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Operational Research Models and the Management of Renewable Natural Resources: A Review

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Abstract

This paper reviews the role that the operational research discipline has played in the understanding and management of renewable resources in the areas of agriculture, fisheries and forestry. The analysis is undertaken with two purposes. First, to assess the past performance of the operational research models in this field. Second, to highlight current problems and future directions of research.

Keywords: Agriculture&Food; Fisheries; Forestry; OR models

1. Introduction

The field of renewable natural resources covers various areas such as: agriculture, fisheries and forestry. The understanding and management of this type of resource is a very complex problem. This complexity is mainly due to the issue of the required sustainability of the underlying natural system. In fact, when we talk about renewable resources, sustainability implies imposing constraints on the model to secure that the harvest rate of the resource does not surpass its natural regenerative capacity. It is clear that the accommodation of such constraints requires the use of suitable operational research (OR) methods.

After a long period of around forty years of applications of OR models to the management of renewable resources, it seems sensible to review the most successful cases in order to evaluate the past performance as well as to highlight current problems and future directions of research. Although the different renewable natural resources share common problems, for expository reasons the three main cases will be presented separately: agriculture, fisheries and forestry. With this type of presentation, the paper aims to give the reader a clear idea of which are the important issues in each area, what has been accomplished in research and applications, and what are current and future research areas.

2. Agriculture

Agriculture is one of the fields where OR models were first used and also where they have been most widely applied. Nevertheless, it should be noted that in many situations, the OR functions simply illustrate methodologies through case studies rather than actual applications. However, its actual use in agriculture has rapidly grown in the last decade or so, chiefly due to the impressive development of personal computers and commercial software programmes. In what follows, the main areas where OR models have been applied are examined in order to assess current problems and the future direction of these advances.

2.1 Agricultural Planning Problems (Farm Level)

A paper by Heady (1954) can be considered the starting point of linear programming (LP) models addressing agricultural decision making situations. The initial models in this direction were formulated at the farm level. The basic model had the following structure. The criterion function is usually defined as gross margin (i.e., sales revenue minus variable costs). The feasible set represents the different constraints that define the environment within which choices are made (e.g., labour requirements, land available, working capital requirements, etc). This basic modelling has been used to: a) determine the optimum cropping pattern, b) analyse interdependence between the different parts of the farm, c) investigate the optimal size of different types of fixed equipment and machines to be added to the farm resources, etc (Beneke and Winterboer, 1973).

LP models have also been used in the last years at the farm level to assess and to simulate the economic impact of several agricultural policies. These models are generally prospective as they try to predict the impact of policy reforms on farmers´ incomes and production patterns. Although this use of LP models is not exempt of difficulties (e.g., aggregation system, identification of the real objectives followed by the farmers, etc), its current interest and future possibilities seem unquestionable. A recent reference showing the potentiality of these efforts can be found in Lauwers et al. (1998).

However there are situations in farm planning, which cannot be accurately modelled only with the use of these basic LP models. For instance, there are cases where the decision variables cannot take continuous values (e.g., number of tractors) or where a certain activity, if it is to be produced, must be set, at least, to a certain minimum level (e.g., milk production). Resorting to integer and zero-one LP models this kind of problem can be solved. The intertemporal character underlying many agricultural decisions demands sometimes the use of multiperiod LP models (Rae, 1994). Two other important issues involve the risk and uncertainty that farmers have to face in real situations and the incorporation of multiple criteria in LP models. These important questions are discussed in more detail in Sections2.4 and 2.5.

2.2 Agricultural Planning Problems (Regional-Sector Level).

Some important modifications must take place when analysis moves from the farm level to the regional-sector level. These changes basically affect the definition of the objective function of the model and the aggregation problem. Let us analyse the two issues separately.

Within the regional-sector context the objective function used at the farm level (e.g., gross margin) becomes economically unjustifiable because, amongst other things, in this context changes in the supply of outputs affect prices. Samuelson (1952) was the first to demonstrate that at a regional-sector level, the objective function of the model has to be made up of two components or maximands: consumer and producer surplus, measuring the welfare of the consumers and producers, respectively. Samuelson´s approach is full of economic meaning as it leads to a Marshallian partial equilibrium. Moreover, this approach can be extended to a case of general equilibrium as Norton and Scandizzo (1981) demonstrated. This method is based upon welfare economics and presents certain difficulties. Indeed, under this situation, the quantity and price vectors are endogeneous to the model, what destroys the linear character of the objective function, which in turns generates a quadratic programming problem. However, the fast growth of non-linear computer packages has considerably reduced the impact of these difficulties. A good survey of this kind of effort is Hazell and Norton (1986).

The second issue is the aggregation problem. As all farms considered in a region or sector model are not alike, it is therefore impossible to consider the region or sector as a single farm. Hence, it is important to choose the appropriate aggregation rules in order to minimise the aggregation bias. Day (1963) was the first to state conditions for exact aggregation. Although these conditions were rigorous, they were too strong. Following Day´s seminal work, weaker conditions for aggregation have been proposed in the literature (e.g., Kutcher and Norton 1982, Önal and McCarl 1989). Notwithstanding, despite these worthwhile efforts aggregation is still an open problem

2.3. Modelling Interaction between Agriculture and Environment

Until recently, agricultural management has focused on higher yield through the intensive use of agrochemicals, fertilisers and other inputs. This policy has produced many unwanted environmental side-effects that can even question the sustainability of many agricultural practices. Fortunately, there is a growing effort to develop models capable of evaluating the economic impacts of environmental effects, and thus achieve sustainable agriculture.

Most of these efforts normally use a crop simulator model to predict the environmental effects of a variety of management practices. The results obtained are then linked to an optimisation model to determine trade-offs between economic returns and environmental impacts. The final output is usually a sustainable compromise between economic achievements and environmental quality.

In what follows, a series of studies in this direction are illustrated. Johnson et al. (1991) linked CERES crop simulator model to a dynamic optimisation model to determine the optimum applications of water and fertilisers under a behavioural assumption of gross margin maximisation. Zekri and Herruzo (1994) combined NTRM crop simulator model and a mathematical mixed multi-objective programming model to assess the effects of an increase in nitrogen prices and drainage water reduction, thus inducing the adoption of best management practices. Finally, Teague et al. (1995) used the EPIC-PST model to predict environmental risks from the use of pesticides and nitrates. These results were then combined to a Target MOTAD optimisation model to evaluate the trade-offs that exist between income and an index that linked both risks associated to the use of pesticides and nitrates.

Although this approach is still very incipient, it will most likely become an important line of research in the near future. Indeed, it can be considered the embryo from which a rigorous framework capable of making the concept of sustainable agriculture operational can be developed as a compromise between economic and environmental criteria (see Section 2.5)

2.4. Risk and Uncertainty Analysis

Agricultural activity is characterised by the risk and uncertainty involved in its management. As farmers face variable income due to variable weather conditions, changes in price markets, crop and animal diseases, etc., agricultural decision making modelling should include elements of risk and uncertainty.

Game theory models involving games against nature are the most conventional means of analysing agricultural decisions under uncertainty. Their purpose is to find a pure or mixed strategy that optimises the aspirations of the decision maker (DM) in a game model, according to a certain behavioural criterion (maximin, minimax regret, benefit criterion, etc.) McInerney (1967) introduced the game theory approach in agriculture, whereas, Hazell (1970) and Kawaguchi and Maruyama (1972) introduced the idea of parametric games, optimising one criterion (e.g., maximin) while considering another criterion as a parametric constraint (e.g., maximum regret). In this way, a trade-off frontier between both criteria is established. This approach can be generalised with the help of goal programming, leading to the idea of compromise games (Romero and Rehman 1989, chap. 7).

The oldest approach to risk programming in agriculture is a direct application of the Markowitz approach (1952) for portfolio theory, as initially suggested by Freund (1956). This approach defines the risk of an agricultural enterprise through the variability of its returns, measured by the variance. Then an efficient frontier is established by minimising the variance of the cropping pattern while the expected return is treated as a parametric constraint. To avoid the use of parametric quadratic programming, Hazell (1971) suggested the minimisation of the mean absolute deviation instead of the variance.

The second phase of the Markowitz´s approach consists in the maximisation of the expected utility of the DM over the efficient frontier.

However, this maximisation is only rigorously possible when returns follow a normal distribution of probability or when the utility function of the DM is quadratic. However, the normal distribution of returns is a hypothesis, which has not been empirically corroborated (at least in many cases) and the quadratic utility functions presents many logical flaws (e.g., its absolute risk aversion increases with wealth). Although some approaches have been proposed to mitigate this problem by approximating the maximum expected utility over the efficient frontier (e.g., Tew et al 1992), the precise determination of the portfolio of maximum expected utility it is still an open question.

The application of game theory rules were criticised in the seventies on the grounds that the decision criteria used are incompatible with the axioms of rational choice (e.g.; Anderson et al. 1977 p.204). However, there is nowadays a revival of games approach and a criticism of the axioms of rational choice underlying Markowitzeans approaches (e.g., Zeleny 1982 pp.437-438). Despite the preponderance of these two approaches, there are other methodologies that have been proposed and applied when dealing with risk and uncertainty in agriculture. Amongst other are safety-first models, chance constraint programming, stochastic programming, etc. Hardaker et al. (1997) is an updated review of these approaches.

2.5. Dealing with Multiple Criteria in Agriculture

Nowadays it is widely recognised that multiple criteria are the rule rather than the exception in agriculture management either at the farm level or at the regional-sector level. In fact, several studies from the sociological field clearly demonstrate that farmers do not seek to optimise a well-defined single objective function. On the contrary, farmers usually seek an optimal compromise between several conflicting objectives, or try to establish satisficing levels of their goals (e.g., Gasson 1973, Harper and Eastman 1980).

The above considerations make it necessary to formulate decision-making models in agriculture management capable of recognising a multiplicity of objectives and goals in the farmers´ objective function. A pioneer work in this direction is a paper by Wheeler and Russell (1977), where a 600 acres mixed farm in the United Kingdom is planned with the help of a goal programming model, which included the goal of gross margin, seasonal cash exposure and provision of stable employment.

Extensive literature addressing several agriculture management problems from a multi-criteria perspective has arisen since this early work. The most widely used approach has been goal programming, although, there are also considerable number of applications using multi-objective programming and compromise programming. The next section shows how another important area in the application of multi-criteria analysis is the livestock diet problem The book by Romero and Rehman (1989) is a comprehensive reference of the state-of-the-art of multi-criteria analysis in agriculture.

2.6. Livestock Rations and Feeding Stuffs Formulation

The first successful application of mathematical programming in agriculture was the use of LP models to establish the least cost combination of feeding stuffs and livestock rations meeting a specified level of nutritional requirements. Since the early work by Waugh (1951) many farmers, and basically all feed mixers have relied on LP for the optimum design of livestock diets.

The original analytical LP framework has been extended in several directions. The use of parametric LP allows the study of the effect of price changes in ingredients (coefficients of the objective function) on the optimum mix. The analysis of the dual models let us establish the shadow price of each constraint (nutritional requirement) of the model. The incorporation of Chanced Constraint Programming increases the realism of the model when there is uncertainty regarding the real content of some of the ingredients. The investigation of the relationship between the bulk of the ration and cost as well as the use of the technique within a practical environment are two other examples of extensions of the LP approach within the commented field. For a good review of some of these improvements see Black and Hlubick (1980).

However despite its proven success, the application of different LP models to determine an optimum animal diet is not exempt from difficulties. Thus, the reliance on the cost of the blend as the only relevant criterion for the decision-maker is an unrealistic assumption, especially when livestock ration at the farm level is calculated. Under this context, the farmer is interested in an economically optimal ration that achieves a compromise amongst several conflicting objectives such as cost, bulkiness of the mix, nutritional imbalances, etc. These considerations transform the diet problem from the traditional LP approach to a question of multiple criteria. In this direction, in the last few years some methodological proposals formulating goal programming models for optimum design of animal diets within a context of multiple criteria have appeared (e.g., Rehman and Romero 1984, Neal et al. 1986, Czyzak and Slowinski 1991).

Another problem underlying the traditional LP approach is the over-rigid specification of the nutritional requirements. In fact, it is unquestionable true that a certain relaxation of the constraints imposed would not seriously affect the animal´s performance. However, this kind of relaxation can considerably increase the size of the feasible set, allowing an important reduction in the cost of the ration. Some attempts to tackle this problem have been made. Thus, Rehman and Romero (1987) have addressed the over-rigid specifications of the nutritional requirements, by incorporating a system of penalty functions to a goal programming model. Other authors like Czyzak (1989) have resorted to fuzzy mathematical programming or Lara and Romero (1992, 1994) to interactive methodologies; that is, to elicit the preferences of the feed mixer or farmer regarding possible relaxation of the nutritional requirements through a computerised dialogue.

An important problem methodologically related to livestock ration formulation is the determination of optimum fertilisers combinations (Minguez et al 1988). Finally, another problems in livestock production addressed with the help of OR models refer to decisions concerning optimum replacement/culling policies, through dynamic programming and Markov´s processes (Houben et al. 1994, Kristensen 1994) and the assessment of adopting new reproductive technologies, through the integration of Markov and LP models (Yates and Rehman 1996) .

3. Fisheries and aquaculture

Applications of operations research to fisheries and aquaculture have been developed extensively in the last three decades. Initial efforts were dedicated towards promoting stock conservation in the case of severely overexploited species. OR has since explored diverse issues in fisheries management, both at a national and international level. In doing so, bioeconomic models integrating biological growth of stock and industry behaviour have played a crucial role. Similarly, OR in aquaculture has combined modelling experiences from fisheries and other disciplines like agriculture and forestry to improve efficiency and economic gain at the farm and industry level.

In Section 3.1 applications of OR to capture fisheries are explored. Influential contributions to biological and in particular economic modelling are described. Economic modelling of capture fisheries is further divided into descriptive mathematical modelling, mathematical programming and optimisation, statistical analysis and estimation procedure, computer simulation, and decision theory. Section 3.2 gives an extensive overview of applications of operations research to aquaculture. The section distinguishes between biological and economic modelling, and the economic models are further categorised according to their approach or technique.

3.1 Applications in Fisheries

The fundamental problem of fisheries management is two-fold as it has to take into account both the conservation of the resource base, as well as the exploitation of the resource by the harvesting/processing sector. Larkin (1988) makes the distinction between biological constraints and social objectives as he claims that the approach to fisheries problem solving must be anthropocentric, i.e., based on social welfare. For stock exploitation this requires a multidisciplinary definition of the short and long term decisions pertaining to economic, social and administrative objectives.

a) Biological Modelling

The task of modelling stock population dynamics is at the heart of fisheries management. Such models are critical to the underlying evaluation of the fishery from an immediate as well as long-term perspective. In particular, effort has been dedicated to areas of investigation such as fish stock population dynamics, stock assessment and survey methods, and population interactions.

The most widely used aggregate model for population dynamics is the Schaefer model. Schaefer's model is a continuous time, lumped parameter model, also known as a surplus production model. Ricker (1975) presented a family of discrete time, lumped parameter models of fish stock and recruitment behaviour which combined long-term growth dynamics of the stock with short-term dynamics of birth and death. Gulland (1983) also presented related work on fish stock assessment and stock population dynamics in edited volumes. Beverton and Holt introduced the important class of discrete dynamic pool models to describe stock growth dynamics. Their cohort model explicitly considered the age structure of the stock and each year class' growth, mortality and yield potential. These models are widely and successfully used e.g. to assign quotas.

Mathematical models have also been used to analyse stock assessments. In Mangel (1985) three main aspects of stock assessment surveys were discussed, along with associated descriptive modelling methods: (1) sampling effectiveness, (2) effort allocation in surveys, and (3) the effect of spatial concentration of fish stocks on survey results.

As a response to perceived inadequacies of single species population models considerable attention was devoted to research in species interaction models during the late 1970s and into the 1980s. An ecosystem modelling approach was developed by Holling (1965), including production of food supply, predators and parasites, and energy distribution concepts. Due to the complexity and uncertainty involved in these problems, however, the approach did not yield operational policies. A collection of papers on complex multispecies systems focused more on management issues than pure stock dynamics (Mercer, 1982). The multispecies models dealt with tactical issues of immediate interest, for instance how much the stock can be harvested during the season in order to maintain a sustainable system in future periods. More recently, Pauly and

Christensen’s (2000) work on multispecies, trophic level models has received considerable attention.

b) Economic Modelling

Economic research in fisheries has had a long tradition which has evolved independently of the modelling of population dynamics. Economic modelling of fisheries management was initiated in the 1950s with the pioneering works of Gordon (1954) and Scott (1955). Gordon used static economic theory of production along with generalisations about the collective behaviour of fishermen in an open access competitive environment to demonstrate that overfishing is rooted in the economic subsystem of fisheries. Similarly, Scott (1955) had been motivated by increased industrialisation in fisheries and growing problems associated with open access to the marine resources.

Operations Research Modelling

Operations research has contributed to the management of fisheries systems through the application of a systematic approach to decision making. Five major areas of fisheries systems modelling can be identified (Lane, 1989a):

(1) Descriptive mathematical modelling
(2) Mathematical programming and optimisation
(3) Statistical analysis and estimation procedure
(4) Computer simulation
(5) Decision theory

Rights-based principles such as individual transferable quotas were derived primarily from analyses of economic systems for the management of common property resources, including fisheries. In general, formal economic analysis, including Scott (1996) and Grafton (1996), has tended to champion the rights-based, marketable quota approach, which is also becoming predominant in fisheries management world wide.

Mathematical programming/optimisation

Applications in this area include analysis of optimal management decisions with regard to target stock levels over time, optimal employment of fishing effort and capital, and cost minimising rules for monitoring and surveying stocks, or for enforcing fishing regulations. Rothschild (1986) pioneered the use of linear programming methods in fisheries to deal with resource allocation problems including harvesting decisions and timing.

Clark (1985) extended the work of Gordon by using a dynamic model formulation. Deterministic problems in population dynamics, stock recruitment, stock exploitation and multiple species interactions described the dynamic transition to optimal bioeconomic population levels and yields. In Clark (1985) applications under uncertainty were considered. Applications included stochastic models for determining optimal stock levels, search and information sharing strategies for fishermen, capital investment in fisheries, regulation of fishing effort and catch, and multiple species models. Clark and Kirkwood (1986) analysed optimal harvest policies in the presence of uncertainty about the resource base. Uncertainty would stem from both natural fluctuations in the stock, and uncertain estimates of the stock abundance. A Bayesian approach was used to model optimal quota decisions. Reed (1979) used inventory theory to show that a pulse fishing policy is optimal for a discrete-time model of harvesting with stochastic recruitment. This result is analogous to the bang-bang control where fishing effort is applied until the safety stock level is reached.

Ludwig and Walters (1982) demonstrated the significant impacts of unreliable catch and effort data on derived optimal catch levels. Their results demonstrate that stock probing and experimental management regimes provide valuable information in determining actual stock behaviour.

Mangel (1985) presented an optimising framework for fishing effort by individual harvesting units including search and fishing activities. Each component of fishing effort by vessels was modelled, and a complete model of the fishing process was constructed. A model of probabilistic encounters of clumped fish stocks and Bayesian updating of past encounters combined to determine adaptive strategies for fishing in successive periods of a season.

A number of papers address the issue of investment in fleet capacity. Clark, Clarke and Munro (1979) analysed the optimal exploitation policies for a renewable resource in the case of irreversible investment. The model was extended by Boyce (1995) by relaxing the assumption of linearity in investment costs and variable harvest profits. Charles (1983) modelled investment decisions in an uncertain environment using a stochastic optimisation framework. Optimal policies for both fleet investment and stock management within an uncertain environment were determined and compared to those of a deterministic model.

Another class of papers are concerned with the optimal timing of harvest. Larkin and Sylvia (1999) incorporated varying fish quality during the harvesting season and estimated the value of including intrinsic quality and quota allocation into the determination of the optimal management plan. Önal *et al.* (1991) developed a multi-period mathematical programming model to determine the optimal harvesting pattern of the Texas shrimp fishery. Comparing with the actual harvesting pattern, the authors found substantial gains from reallocating fishing effort throughout the season in order to improve the size composition of the catch.

Statistical analysis

The inability to observe the stock fully represents an intrinsic source of uncertainty in capture fisheries. Statistical analysis is therefore a key component in fisheries modelling.

Schnute (1985) described a general theory for the estimation of population dynamics from catch and effort data. In later work, Schnute focused on the problem of data uncertainty and ambiguity in fisheries growth model identification and presented an analysis of fish growth, maturity and survivorship data which unified existing approaches.

Age-structured stock population analyses routinely used today are based on the work by Pope (1972) on cohort or virtual population analysis. Pope recognised the existence of many different age groups in the fishery and the complex and variable harvesting impact on different cohorts. The numerical analysis procedure allowed estimates of fishing mortality to be based on fishing gear at age selectivity.

Computer Simulation

A collection of simulation efforts to ecosystem models is presented in Mercer (1982). Systems simulations have also been undertaken on the structure and evolution of fisheries industries to predict multiobjective outcomes of industrial behaviour dynamics. A simulation model of within season fleet dynamics is described in Hilborn and Walters (1992). A simple movement decision rule was developed for the members of the harvesting sector, and computer simulation was used to model the movement of the fleet over various areas of the fishing ground during a season. Finally, property right management schemes have been evaluated by simulation techniques.

Decision Theory

Decision theory is applied to decision-making on both the management side and the harvesting side in fisheries. Management decisions include regulation and allocation of harvest, while the fishermen typically make decisions about search, fishing effort, vessel movement and investment.

Walters (1986) described a decision model framework using feedback from Bayesian updating on statistics from catch and effort data to identify statistically valid population dynamics model alternatives. Dynamic programming was used to solve for optimal decision policies. Walters showed that dynamic adaptive management schemes and stock probing policies increase the value of information in the understanding of stock dynamics behaviour.

Opaluch and Bocksteal (1984) applied decision analysis in a discrete alternative model of stock switching behaviour by fishermen. They developed a behavioural model of fishermen based on utility analysis and economic incentives using data from the New England fisheries.

Lane (1988, 1989b) modelled fishermen’s dynamic intraseasonal movements and interseasonal investment decisions as a Markov decision process. The results anticipate the impacts of area closure regulation and landed value taxes on the harvesting decisions of fishermen.

Clark (1985) and Mangel and Clark (1983) have examined information processing by fishermen for future decision-making. They used decision models of Bayesian updating by fishermen in finite horizon dynamic programming models with passive adaptive strategies and simulation analysis.

Finally, game theory has been used to model decision-making. Management problems associated with shared and straddling fish stocks have been addressed by Bjorndal et al. (2000). A game theoretic approach was used to model the equilibrium positions of player nations desiring shares of the exploited resource. Issues of cooperation and games with side payments illustrated the underlying political structure of international fisheries problems.

While computer simulations in some instances have been successfully implemented, the other approaches have been important in gaining insights into complex management problems.

3.2. Application to Aquaculture

Work in related fields such as agriculture and fisheries management has influenced the development of modelling applications to aquaculture. Conceptually, aquaculture is more related to forestry or animal husbandry than to capture fisheries. Operational research in aquaculture integrates a biological model of growth of the species as a function of body weight, water temperature, feed etc, and an economic model linking the biological production process to the market through input and output prices and resource constraints.

a) Biological models

Biological models describe the production system and its relationships with the environment. Construction of the biological model is usually the most difficult part of the modelling process due to the complexity of the biological organism and its interaction with the environment (Leung, 1986).

A new line of research has been the introduction of nutritional responses in modelling biological process. Cacho *et al.* (1990) developed a bioenergetic model of fish growth. Fish growth was simulated by a system of 15 non-linear differential equations. Simulation started with food intake and followed the energy flow inside an individual fish to estimate growth rate.

b) Economic models

The economic model provides a link between the biological production system and the market. Factor prices play a key role in determining the optimal input mix for maximising the value of the stock, and varying output prices may influence the optimal time of harvest when the price depends on individual size or particular qualities of the species. Moreover, risk and uncertainty regarding prices may induce further changes in optimal harvesting patterns.

Linear Programming

Hatch and Atwood (1988) developed a mixed integer target model to assess risk-income trade-offs for alternative activities of producers of farm-raised catfish. The target was variable cost, and alternative activities included different fish growth stages such as egg, fry, fingerling, and food fish.

Shaftel and Wilson (1990) presented a linear programming model to address real-world strategic planning requirements of an emerging technology, as well as production schedule requirements of a mature aquaculture facility. The authors solved a large-scale model through a series of smaller linear programming problems.

Forsberg (1995) analysed the optimal management of size-structured farmed Atlantic salmon in land-based grow-out systems. To model production planning decisions a multi-period linear programming model was developed. Production planning decisions included the determination of the optimal number of smolts to recruit into the grow-out system, the estimation of population growth and production cost, and the choice of the optimal harvesting schedule in order to maximise profit.

Comparative Static and Dynamic Optimisation

Bjørndal's (1988) paper on optimal harvesting of farmed fish prepared an avenue of research by adapting a Beverton-Holt model to describe optimal harvesting time for farmed fish. This paper connected aquaculture with the theory of optimal exploitation of renewable resources. By adding output price and costs a bioeconomic model was constructed. The author then used comparative statics to analyse the effect of changes in different model parameters on the optimal harvest time for a one-time investment in fish. Linear weight-dependent output prices were also introduced, and applications to salmon and turbot were made.

The paper by Bjørndal was later extended by several authors. Arnason (1992) introduced endogenous feeding rates in an optimal control framework and derived optimality conditions for the interrelated questions of the optimal feeding trajectory and optimal time of harvest for different biological growth functions. Heaps (1993) drew on both Bjørndal (1988) and Arnason (1992) and used an optimal control framework to analyse the effect on harvest time and fish weight and age of changes in model parameters when feeding is endogenous. In Heaps (1995) a density dependent biological growth function is further introduced and the optimal culling rate is analysed. It was shown that the optimal management policy may include a period of culling of the stock up to a final slaughter date where all the remaining fish are slaughtered. In Mistiaen and Strand (1999) weight-dependent output prices were revisited. The authors developed optimality conditions for feeding rates and time of harvest when output price is piece-wise linear in weight. Their model was applied to sea bream aquaculture in Greece to show that only marginal changes in model parameters could induce substantial deviations in optimal fish weight.

Cacho *(1997)* determined cost-effective feeding regimes for pond–reared fish. The authors modelled the interaction among feed allowance, diet quality and harvest date. Optimal control theory was used to optimise management schemes under different scenarios

Stochastic models

Hatch and Atwood (1988) presented a pioneering work by incorporating risk into an aquaculture decision-making model. They used a risk-programming model for farm-raised catfish.

Hochman *et al.* (1990) presented a stochastic dynamic decision model for evaluating the potential of the round pond technology. The model provided optimal stocking and harvesting schedules for a shrimp pond using a set of intra- and interseasonal rules.

Allen et al. (1992) treat both biological and economic issues in their multidisciplinary work. They point out that are few bioeconomic analyses worthy of comment, however, more of this kind of linked analysis should be applied to aquaculture.

Aquaculture as an industry has expanded world wide for the past 20 years. Models that have been described here are likely to become ever more important for this industry.

4. Forestry

The use of OR models in forest planning started in the 60's, as theoretical developments, but also in actual use, as reported in the well known TimberRam (Navon 1971) LP model used by the US Forest Service in long range harvest planning. Basic developments in the 70's incorporated multiple use and concerns in forests, accentuated in the 80's and 90's where in developed countries ecological issues, biodiversity, wildlife and preservation have taken precedence over timber production, in particular in native forests. These concerns have led to the development of interesting algorithms mostly of combinatorial nature that are used to provide spatial properties needed to characterize environmental constraints. The incorporation of uncertainty and multiple objectives in this context has had importance but mostly as methodological propositions and case studies. In parallel, models to support decisions for private plantations, mostly at operational level have also been developed successfully in the last decade. In what follows, we discuss the main areas where OR models have been developed. For recent review articles see Weintraub and Bare (1996), and Martell et al. 1998.

4.1 Strategic Decisions

The introduction of TimberRam, an LP model for long range harvest planning in the US Forest service in the late 60's marks in a way the coming of age of OR in the forestry sector. LP models started being used widely to support long range, strategic decisions in harvesting. Previously, decisions were supported by manual analysis or simulation models. While simulation provides ample flexibility in decision processes, as is well known it has limitations in finding optimal or feasible solutions. This was the case in forestry planning, as requirements to have even production along time proved to be difficult to determine without the use of LP models. In these early harvesting models, environmental issues were handled implicitely, through eliminating certain harvesting practices or setting some areas aside. The increasing need to include multiple uses and concerns for forests limited the use of these models and led to the development of models that incorporated multiple uses such as recreation, range and mainly environmental considerations. This led in the US Forest Service to the introduction of FORPLAN (Johnson et al 1986) which adresses the many concerns of nontimber values, where different uses of the forest where regarded equally, timber harvesting being one of them.

FORPLAN was widely used by the US Forst Service in its planning cycle in the 80's and early 90's as well as by other agencies and also private firms.

A new system, Spectrum (USDA Forest Service, 1995) being introduced now, improves in the user friendliness and it emphasizes even further the concept of preservation and viewing the forest as an ecosystem. All these are basically LP models, though the use of 0-1 variables as an option was introduced into FORPLAN to account for road building.

Strategic models have also been used for managing plantations, usually owned by private industry, where the main objective is to maximize net present worth, subject to existing regulations that relate to environmental, legal or social issues.

These models deal with timber harvests on their own, when large firms own timber lands and sell timber in the market (Fletcher et al. 1999). In other cases the firms are vertically integrated to industrial instalations, and the basic function of the timberland is to provide raw material to the plants, typically sawmills and pulp plants. The models used are typically LP's , of moderate size as the land areas are aggregated to consider major harvesting policies, not spatially defined.

In the case of integrated systems, models need to interact with investment and operation of plants, typically pulp and sawmills. This leads to adding 0-1 variables to the models (Cea and Jofré, 2000).

In general we can consider that use of LP models for strategic planning is in a mature state, and is used commonly and successfuly in many countries including the US, Canada, New Zealand, Chile; Brasil and Sweden (García 1990).

4.2 Tactical, medium range models.

These models look at horizons which include the next harvest only. They are more detailed in terms of spatial resolution. Roads for access are defined explicitly and other spatial considerations due to environmental issues are also considered. Decisions on harvesting and other managerial actions are usually still at some level of aggregation though. In the 60's and 70's road building was considered separate from harvesting decisions, leading to clear suboptimalities (Jones el al 1986).The first models integrating road building to harvesting were proposed in the late late 70,s and the first implementations were used in the 80's.(Kirby al 1986). These are mixed integer problems of the network design type, often difficult to solve. Solution approaches have included the use of commercial packages (accepting sub optimal solutions for the more difficult problems), and heuristics mixed with LP solutions (Weintraub and Jones, 1994). Addition of logical inequalities, lifting and careful use of priorities in the branching process has led to improved solution processes (Guignard et al, 1998).

In most cases the road network design has been considered jointly with other spatial characteristics induced by environmental considerations.

Most of these environmental considerations are based on the geometry of the harvesting patterns and their impact on wildlife, scenic beauty and other preservation considerations. A very well known constraint is to consider as not acceptable to harvest large contiguous areas. This has led to the formulation of a well known problem by now, the adjacency problem. Basically it states that, given a forest, no two adjacent areas can be harvested in the same period. These areas are tipically of about 20 to 40 hectares. This leads to a problem similar to a chessboard, where only the white cells can be harvested in the same period. This is a hard combinatorial problem. The problem can be modeled as a 0-1 integer problem, but only moderate size problems can be solved exactly using conventional branch and bound algorithms. As described in Martell et al. (1998), solution approaches have included solving a strengthened the LP formulation or solving a relaxed LP version of the problem and using column generation. Typically for real implementations heuristic approaches such as Tabu search, simulated annealing and randomization are used (Murray and Church 1995). In the next section we discuss extensions led by environmental criteria.

4.3 The Environmental Question

As described in the previous section, environmental issues have become increasingly important in forest management and planning. Increasingly, more complex conditions have been established, which require model specifications different from adjacency constraints. These conditions can be viewed as:

a) The sheer amount of habitat protected, which can be approximated to a reserve design problem, that is, decisions must be made on which areas to leave unharvested, in a compromise between economic and wildlife protection goals. One way in which this problem can be defined is as the minimal reserve set. That is, what is the minimal number of areas that needs to be reserved so that each species to be protected is represented at least in one reserved area (Clements et al 1999). Since different species require different habitat types defined by levels of growth of trees or seral stages, this specification corresponds to a simplification of the real problem.

b) The second problem relates to sizes of thresholds for habitat patches, or areas with no grown trees. These patches can have both minimum or a maximum area constraints, and correspond basically to the adjacency problems.

c) The habitat fragmentation problem, which concerns to the dynamic movement of different wildlife species, including the study of spatial dispersion of species along time as a way to control population, and the definition of corridors of mature trees between feeding habitats to allow animal movement (Hof and Bevers, 1998). Typical solution procedures include linear and non linear programming, integer programming heuristics and Montecarlo simulation.

d) The edge effect which has to do with the juxtaposition of trees of different ages, and is important because many species have requirements for multiple habitat type, such as cover, feeding and foraging and they cannot travel far without enduring mortality or loss of efficiency from energy expenditure.

In addition, water quality, in terms of temperature increases and sedimentation caused by harvesting operations is also important.

In these problem areas there have been important algorithmic and system developments. Programs such as SNAP 3 (Sessions and Sessions, 1991), are widely used in planning by the US Forest Service and other organizations. In these packages, which rely on GIS linkage to databases, the algorithmic engines are mostly through heuristic approaches, such as local search algorithms and graph or network algorithms. But as mentioned, there have also been models developed for specific problems, in particular related to wildlife based on LP, Integer 0-1 LP models and non linear programming (Hof and Bevers, 1998).

4.4 Uncertainty and Multiple Objectives

These two issues have been important in forest planning as they arise naturally. While there have been important theoretical developments in both cases, very little of these have been applied, mostly due to the difficulties in implementation and lack of reliable data. In terms of uncertainty, most of it is due to uncertainty in future prices and timber production (Hof, 1995). Techniques proposed go from the traditional making of conservative estimates to dynamic programming, chance constrained models and stochastic programming models (Lohmander 1994, Haight 1997). As environmental factors become more important, this adds new dimensions of uncertainty, and should lead to novel modeling issues.

The issue of multiple objectives arose naturally given the multiple use defined for forests. Typical techniques used involve goal programming, multiple-objective LP and compromise programming (Diaz-Balteiro and C. Romero, 1998). Again, as environmental issues become more prevalent, there should in theory have been an increasing interest in using multiple objectives modeling tools. So far however, there have not been many applied developments along these lines, and it is not likely that there will be an important use of sophisticated tools in this area in planning.

For more details on both areas see Martell et al 1998, Weintraub and Bare 1997.

4.5 Operational decisions.

There has been an increasing use of OR tools for operational decisions in basic forest activities of harvesting and transportation. These decisions involve what areas should be harvested in the near future, how should the trees be cut up into pieces of defined quality, length and diameter so as to meet specific product demand, how to use and where to locate the harvesting machinery, (which typically consists of skidders of tractors for flat terrains and towers or cable logging for steep areas), and how to transport logs from the forest to destinations such as mills. Models to solve at least some these problems have been implemented successfully in countries such as the US, Sweden, New Zealand, Chile and Brasil.(Weintraub et al. 1999). The models typically interact with GIS systems to collect detailed terrain and forest inventory data. Solution models for harvesting problems are based on LP models and heuristic approaches to solve the combinatorial problems induced by 0-1 decisions such as machine locations. The truck scheduling problems for efficient transportation have been solved via simulation with heuristics or exact mathematical formulations with heuristic approximations.

4.6 Integration of decisions

One problem that remains open from a methodological angle is the interaction of decisions at different hierarchical levels. These decisions range from horizons of many decades to daily ones, from areas of hundreds of thousands of hectares to a few.

Models have been developed and implemented to deal separately with different levels of these decisions (Martell et. al 1996). The linking of them however has been carried out mostly in a ad-hoc way. The main issue is that of aggregation and disagregation between decision levels which becomes particularly difficult when 0-1 variables are present, as is the case for example when road building is carried out.

5. Concluding remarks

Management of renewable natural resources is one of the first fields of massive successful applications of different OR models. It seems sensible to conjecture that the impressive past performance of OR models in this field will keep its pace in the near future. In fact, the emergence of global, competitive markets has increased the need to derive efficient production processes, to reduce investment and operational costs, and to increase productivity. Consequently, better management practices will play an increasing vital role. On the other hand, the increasingly more complex environmental issues present additional challenges for OR models. In this context, the significant role of OR models and methods for the understanding and management of renewable natural resources seem unquestionable.

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