1963, only either linear models were used or the use of nonlinear models was confined to only using intrinsically linear models. The nonlinear estimation procedure due to Levenberg and Marquardt, which is currently widely used, was developed in 1963. However, as it was extremely complicated, it was hardly ever used for the next two decades or so. In 1980s, software packages for fitting Nonlinear statistical models through nonlinear estimation procedures were developed. In a few years' time, i.e. around early 1990s, most of the standard software packages, like SPSS, SAS, GENSTAT and SPLUS contained such programs. In the subsequent sections, we discuss briefly the salient features of research work carried out at I.A.S.R.I. during last five decades in various sub-areas of Statistical modelling, viz. Nonlinear growth models, Contagious distributions, Structural time-series analysis, Parametric nonlinear time-series modelling, Nonparametric regression methodology, Soft computing, and Growth models in random environment.

2. Nonlinear Growth Models

In any fishery, it is of paramount importance to have a knowledge of sustainable yield that can be harvested in perpetuity without altering the fish stock level. Scientific fishery management is generally based on the concept of Maximum sustainable yield (MSY), according to which, at any given population level less than the carrying capacity, a surplus production exists. To this end, several models, like Schaefer and Fox models have been developed for assessing MSY and the optimum fishing effort to achieve the same. These models are widely used for efficient fishery management as these require only the information regarding time-series data on catch and effort, which is readily available in our country for a large number of fish species. As the surplus production models, like Schaefer and Fox models are 'intrinsically linear', the usual practice followed for fitting of these models had been to get rid of the nonlinearity by converting these to a linear model by applying a suitable transformation, like logarithmic, and reciprocal. A disturbing feature of this approach is that it is incorrect and leads to erroneous conclusions. Prajneshu (1991) emphasized that Nonlinear estimation procedures, like Levenberg-Marquardt procedure should invariably be employed to fit these models with additive errors. The author demonstrated that the best model identified for some fisheries data was not only different from the one obtained through the conventional approach but was also biologically more meaningful. Further, the allometric model is widely used for determining the length-weight relationship in animal sciences and fisheries. Generally, the error terms are assumed to be identically and independently distributed. However, this assumption is quite often violated, particularly for time-series data. Venugopalan and Prajneshu (1997) studied a generalization of allometric model and developed the methodology for fitting the same when the errors follow autocorrelated AR(1) structure.

Prajneshu and Das (1998) carried out a detailed study dealing with modelling of wheat production data at State level in post-Green revolution era. Specifically, several mechanistic nonlinear growth models, viz. monomolecular, logistic, Gompertz, mixed-influence and Richards were applied using Levenberg-Marquardt procedure. The heartening feature of a mechanistic model is that the parameters have specific agricultural/ biological interpretation and provide insight into the underlying mechanism. Six major wheat-growing States, viz. Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Rajasthan and Bihar were considered. For each of these States, it was found that logistic model has performed the best. It was also concluded that, for the data under consideration, Haryana's performance was the best in view of high intrinsic growth rate of wheat production in that State coupled with the fact that wheat production in that State was still in the fast phase of growth. The utility of these modelling efforts is that it is possible to evaluate the comparative performance of various States as far as wheat production is concerned, This, in turn, may be of immense help to the planners in making important policy decisions. Further, the proportion of area time-series data under high yielding varieties of wheat in India during post-Green revolution era was modelled by Prajneshu and Kandala (2002) through mixed-influence nonlinear growth model. The methodology of replacing one parameter by an 'Expected-value parameter' was employed for fitting of the model. Subsequently, hypothesis testing was carried out by using Wald's test. For the data under consideration, it was concluded that the process of innovation had played a significantly greater role vis-a-vis that of imitation so far as diffusion of high yielding varieties of wheat in India is concerned. This type of result is very satisfying to the research efforts made by Agricultural Scientists. It may be noted that the methodology developed was successful in segregating the effects of the two processes, viz. Innovation and imitation, which otherwise was not possible.

It is well-known that the success rate of fitting the four-parameter nonlinear Richards growth model by using nonlinear estimation procedure is extremely low. Fortunately, a very powerful and versatile optimization technique of Genetic algorithm (GA), motivated by the principles of Genetics and natural selection, has recently been developed. In this methodology, some fundamental ideas of Genetics are borrowed and used artificially to construct search algorithms that are robust and require minimal problem information. The three operators, viz. Selection, crossover, and mutation make GA an important tool for optimization. When a string (parameter solution) is created by GA, it is evaluated in terms of its fitness, which is taken to be the Residual sum of squares. A detailed description of the entire methodology is given by Iquebal *et al.* (2009). The authors have also demonstrated that, for India's total foodgrain time-series data, the GA methodology is successful in fitting the Richards model. The importance of this work is that the GA methodology is applicable even in those cases in which Nonlinear estimation procedures fail to converge.

If there is one concept that has been used the maximum number of times during the past four decades or so in research papers published, particularly in the discipline of Agricultural Economics, it is undoubtedly the 'Computation of compound growth rate'. In a seminal work, the methodology for the same was proposed by Panse (1964). Here, the value of variable under study, like Agricultural production, productivity, or area at various time-epochs is assumed to be related to the value of that variable at some previous time-epoch through Malthus model. Next, a multiplicative error is generally assumed to describe the random fluctuations. As the underlying model is intrinsically linear, it is transformed to a linear model by means of a logarithmic transformation. The resulting model is fitted to data by the 'Method of least squares' and goodness of fit is assessed by the coefficient of determination R^2. Finally, the compound growth rate is estimated as some specific function of one of the parameters. Although, the above methodology has been very widely employed, it has several drawbacks. Firstly, the Malthusian model envisages that the response variable tends to infinity as time tends to infinity, which can not happen in reality. Therefore, continuing to sticking to only this model does not make much sense, particularly when several other more realistic models, like logistic and Gompertz models exist. Secondly, the assumption of multiplicative error tends to be valid only when variability of response variable increases as the variable increases, which rarely holds. The third drawback is that the goodness of fit of the original intrinsically linear model is assessed by reporting the same value of R^2 as that obtained for the corresponding linearized model, which is incorrect. A detailed discussion of all these aspects is given by Prajneshu and Chandran (2005). The authors also suggested the correct procedure that needs to be followed for computation of compound growth rates and illustrated the same on India's total foodgrain production time-series data.

The input-output relationship between a response variable and a set of explanatory variables is quite often expressed through Cobb-Douglas production function approach. However, the underlying model is again intrinsically linear. The usual practice is to get rid of the nonlinearity by transforming it into a linear model by means of logarithmic transformation. Prajneshu (2008) highlighted the deficiencies and emphasized that Nonlinear estimation procedures should be employed for fitting the original model. Even when this approach is adopted, the parameter estimates generally exhibit extremely high correlations, implying thereby that the parameters are not estimated independently. To this end, Prajneshu (2008) advocated the use of 'Expected-value parameters' and derived formulae when there are one or two explanatory variables. The methodology developed was demonstrated on wheat yield time-series data of Punjab.

Aphid is a small insect which infests almost every plant. In India, aphids are recognized as serious pests of cereals, oilseeds, pulses and vegetable crops. They cause damage directly to host plants by sucking the plant sap and arrest their growth and development. Accordingly, it is highly desirable to investigate optimal control policies for controlling this pest. To this end, as a first step, Prajneshu (1998) developed a Nonlinear statistical model for describing the dynamics of aphid population growth. The model, in terms of an integro-differential equation, was solved analytically. The formula for obtaining optimal time for insecticidal spray was also derived. Subsequently, the model was successfully applied to ten data sets. Further, it is well established that a plant disease generally progresses at a slow rate in the beginning and subsequently growth rate picks up and reaches the maximum, beyond that again it starts decreasing. This type of behaviour can be captured by several nonlinear growth models, like logistic and Gompertz models. However, one limitation of these models is that the plant parts, viz. number of leaves or number of panicles are assumed to be constant. In reality, as disease grows, plant parts also have same pattern of growth as the disease, though at a slower rate. Accordingly, Chandran and Prajneshu (2005a) theoretically developed generalizations of monomolecular, logistic and Gompertz models and applied these to powdery mildew disease data of mango.

A nonlinear model involving one predator and two prey species was studied by Prajneshu and Holgate (1987). The predators can feed on either species of prey. However, instead of choosing individuals at random, so that the chance that a predator would catch a member of one or other prey species is proportional to their abundances, the predators are assumed to feed preferentially on the most numerous species. This implies a kind of switching from one source of food to another as the prey species alternate in numerical superiority. In population ecology literature, it was believed that switching mechanism invariably leads to stability. However, the authors showed analytically that this is not so and switching mechanism can even have a destabilizing effect.

3. Contagious Distributions

Knowledge of Spatial spread is useful in several ways, like Designing efficient sampling programmes for population estimation, development of population models and efficient pest management. To describe the aggregation or clustering behaviour, negative binomial distribution has generally been used. However, there are many instances in which this distribution does not provide a good fit to the data. To this end, Prajneshu and Sarada (1999) advocated the use of some other more advanced contagious distributions, viz. Neyman type A and Thomas distributions. The relevant computer programs for fitting these distributions were also appended using 'Method of moments' as well as 'Method of maximum likelihood' and the methodology was applied to some aphid count data. Similar type of work dealing with the Lagrangian-Poisson distribution (LPD) was also carried out by Sarada and Prajneshu (2000). Although LPD has only two parameters and a simple form, yet it is extremely versatile due to its capability of incorporating greater changes in variance than mean. The variance of LPD can be greater than, or equal to, or less than the mean according as one specific parameter is positive, zero, or negative. This distribution is generally unimodal except in one particular case, where it is bimodal. Further, Sarada *et al.* (2001) thoroughly studied yet another contagious distribution, viz. Polya-Aeppli distribution and applied it to onion thrips' data. An explanation as to why the negative binomial distribution was not appropriate for this data was also provided. The utility of the work described in this Section is that the research workers should start applying these contagious distributions to describe Spatial spread, particularly in those cases where negative binomial distribution does not provide a good fit.

4. Structural Time-series Analysis

Statistical modelling of time-series data in Agriculture is usually carried out by employing the well-known Box-Jenkins Autoregressive integrated moving average (ARIMA) methodology. One disadvantage of this methodology is that the data series under consideration is assumed to be either stationary, or can be made so by differencing or some other means. However, this is not always possible. A very promising approach, which does not suffer from the above drawback, is 'Structural time-series modeling (STSM)'. The distinguishing feature of this methodology is that the observations are regarded as made up of distinct components, such as trend, and cyclical fluctuations and each of which is modelled separately. The techniques that emerge from this approach are extremely flexible and are capable of handling a much wider range of problems than is possible through ARIMA approach. Prajneshu *et al*. (2002) thoroughly studied the STSM approach when there are prominent cyclical fluctuations. Specifically, three models of this type, viz. Cycle plus noise model, Trend plus cycle model, and Cyclical trend model were considered. Estimation of parameters was carried out by putting the models in State space form and then applying

Kalman filter. As an illustration, more than sixty years' data on India's lac production exhibiting prominent cycles, was utilized. It is hoped that Agricultural Statisticians would employ STSM methodology for modelling and forecasting purposes.

Achieving food security is one of the foremost aims of our country's agricultural policy. The total foodgrain production witnessed a three-fold increase in nearly three decades during post-Green revolution era. However, this quantum jump barely keeps pace with the burgeoning population growth. Further, in view of setting up of World Trade Organization, farmers are being asked to produce those crops that are suitable for export in the international market. Therefore, it is highly desirable to model and forecast India's total foodgrain production time-series data. Narain *et al.* (1985) developed India's total foodgrain production projections under two alternative scenarios: (i) Constant trend of input factors used for the utilized period, and (ii) 10% increased level of input factors. The authors first projected the explanatory variables themselves on the basis of their linear annual growth rates and then substituted these in the production functions. Ravichandran and Prajneshu (2002) employed two promising dynamical modelling techniques, viz. Bayesian analysis of time-series and Structural time-series modelling. Utilizing the data from 1966 to 1998, both these procedures yielded the forecast for 2020 between 280 and 285 million tonnes, which was much less than similar forecasts made by some other authors. Therefore, a wake-up call was also issued that India's total foodgrain production in future may not even suffice for domestic consumption unless some drastic steps are taken urgently. Evidently, this type of study would help policy makers in formulating appropriate strategies to face the challenges ahead.

5. Parametric Nonlinear Time-series Modelling

The area of parametric nonlinear time-series modelling has been rapidly growing during the last three decades or so. The main feature of these models is that these are 'Nonlinear', unlike ARIMA and STSM methodologies discussed in Section 3. There are some aspects in real data sets, like existence of limit cycles, and chaos, which can not be described through linear approaches. The most promising parametric nonlinear time-series model has been the Autoregressive conditional heteroscedastic (ARCH) model, which was introduced by Robert F. Engle in 1982, and for which he was awarded the most prestigious Nobel Prize in Economics in 2003. The main characteristic of this model is that it allows the conditional variance to change over time as a function of squared past errors, leaving the unconditional variance constant. Accordingly, this model is capable of describing data sets exhibiting volatility. In our country, onion prices have been in the headlines, particularly in 1998-99, for their tear jerking effect on consumers, farmers, and Government alike. The temporal variation in onion prices has an impact on consumers if the prices are high, on farmers if these are low, and on Government on both the occasions. Ghosh and Prajneshu (2003) thoroughly studied the modelling and forecasting of volatile onion price data through AR(p)-ARCH(q)-in-mean methodology. It is satisfying to note that the model was successful in capturing the sudden burst in onion prices during the second half of the year 1998.

One limitation of ARCH model is that the unconditional autocorrelation function of squared residuals, if it exists, generally decays very rapidly compared to what is observed in real data. Accordingly, T. Bollerslev in 1986 proposed the Generalized ARCH (GARCH) model in which conditional variance is also a linear function of its own lags. The main objective of GARCH model is not to give better point forecasts but rather to give better estimates of the variance which, in turn, allows more reliable forecast intervals leading to a better assessment of risk. Recently, Paul *et al*. (2009) thoroughly studied this model and applied it for modelling and forecasting of India's volatile monthly spices export data using EViews software package. Superiority of GARCH model over ARIMA approach was also demonstrated. This study would be of help to the planners to take appropriate policy decisions well in advance in order to meet the targets set for Indian spices export. This, in turn, would help the farmers engaged in spices production in getting timely advice based on sound statistical methodologies. Further, another family of Mixture distributions, viz. Gaussian mixture transition distribution, Mixture autoregressive (MAR) and MAR-Autoregressive conditional heteroscedastic (MAR-ARCH) nonlinear time-series models may be employed to describe those data sets that depict sudden bursts, outliers and flat stretches at irregular time-epochs. Ghosh *et al*. (2006a) derived the formulae for carrying out out-of-sample forecasting up to three-steps ahead through recursive use of conditional expectation and conditional variance. These results enable us to compute best predictor, prediction error variance, and predictive density. The theory developed was successfully applied for modelling and forecasting of volatile weekly wholesale onion price data.

Another important family of parametric nonlinear time-series modelling is the Self-exciting threshold autoregressive (SETAR) models. A heartening feature of this family is that it is capable of describing cyclical data. Some examples of such behaviour are: India's annual lac production/export data, India's summer monsoon rainfall data and Population-sizes of several fish species having prey-predator type of interactions. Formulae for carrying out multi-step ahead out-of-forecasting were derived by Ghosh *et al*. (2006b). The methodology developed was successfully demonstrated on India's lac export time-series data. A mechanistic interpretation for occurrence of cyclicity in the data was also provided.

6. Nonparametric Regression Methodology

In Section 1, the parametric approach that needs to be adopted for Computation of compound growth rates was discussed. Quite often it is noticed that there is no appropriate parametric form to describe the time-series data under consideration in a satisfactory manner. In such cases, the powerful 'Nonparametric regression methodology (NRM)' may be employed. This technique imposes very few assumptions about shape of the underlying functions and is, therefore, extremely flexible. Chandran and Prajneshu (2004a) thoroughly discussed the methodology and developed relevant computer programs. The methodology was successfully demonstrated for computing compound growth rates of India's total foodgrain production time-series data. Further, it is well-known that India is among the largest oil economies in the World occupying a distinct position in terms of diversity in annual oilseed crops. Main oilseed crops are: Groundnut, Rapeseed, Mustard, Soybean, Sunflower, Safflower, Sesame, Niger, Linseed, and Castor. Annual production of oilseed crops was virtually stagnating at around 10 million tonnes over a span of more than 15 years despite considerable increase in area under these crops. Generally, the supply lagged far behind the demand, thus forcing the Government to import large quantities of edible oils. Turning point came in 1986 with the setting up of 'Technology Mission on Oilseeds (TMO)'. Chandran and Prajneshu (2005b) employed the nonparametric regression with jump points methodology for describing India's oilseed yield time-series data. It was satisfying to note that the model was able to capture the quantum jump in oilseed productivity due to the efforts of TMO. The 'Additive nonparametric regression approach', which is an extension of NRM to the situation of two explanatory variables was described by Chandran and Prajneshu (2004b). Superiority of proposed methodology over the well-known Multiple linear regression methodology for explaining Rice productivity data in terms of Fertilizer consumption and Area under irrigation data was also demonstrated.

During last few years, an extremely powerful nonparametric methodology of ‘Wavelet analysis’ has been rapidly emerging. Novel idea of wavelets is that these are localized in both time and space, whereas traditional Fourier bases are localized only in frequency but not in time. The theory of wavelets permits decomposition of functions into localized oscillating components and so is an ideal tool for modelling and forecasting purposes. Sunilkumar and Prajneshu (2004) discussed various aspects of this methodology with thresholding and applied the same to model and forecast meteorological subdivisions rainfall time-series data using SPLUS wavelets toolkit. Superiority of the methodology over other competing methodologies, like ARIMA and NRM was also demonstrated. Extension of the above methodology, when the errors are not independent but are autocorrelated was carried out by Sunilkumar and Prajneshu (2008). The methodology was successfully applied for modelling and forecasting of India’s marine fish production time-series data.

7. Soft Computing

It is, by now, well recognized that Agriculture is a ‘Soft science’, unlike Physics or Chemistry, which are ‘Hard sciences’. In the former, there is always some amount of impreciseness or vagueness or fuzziness in the underlying phenomenon, and/or explanatory variables, and/or response variable(s). So, by assuming a crisp relationship, some vital information is lost. Therefore, for a more realistic modelling, there is a need to incorporate this aspect in traditional models, like Multiple linear regression (MLR) model. It may be emphasized that the traditional statistical methodologies are not capable of handling data in which explanatory and/or response variables are expressed in intervals. Kandala and Prajneshu (2002) studied Fuzzy linear regression methodology for crop yield forecasting using remotely sensed data. The underlying phenomenon was considered as fuzzy and so the value of response variable was expressed in intervals. It was shown that the methodology is not only superior to MLR methodology but is also applicable when explanatory variables are highly correlated.

Presently, more than five lakhs Crop-cutting experiments (CCE) in respect of principal crops of foodgrains, oilseeds and horticultural crops, etc. are conducted every year in our country by the Directorate of Economics & Statistics, Ministry of Agriculture to arrive at crop yield estimates at district level. With the growing demand for micro-level planning, the need for building reliable estimates at small area level, say block or even gram panchayat is imperative. To achieve this, the number of CCE has to be increased many folds, which is not practicable. Additional information about farmers’ estimates of crop yields at block level, which are crisp values, could be made use of provided these can explain the actual crop yields, which are fuzzy. To this end, Ghosh *et al.* (2008) studied three methods of fuzzy linear regression analysis, viz. Minimization, Maximization, and Conjunction. Subsequently, the methodology was applied to employ farmers’ estimates at block level for modelling cotton crop yield at block levels of Sirsa district, Haryana. The Conjunction method performed the best. It was concluded that the farmers’ estimates were able to explain satisfactorily the actual crop yields. It is hoped that these types of studies would go a long way in arriving at efficient crop yield estimates at small area level.

The main limitation of Multiple linear regression (MLR) methodology is that it is useful only when the underlying relationship between response and explanatory variables is assumed to be ‘Linear’.

However, in a realistic situation, this assumption is rarely satisfied. Also, if there are several explanatory variables, it is well nigh impossible to have an idea of underlying nonlinear functional relationship. Fortunately, to handle such a situation, an extremely versatile approach of 'Artificial neural network (ANN)' is rapidly developing. A distinguishing feature of ANN that makes it valuable and attractive for a statistical task is that, as opposed to traditional model-based methods, ANN is a data-driven self-adaptive method. This modelling approach with ability to learn from experience is extremely useful in many practical problems since it is often easier to have data than to have good theoretical guesses about the underlying laws governing the systems from which data are generated. Singh and Prajneshu (2008a) investigated a particular type of ANN, viz. Multilayered feedforward ANN. To train such a network, two types of learning algorithms, namely Gradient descent algorithm and Conjugate gradient descent algorithm were employed. The methodology was illustrated by taking Maize crop yield data as response variable and Total human labour, Farm power, Fertilizer consumption, and Pesticide consumption as explanatory variables. Superiority of this approach over MLR was also demonstrated.

Incorporating the aspect of 'Fuzzy logic' in ANN, a rapidly developing area of current interest is 'Neuro-fuzzy', which involves a judicious integration of merits of fuzzy and ANN approaches. Singh and Prajneshu (2008b) thoroughly studied an important model, viz. Adaptive neuro-fuzzy inference system (ANFIS). The model was implemented on fuzzy logic toolbox of MATLAB software package using ANFIS. As an illustration, the methodology was applied for development of a forecasting model for secondary data of yield of banana plants on the basis of data at six different stages of growth using several biometrical characters, like plant height, plant girth, and leaf length as predictors.

8. Growth Models in Random Environment

The models considered in Section 1 were generally 'Nonlinear statistical models' obtained by adding an error term to the corresponding deterministic model. However, this approach may not be totally satisfactory, particularly for longitudinal data. Thus for a more realistic modelling, a stochastic term describing fluctuations should be added to the deterministic model and then the resulting model should be investigated. Prajneshu (1983a) considered the stochastic version of the logistic model with continuously distributed time delay. The explicit expression for the stationary distribution was worked out and the effect of time delay on various statistics was discussed. Further, Prajneshu (1983b) studied the stochastic Gompertz model with continuously distributed time delay when the parameters are described by correlated Gaussian white noise stochastic processes. Exact expressions for the first and second order moments of logarithm of population size were derived and stability in mean as well as in mean-square was discussed. Prajneshu *et al.* (1986a) considered a nonlinear stochastic model for the spread of an epidemic when there are seasonal variations in infection rate. The resulting model was analyzed by employing the Diffusion approximation technique. It was shown that, for a large population, the process, on suitable scaling and normalization converges to a nonstationary Ornstein-Uhlenbeck stochastic process. Consequently, the number of infectives has, in the steady state, a Gaussian distribution. Prajneshu *et al.* (1986b) also studied the general two-compartmental system with environmental stochasticity. The transfer rates and outputs were assumed to be described by random telegraph processes. The Laplace transforms of the mean-value functions of the amount of substances present in the two compartments were derived. The Gaussian white noise limit case was also discussed and the stability of the system was examined. It was shown that, while the deterministic model was always stable, environmental stochasticity may induce in the mean-value function all sorts of behaviours, viz. stable, unstable, and oscillatory.

The von Bertalanffy growth model (VBGM) for describing age-length relationship plays a very important role in fisheries research. Prajneshu and Venugopalan (1999) thoroughly studied the VBGM in a random environment. The fluctuations in the system were assumed to be described by a Gaussian white noise stochastic process. The resulting model, in terms of a stochastic differential equation, was solved analytically it was shown that the probability density function of length of a fish follows a Gaussian stochastic process. As an illustration, the methodology was applied to a set of pearl oyster age-length data.

9. Concluding Remark

In the above, salient research work done at IASRI, New Delhi during the last fifty years in seven sub-areas of Statistical modelling has been highlighted. However, there is a need to consolidate this area by continuing to conduct basic, applied, as well as adaptive type of research work in the methodologies described above. This type of endeavour would go a long way in arriving at optimal policies for efficient agricultural management.

References

Chandran, K. P. and Prajneshu (2004a). Computation of growth rates in agriculture: Nonparametric approach. *J. Ind. Soc. Ag. Stat.*, **57**, 382-92.

Chandran, K. P. and Prajneshu (2004b). Modelling rice productivity: Additive nonparametric regression approach. *Natl. Acad. Sci. Lett., India*, **27**, 261-67.

Chandran, K. P. and Prajneshu (2005a). Nonlinear statistical models for plant disease. *Ind. J. Ag. Sci.*, **75**, 361-63.

Chandran, K. P. and Prajneshu (2005b). Nonparametric regression with jump points methodology for describing country's oilseed yield data. *J. Ind. Soc. Ag. Stat.*, **59,** 126-30.

Ghosh, H., Iquebal, M. A. and Prajneshu (2006). On mixture nonlinear time-series modelling and forecasting for ARCH effects. *Sankhya*, **68**, 111-29.

Ghosh, H. and Prajneshu (2003). Nonlinear time-series modelling of volatile onion price data using AR(p)-ARCH(q)-in-mean. *Cal. Stat. Assn. Bull.*, **54**, 231- 47.

Ghosh, H., Singh, R. K. and Prajneshu (2008). Possibilistic linear regression analysis with fuzzy response variable for crop yield estimation. *Cal. Stat. Assn. Bull.*, **60**, 123-44.

Ghosh, H., Sunilkumar, G. and Prajneshu (2006). Self exciting threshold autoregressive models for describing cyclical data. *Cal. Stat. Assn. Bull.*, **58,** 115-32.

Iquebal, M. A., Prajneshu and Ghosh, H. (2009). Application of genetic algorithm optimization technique for fitting nonlinear Richards model. *Ind. J. Ag. Sci.*,**79**, 399-401.

Kandala, V. M. and Prajneshu (2002). Fuzzy regression methodology for crop yield forecasting using remotely sensed data. *J. Ind. Soc. Rem. Sen.*, **30**, 191-95.

Narain, P., Pandey, R. K. and Sarup, S. (1985). On foodgrain production projections. *Ag. Sit. Ind.*, **40,** 383-88.

Panse, V. G. (1964). Yield trends of rice and wheat in first two Five-Year Plans in India. *J. Ind. Soc. Ag. Stat.*, **16**, 1-50.

Paul, R. K., Prajneshu and Ghosh, H. (2009). GARCH nonlinear time-series analysis for modelling and forecasting of India's volatile spices export data. To appear in *J. Ind. Soc. Ag. Stat.*, **63**.

Prajneshu (1983a). A stochastic logistic model with time delay. *Aust. J. Stat.*, **25**, 130-35.

Prajneshu (1983b). Environmental stochasticity of Gompertz model with time delay. *Comm. Stat.*, **A12**, 1359-69.

Prajneshu (1991). Cautionary note about nonlinear models in fisheries. *Ind. J. Fish.*, **38**, 231-33.

Prajneshu (1998). A nonlinear statistical model for aphid population growth. *J. Ind. Soc. Ag. Stat.*, **51**, 73-80.

Prajneshu (2008). Fitting of Cobb-Douglas production functions: Revisited. *Ag. Econ. Res. Rev.*, **21**, 289-92.

Prajneshu and Chandran, K. P. (2005). Computation of compound growth rates in agriculture: Revisited. *Ag. Econ. Res. Rev*., **18**, 317-24.

Prajneshu and Das, P. K. (1998). Modelling wheat (Triticum aestivum) production at state level in post green revolution era. *Ind. J. Ag. Sci.*, **68**, 23-26.

Prajneshu, Gupta, C.K. and Sharma, U. (1986a). A stochastic epidemic model with seasonal variations in infection rate. *Biom. J.*, **28**, 889-95.

Prajneshu, Gupta, C.K. and Sharma, U. (1986b). Stochastic analysis of environmental fluctuations in a compartmental system. *Biol. Cybernetics*, **53**, 343-46.

Prajneshu and Holgate, P. (1987). A prey-predator model with switching effect. *J. Theor. Biol*., **125**, 61-66.

Prajneshu and Kandala, V. M. (2003). Mixed-influence nonlinear growth model. *J. Ind. Soc. Ag. Stat.*, **56**, 19-24.

Prajneshu, Ravichandran, S. and Wadhwa, S. (2002). Structural time series models for describing cyclical fluctuations. *J. Ind. Soc. Ag. Stat.*, **55**, 70-79.

Prajneshu and Sarada, C. (1999). Some contagious distributions for describing spatial spread of aphids *(Homoptera. Aphididae*) when negative binomial distribution fails. *J. Aphidol.*, **13**, 17-26.

Prajneshu and Venugopalan, R. (1999). Von Bertalanffy growth model in a random environment. *Can. J. Fish. Aqu. Sci.*, **56**, 1026-30.

Ravichandran, S. and Prajneshu (2002). Dynamical modelling and forecasting of India's foodgrain production. *Proc. Natl. Aca. Sci., India*, **B 72**, 37-46.

Sarada, C. and Prajneshu (2000). Lagrangian-Poisson distribution for describing spatial spread of aphids. *J. Aphidol.*, **14**, 33-40.

Sarada, C., Prajneshu and Chander, S. (2001) A contagious distribution for describing spatial spread. *Shashpa*, **8,** 131-37.

Singh, R. K. and Prajneshu (2008a). Artificial neural network methodology for modelling and forecasting maize crop yield. *Ag. Econ. Res. Rev.*, **21**, 5-10.

Singh, R. K. and Prajneshu (2008b). Neuro-fuzzy approach for modelling and forecasting: An application. *J. Ind. Soc. Ag. Stat.*, **62**, 214-20.

Sunilkumar, G. and Prajneshu (2004). Modelling and forecasting meteorological subdivisions rainfall data using wavelet thresholding approach. *Cal. Stat. Assn. Bull.*, **55**, 253-65.

Sunilkumar, G., and Prajneshu (2008). Modelling and forecasting India's marine fish production data using wavelet thresholding for autocorrelated errors. *Ind. J. Fish.*, **55,** 291-94.

Venugopalan, R. and Prajneshu (1997). A generalized allometric model for determining length-weight relationship. *Biom. J.*, **39**, 733-39.