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Environmental Biometrics
Summary of Papers Presented at the International Conference on Environmental Biometrics, Sydney, Australia, 14–15 December 1992

JOHN C. EVANS[1] *AND WALTER W. PIEGORSCH*[2]

1. INTRODUCTION

Environmental biometry is the application of statistical methods in environmental studies of biological and ecological systems. Such application is growing, as scientists recognize the challenge and need to collect, analyse, and interpret data on environmental impacts to biological organisms. To provide an opportunity for improving scientific coverage of these applications, a conference on this topic was convened at the Women's College, University of Sydney, Australia on 14–15 December 1992. Presentations by statisticians and scientists included invited, contributed and poster papers, collected into sessions on (i) Environmental Monitoring, Assessment, and Prediction of Change; (ii) Environmental Sampling; (iii) Analysis of Environmental Data; and (iv) Statistics in Environmental Health. An additional goal of these efforts was to stimulate and encourage further cross-disciplinary interactions among scientists and statisticians studying the environment, resulting we hope in additional research and understanding of environmental processes and how they impact biological systems.

Over 130 conference attendees were welcomed to the Women's College by its Principal, A. Eyland. Dr Eyland called upon her great experience as a practising statistician and her ongoing interests in environmetrics to urge further study and investigation into the many exciting scientific and statistical problems engendered by environmental research. She also echoed and applauded the conference's underlying theme of collaboration and

[1] Mathematics, Statistics & Computing, AWT Science & Environment, Water Board, West Ryde 2114, NSW, Australia.
[2] Department of Statistics, University of South Carolina, Columbia, SC 29208, USA.

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interaction between environmental scientists and biometricians so that both fields may prosper and grow.

Seven invited papers were given, covering various issues in each of the four main topic areas. These papers follow this conference summary. Herein, we review briefly the 28 contributed platform and poster presentations (a list of all presentations appears in the Appendix), with the goal of illustrating the broad nature of scientific and statistical issues discussed at the conference. These included ecological monitoring and studies of environmental impact, monitoring air and water quality, assessing effects of pollutants on animal and plant populations, and environmental health assessment. We begin with a review of those papers considering environmental monitoring.

2. ENVIRONMENTAL MONITORING

Biometric issues in environmental monitoring and assessment played an integral part of the conference's aims and scope. Two full sessions were devoted to these issues, both of which were led by invited talks. The first was the keynote address by A. H. El-Shaarawi on monitoring, assessment and prediction of change (as with all invited presentations, the paper associated with this talk follows our summary in this issue); the second was a paper on matching sampling designs and significance tests in environmental studies by J. C. Evans and B. G. Coote.

The contributed presentations from both sessions illustrated a variety of technical issues relevant to monitoring and assessment. For instance, both G. De'ath and B. D. Mapstone noted the problems data analysts encounter when employing standard significance testing methodologies in monitoring studies. De'ath suggested that one must define one's monitoring standards not in terms of whether the systems have changed (i.e. a classical dichotomous hypothesis decision problem), but instead in terms of how much the systems changed. De'ath noted that this can involve complex, hierarchical statistical models, prior information, and perhaps Bayesian methodologies. Mapstone argued a similar point, noting that important social and environmental decisions are associated with monitoring studies; their impact is far greater than that typically subsumed in the usual (frequentist) two-hypothesis decision framework. He questioned the propriety of strict "yes–no" decisions based on classical α-level significance testing when the impacts from such decisions are so important, and suggested re-evaluating this approach. For example, one could establish a desired level of α/β (i.e. the ratio of type I to type II errors), and incorporate subject matter considerations when deciding upon the results of one's statistical test calculations. (Note that De'ath in effect argued for similar considerations when he called for incorporation of prior information into the decision setting.) Implicit in Mapstone's discussion was the need to recognize and respond to the consequences of *both* type I and type II errors in the context of the particular environmental system under study. (A similar argument has been put forth by L. Hothorn 1991 in the context of environmental toxicity studies.)

Statistical methodology was the focus in other talks on monitoring and assessment. Anticipating Mapstone's concerns, I. Shannon noted that sampling and monitoring conditions (such as meteorological and atmospheric conditions, waste water production levels, etc.) change from site to site or even within a site. The statistical design and analysis must be flexible enough to adapt to such variability. Hence, Shannon suggested use of less model-dependent methods, such as non-parametric regression (Eubank 1988) or other distribution-free or model-free approaches.

Applications to reservoir monitoring were noted in a poster paper by M. J. Swincer. She related a study in a New South Wales (Australia) water source where monitoring efforts were employed to study the spatial variation in the source's water quality, and possibly determine if specific outlets were providing lower quality drinking water. Various forms of multivariate statistical analyses were performed, and no statistical differences or clusters of pollution were observed. Swincer noted, however, that further sampling and analysis of the reservoir were necessary to corroborate these findings. Implicit in her call was the need to remain flexible in the statistical monitoring and analysis (echoing Shannon's comments), since reservoir conditions exhibited great plasticity. R. L. Correll discussed similar concerns when monitoring and studying pulp mills and their potential toxic effects on surrounding ecosystems. Assessing the risks of a mill's effluent discharge is a difficult task, since many sources of variation exist in a given system's or species's response to toxic insults. Further, an ecosystem harbours many interdependent systems, so that truly independent statistical observations may be difficult to obtain. Correll proposed a novel way of viewing problematic ecotoxicological data of this sort, incorporating relative risk indices to estimate environmental impact.

The last of the monitoring and assessment papers was given by D. R. Fox. His presentation included some mathematical complexity, centring on the properties of an estimator for radiation dosimetry using order statistics of a Poisson process. It illustrated the application of quantitative methods to an applied environmetric problem and in particular provided an excellent example of flexible statistical methods for dealing with the greater complexity and variability of monitoring problems in environmental studies. The key issue in Fox's paper is the high variability in gamma radiation levels over a given terrain. This variation was modelled via a Poisson process, and the estimator of radiation dose was based on an adaptive linear combination of the largest and smallest observations (i.e. the order statistics $Y_{(n)}$ and $Y_{(1)}$, respectively). Fox's calculations suggested that if the adaptive estimator gives greater weight to $Y_{(1)}$ as dose decreases, the sampling interval of the process can be chosen to minimize the variance of the estimator.

3. ENVIRONMENTAL SAMPLING

Statistical issues in environmental sampling garnered almost as much conference attention as those in environmental monitoring, and clearly the two topics are closely interrelated. Again, two full sessions were devoted to environmental sampling, and there were many interesting issues discussed by the participants. An invited paper on ranked set sampling by G. P. Patil (which, again, follows this summary) led the presentations and set the tone. A major theme as identified therein and by the other presentations was that various complexities can arise when sampling environmental data, and the design and analysis must be flexible enough to account for these complexities.

The contributed papers on environmental sampling covered a fairly broad range of topics within the theme of accounting for complexity. Much consideration was directed at so-called BACI (before and after, control versus impact sites) designs, and the associated sampling issues they engender. The BACI design ostensibly is employed in a situation where an environmental impact is studied at a contaminated site and concurrently at a "control" site, to better gauge the extent of the environmental damage. For instance, E. A. Roberts gave an informative discussion of the uses (and misuses) of BACI designs as applied to the study of sewage outfall on Australian beaches. He noted that when the sampling proceeds in an appropriate manner, various forms of analysis of covariance can be employed to assess the improvement in beach water resulting from a change-over to offshore outfalls from cliff-face outfalls. A similar application was noted by A. G. Church, where the environmental objective was to sample and identify if any impact *mitigation* had been successful in reducing some previous contamination in small, contained marine ecosystems such as bays or inlets. Church noted that mitigation monitoring is more difficult than classic control-versus-impact approaches, and a specialized form of BACI multiple-site sampling design was recommended.

A form of BACI sampling was also advocated by A. O. Nicholls, in a study of how habitat fragmentation affects species diversity in a forested region. Although not exactly the same as the classical BACI design discussed e.g. by Roberts, Nicholls's study exhibited many of the same features, including sampling at both control and fragmented (impacted) habitat sites. Preliminary results from the study suggested that, as might be expected, habitat fragmentation disturbed and reduced species diversity, although the high within-species variation made strong statistical inferences difficult with limited data. Greater within-species sampling replication was recommended. G. Riley noted a similar problem–complex sources of variability–in his description of a reforestation project. The goal was to develop, evaluate, and eventually optimize a sampling scheme for measuring seedling density after reforesting a commercially mined area. To adjust for the many sources of spatial variability (e.g. complex variability perpendicular to mining rip lines), a multiple quadrat scheme along zigzag transects was employed. The scheme was seen to possess an important flexibility that allowed for minor adjustments.

Design and sampling concerns such as those noted by Roberts, Nicholls and Riley were at the core of many other presentations. For example, C. A. Preston described a case study of point source pollution in an Australian river wherein large spatial and temporal variaion was exhibited. As above, these variations serve to undermine the statistical analysis if not taken into consideration. For Preston's data, a careful application of mixed model analysis of variance was employed to improve the inferences and allow for proper interpretation of the data. B. R. Hodgson echoed these concerns, noting that spatial and temporal (serial) correlations can wreak havoc on standard analysis of variance-type methods. Hodgson presented computer simulations showing that such correlations, when left unadjusted, dramatically increase the underlying type I error of the statistical test. Hodgson's presentation appeared during the sessions on analysis of environmental data–summarized in Section 4–but they are clearly of interest here. Indeed, the issue of type I error inflation due to unrecognized correlations appears throughout environmetrics; W. W. Piegorsch and L. Ryan describe similar effects from an environmental health perspective in their invited papers at the end of this issue.

It should, of course, be obvious that unusual or complicated variance patterns are common when studying highly complex ecological systems. This was the theme argued by A. J. Underwood in his presentation. He noted that single control sites or point sampling sources will often fail to capture the full extent of a system's variability, and such simplistic designs should be discarded in favour of carefully constructed monitoring and sampling designs. A good illustration of this philosophy was given by M. Scammell, in his presentation of a multiple component assay designed to measure pollutant damage to oysters. Scammell was able to combine techniques from statistical sampling design and modern biotechnology in developing the assay. Analysis of the data required a complex nested analysis of variance, but this led to increased sensitivity in assessing the toxic potential of various pollutant sources.

When there are multiple endpoints of interest, the sampling programme must be very carefully designed. G. D. Judd described some success when sampling drinking water sources for compliance with established standards over a variety of endpoints (e.g. pH, faecal coliforms, colour etc.). By taking a multivariate approach, he was able to determine the appropriate sampling strata and in fact reduce the number of sites needed for sampling. Cost reduction (with equal or even improved statistical precision and accuracy) is an obvious consequence of this redesign. J. Donnelly was able to achieve the same goal using linear regression splines in his study of sampling river surface water quality. By constructing a piecewise linear response model (Esterby and El-Shaarawi 1981) to describe the sewage - pollution indicator variables (as a function of distance from a common source or outlet), an algorithm for selecting future sampling sites was developed. The algorithm was seen to work better when the piecewise response functions did not change slope sharply at the segmentation points.

4. ANALYSIS OF ENVIRONMENTAL DATA

Sampling and monitoring are, of course, only the first stages in an environmental study. As was noted in a number of presentations (and has already been suggested above), the statistical analysis of environmental data takes on many forms. This was evidenced by the discussions and presentations in the conference's two sessions on environmetric analysis, as summarized below. The two sessions also included important invited presentations, one on relating sets of variables by R. H. Green, and the other on trend analysis by S. R. Esterby. These invited papers are presented later in this issue.

Among the contributed papers on analysis of environmental data, regression methods were a popular central theme. M. R. Donald presented a regression analysis of heavy metal concentrations in sewage, where the outcomes often were censored owing to measurement device limitations. The censored regression approach modified sets of orthogonal contrasts that compared various sewage treatment methods for their removal of metals from the sewage. The losses in orthogonality due to the censoring were seen to be slight.

Prediction from a poster paper on regression model is a common goal, and A. O. Nicholls presented a poster paper on a regression application to predict species distributions from selected environmental variables. Since the survey data on speciation take a binary form (i.e. 1 if the species is observed, 0 if it is not), logistic regression was used to model the species distribution. Preliminary study of the methods suggested that they exhibit great promise in their application to this prediction problem.

The possible impediments to predictive quality that environmental studies engender was illustrated best by J. Filar, in his presentation on models for atmospheric greenhouse gas accumulation. Filar's construction took an integrated form, incorporating a multitude of compartments and factors to model the greenhouse effect. Filar noted that when only a few elements of this complex multicompartment model (or, more precisely, when the variability in response due to elements of the model) were ignored, substantive errors in the predicted effect could be reported. The message paralleled that noted in Section 3: it is critical to incorporate the stochastic nature of the many inputs to environmental systems when predicting an outcome based on selected environmental impacts. Failure to do so can seriously affect any statistical inferences drawn from the model. Portier and Kaplan (1989) described a similar effect in their models and analyses of carcinogenic response to environmental toxins.

If the only predictor variable is time, then a time series analysis may be appropriate, and C. H. Badcock described an example of such for monitoring beach pollution. In her study, temporal correlations invalidated the use of standard regression or linear model approaches to describe the dynamic relationships between the variables of interest: faecal coliforms in the beach water and rainfall and faecal coliforms in storm water drains into the beach area. A Box-Jenkins transfer model (Chatfield 1984) was seen to provide useful inferences in describing the relationships among these variables.

When the prediction is directed at imputing or estimating missing values from environmental data, P. E. Cheng's presentation would prove useful. Cheng described a regression analysis applicable for when data are missing, such as in meteorological studies of suspended particulates on global climate change. (Cheng noted that one often finds missing particulate observations on certain days or at certain sites owing to resource or personnel constraints.) Since such settings involve highly complex response functions, Cheng recommended a non-parametric method, involving functional smoothing methods. From these, imputation methods were described that allow for estimation of the missing response(s). R. Goudey presented allied methods for studying spatial and temporal trends in chlorophyll concentrations in an Australian bay. Smoothing approaches, including spatial kriging (Cressie 1991), were employed to interpolate surface water chlorophyll concentrations. From these results, cluster analysis identified zones of differing chlorophyll concentrations around the bay, for use in predicting future chlorophyll concentrations, and their effect on the marine ecosystem.

The application of cluster analysis played an important role in another study, presented by R. Nahhas. He described a case study on the influence of various types of runoff on water quality of different types of aquatic ecosystems (a similar issue to that in Badcock's study). The results suggested that the different types of ecosystems exhibited differences in sewage-pollution response, i.e. creeks appeared different from beaches, while stormwater drains appeared different from bays, etc. These results should lead environmental scientists to study more carefully the factors that appear to influence the different forms of ecosystems.

G. Robinson described, in a poster paper, a slightly different approach for quantifying nutrient or pollutant concentrations in aquatic ecosystems. In particular, if the system is a river, a pollutant's concentration multiplied by its flow is defined as its load, which is affected by various hydrologic factors. Robinson proposed the use of a form of quantile plot (Fisher 1983) to describe "flow duration". By plotting observed (instantaneous) loads corresponding to a given flow on the same horizontal axis, a "load duration" curve was constructed. The area under this curve has interpretation as an estimate of total streamflow loading. These methods were shown to provide fairly consistent load quantifications under a variety of sampling regimes.

5. STATISTICS IN ENVIRONMENTAL HEALTH

Application of statistical approaches to data on the biomedical effects of environmental stimuli constitutes a growing branch of environmetrics, and the conference devoted a session to this topic. Invited papers were given by W. W. Piegorsch and by L. Ryan on such applications using laboratory animal data, and these are provided at the end of this issue. Contributed papers on statistics in environmental health also touched upon examination of human response to environmental stimuli, i.e. environmental epidemiology (Goldsmith 1986). As with other branches of epidemiology, biometric data analysis plays a crucial role, and this entered into the contributed discussions. G. Berry began by describing a study of asbestos exposure in Australian miners and its relationship with subsequent onset of mesothelioma, a typically fatal form of lung cancer. His analysis showed that both increasing exposure to asbestos and time since first exposure were associated with increasing cancer risk in miners. Berry suggested the use of non-linear power functions to model the time–cancer relationship, and then illustrated their use for predicting low-dose effects of asbestos exposure in other 'at risk' populations. L. S. Khawar described similar interests in a poster paper on a study of heavy metal exposure near a New Guinean mine. She highlighted a biopsy of metal concentrations in scalp hair as a dosimeter of individual exposure, and showed that this measure has some value as an observational quantity, particularly for assessing mineral iron exposures in populations living near mining areas. As might be expected, however, person-to-person variability was quite high, and this limited the statistical power to detecting only very strong differences among population groups.

Environmental epidemiologic studies were also presented that considered potential human illness derived from water-borne exogens. J. F. Harrington described a cohort study (Breslow and Day 1987) of recreational users of an Australian river in which exposure to faecal bacteria was examined as a risk factor for disease onset. Analysis of the cohort data showed that various forms of respiratory and gastrological infections were more common in river users than in external controls, with approximately a fourfold increase in odds of succumbing to disease. The data clearly indicated that technological measures to remove bacteria and other exogens from wastewater prior to river delivery are essential for maintaining public health. Similar results were presented by H. C. Kirton in a retrospective study of whether selected swimming locations at Australian beaches yielded higher odds of infection or disease to their recreational users. Specialized forms of risk indices (literally, illness potency estimators) were developed to assess this issue. The data suggested that certain beaches could lead to higher-than-average risk of illness to swimmers. This risk relationship depended, however, on how the retrospective features of the data were incorporated into the analysis, suggesting that further study of the complex data features of the study was necessary.

6. OTHER PRESENTATIONS

Along with the various scientific papers summarized above, the conference included selected other demonstrations and presentations. Computer software exhibitions highlighting packages and programs useful in environmetric applications were given by C. Fry and J. Filar. Also, a delightful banquet speech was given by O. Mayo of the Australian CSIRO. Dr Mayo is a leading expert in biometrical applications in animal breeding and genetics, and fortuitously also lived with R. A. Fisher in the last few years of Fisher's life in Adelaide, Austrialia. His views on modern environmental problems and how statistics can serve to improve our understanding of them were complemented by his unique perspectives on what Fisher's standpoints (both encouraging and discouraging) might have been regarding these issues!

7. CONCLUDING REMARKS

In closing, we wish to echo the concluding remarks of the conference's welcoming speaker, A. Eyland. We share her view that exciting scientific discoveries are possible in environmental research, and particularly in the study of environmetrics. We hope that this conference will serve to encourage further study and investigation in issues described by the presenters, and into other issues that those problems may engender. Our underlying theme has been that of collaboration and interaction between scientists and biometricians, through which both fields can prosper and grow.

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APPENDIX

PRESENTATIONS AT THE INTERNATIONAL CONFERENCE ON ENVIRONMENTAL BIOMETRICS

Environmental Monitoring, Assessment, and Prediction of Change I. Dr G. P. Patil, Chair.

Keynote Address: Environmental monitoring, assessment, and prediction of change. Dr Abdel H. El-Shaarawi, National Water Research Institute, Canada.

Perspective on the statistics of environmental monitoring: modelling and estimation or power of tests. Dr Glenn De'ath, James Cook University, Australia.

EPA guidelines for utilization of wastewaters by irrigation, or "Don't pollute the water, irrigate the land". Mr Ian Shannon, New South Wales (NSW) Environment Protection Authority, Australia.

Environmental Monitoring, Assessment, and Prediction of Change II. Dr Sylvia R. Esterby, Chair.

Matching sampling designs and significance tests in environmental studies. Dr. John C. Evans and Mr Brian G. Coote, Sydney Water Board, Australia.

Feasibility of applying risk assessment techniques to a new pulp mill in Australia. Dr Ray L. Correll, CSIRO, Australia.

Flexible decision rules for hypothesis testing in environmental science. Dr Bruce D. Mapstone, Great Barrier Reef Marine Park Authority, Australia.

A simple protocol for background radiation dosimetry. Dr David R. Fox, CSIRO, Australia.

Environmental Sampling I. Mr H. Cameron Kirton, Chair.

Observational economy of ranked set sampling: comparison with the regression estimator. Dr G. P. Patil, A. K. Sinha and C. Taillie, Pennsylvania State University, United States.

Redesigning an existing drinking water quality monitoring programme: a multivariate approach. Mr Graeme D. Judd and Dr. John C. Evans, Sydney Water Board, Australia.

The Wog Wog habitat fragmentation experiment: objectives, design, constraints and some preliminary results. Dr A. O. Nick Nicholls, CSIRO, Australia.

Measuring seedling densities in rehabilitated bauxite pits. Dr Geoff Riley, Sam Ward, John Koch and Glen Ainsworth, Alcoa Pty Ltd, Australia.

Environmental Sampling II. Mr Ellis A. Roberts, Chair.

Application of appropriate statistical design and analysis to assessment of water quality in urban waterways. Ms Catherine A. Preston and Mr Steve Mackay, Sydney Water Board, Australia.

Designing a sampling scheme for water quality monitoring along a river. Mr John Donnelly, Dr Glenn Stone and Dr Michael Buckley, CSIRO, Australia.

Seasonal cycles, environmental change, and BACI designs. Mr Ellis A. Roberts, Sydney Water Board, Australia.

Field bioassays and spatial extrapolation of impacts. Dr Marcus Scammell, Sydney Water Board, Australia.

Sampling designs for assessment of environmental changes for marine populations. Dr Tony J. Underwood, University of Sydney, Australia.

Preliminary design of a monitoring programme to detect long-term impact mitigation for a Sydney waterway. Mr Tony G. Church, Dr Marcus Scammell, Mr Troy Collie and Mr. Mark Ramsay, Sydney Water Board, Australia.

Statistical Analysis of Environmental Data I. Dr Abdel H. El-Shaarawi, Chair.

Type I and type II errors when using ANOVA for environmental impact studies. Mr Bruce R. Hodgson, University of NSW, Australia.

Variability analysis of integrated greenhouse models. Dr Jerzy Filar, University of South Australia.

Regression analysis of censored heavy metal concentrations in influent to and effluent from four primary sewage treatments: a report of a pilot study at Malabar STP. Ms Margaret R. Donald, Sydney Water Board, Australia.

Relating sets of variables in environmental studies: the sediment quality triad as a paradigm. Dr. Roger H. Green, Janice Boyd and Steve Macdonald, University of Western Ontario, Canada.

Trend analyses for environmental data. Dr Sylvia R. Esterby, National Water Research Institute, Canada.

Statistical Analysis of Environmental Data II. Ms Margaret Donald, Chair.

Time series analysis of beach monitoring data: an example. Ms Caro H. Badcock, Sydney Water Board, Australia.

Trend surface analysis of water quality monitoring data to determine spatial and temporal variation. Mr Rob Goudey, Victoria Environment Protection Authority, Australia.

Multivariate analyses of environmental data of areas considered for sewage disposal options. Dr Raghid Nahhas and Mr Brian G. Coote, Sydney Water Board, Australia.

On semiparametric regression estimation with incomplete data. Dr Philip E. Cheng, Academia Sinica, Taiwan.

Statistics in Environmental Health. Dr Geoffrey Berry, Chair.

Assessing impacts of environmental stimuli via animal and microbial laboratory studies. Dr Walter W. Piegorsch, National Institute of Environmental Health Sciences, United States.

Assessing environmental risks to reproduction and development. Dr Louise Ryan, Harvard School of Public Health, United States.

Predictions of future mortality in former workers at the Wittenoom crocidolite asbestos mine and mill in Western Australia. Dr Geoffrey Berry, University of Sydney, Australia.

River users study: an epidemiological study of river recreational users of the Hawkesbury-Nepean river. Dr John F. Harrington, Dr David N. Wilcox, Dr Nicholas J. Ashbolt and Mr Paul S. Giles, Sydney Water Board, Australia.

Which swimming locations were responsible for sickness? Mr H. Cameron Kirton, Aquatech Pty Ltd, Australia.

Posters

The prediction of species distributions from binary data: the prospects and the limitations. Dr A. O. Nick Nicholls, CSIRO, Australia.

Application of flow-duration curves in calculating nutrient/pollutant loadings. Mr Grant Robinson, New South Wales Department of Water Resources and Mr Eric Hatfield, New South Wales Environment Protection Authority, Australia.

Changes in hair heavy metal levels in populations near the OK TEDI mine site, PNG. Dr Graham Jones, Ms Lubna S. Khawar and Dr Ken Watson, University of New England, Australia.

Reservoir monitoring: supplementing an existing design. Ms Margaret J. Swincer, Mr Michael Goti, Dr John C. Evans and Mr. Percy Ridley, Sydney Water Board, Australia.

Software Presentations

Variability analysis of integrated greenhouse models. Dr Jerzy Filar, University of South Australia.

SAS under Windows. Ms Cathy Fry, SAS Institute, Australia.