FROM PROGENY TESTING TO SEED ORCHARD THROUGH MATHEMATICAL PROGRAMMING

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Abstract.--Ideal seed orchards have balanced, maximized genetic gain on all favorable traits, produce a maximum number of seed at the earliest age, enjoy the greatest longevity, have minimum costs for establishment and maintenance, and have minimum risk of failure. The conflicting objectives of such an orchard, as well as the many associated restraints and interactions, obviously call for many compromises. Mathematical programming seems to be a logical approach to maximizing gain in this complex problem. A hypothetical case study, using black walnut, is outlined.

Additional keywords: Operations research, breeding value, optimization

HISTORY AND DEVELOPMENT OF OPERATIONS RESEARCH

During World War II, a team of British scientists was called together to study the strategic and tactical problems associated with the defense of England. Because the team was working with research on military operations, they coined the term "Operations Research". The team was concerned with developing the "best" defense system with the resources available. Encouraging results achieved by the British team motivated the United States to try similar military management programs.

After the war, word began to leak out about the accomplishments of operations research. Industrial and business managers began using the new tool in quantitative decision making. Soon the applications of operations research, or the management sciences, spread into many fields and organizations.

Operations research in forestry has been concerned with problems involving forest-produced goods and services. About 400 papers have been published between 1960 and 1970 on this subject (Martin and Sendak 1973). In forest tree improvement Buijtenen and Saitta (1973) applied linear programming to the economic analysis of seed orchard operations. Porterfield (1974) used goal programming to seek a combination of traits to be selected and define the optimum intensity of selection for each trait. In this paper we will try to illustrate the feasibilities of utilizing mathematical programming in a genetic reproduction system.

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OUTLOOK FOR BIOLOGICAL SYSTEMS MANAGEMENT SCIENCE

The advancement of population biology has followed the development of mathematical theory. During the period 1920 to 1940, Fisher, Lush, and Wright developed quantitative genetics through mathematical statistics. Using their work as a basis, many population studies were made. From network and control system technology developed by electrical engineers during the 40's and 50's, we now have systematic ecology. We believe that in the next few years, operations research will be commonly applied to biology and a new discipline of biological systems management science will emerge.

Cost, volume, profit analysis can be used for population behavior study. Game theory can be used to analyze biological interrelations. Transportation problems and network models are valuable in simulating food chains. In forest tree improvement programs, the product mix model may offer the best approach for seed orchard establishment and management.

Seed orchards may have several objectives. One consumer (tree grower) may want maximum growth rate, while another desires seed production, winter hardiness, or frost avoidance. The ideal seed orchard would have balanced, maximized genetic gain on all favorable traits, produce a maximum number of seed at the earliest age, enjoy the greatest longevity, have minimum costs for establishment and maintenance, and have minimum risk of failure.

The conflicting objectives of such an orchard, as well as the many associated restraints and interactions, obviously call for many compromises. Genetic correlation among traits, balance between: vegetative growth and reproduction, timing of flowering among selected trees, and associated costs for each expected genetic gain must all be considered. Mathematical programming seems to be a logical approach to maximizing gain in this complex problem.

A HYPOTHETICAL EXAMPLE

For our example, we will use black walnut and consider progeny tests followed by establishment of grafted elite orchards (Gustafsson 1949). Such an approach offers flexibility in seed orchard design, maximum use of land, opportunity for expansion of the orchard with the need for additional seed, and greater genetic gain (Wright 1964, Stern and Hattemer 1964). The grafted elite orchard approach is more expensive and requires a longer wait for improved seed than for orchards developed by thinning test plantations.

In planning a black walnut seed orchard, we will assume it will begin with a half-sib progeny test. Mother trees are randomly selected from their native range. The performance of the offspring of the best three wind pollinated mother trees and the commercial stock (assumed to be equal to the average performance in the test plantation) are listed as follows:

Mother tree	Trait			Cost per seed tree
	Volume produced at age 50	Nut meat quality	Annual nut yield	
	(Bd.ft.)	(Grade)	(No.)	($)
"Wood"	437.5	5.0	1050	7
"Meat"	427.5	7.5	1010	8
"Nut"	387.5	6.5	1100	9
Commercial stock	375.0	5.0	1000	8

The mother tree "Wood" is for superior wood production, "Meat" is for tine best kernel quality, and "Nut" is for the greatest number of seed yield. The cost per seed tree included the present values of grafting, land and other maintenance costs.

The breeding value for the three mother trees can be computed from the formula $X_{ij} = 1/2(BV_{ij} + \text{Ave.})$ or $BV_{ij} = 2X_{ij} - \text{Ave.}$

where X_{ij} is the performance of half-sib family i for trait j.

BV_{ij} is the breeding value of the mother tree i for trait j.

Ave. is the mean of the population, or the breeding value of a random-sampled, wind-born pollen.

The results are as follows:

Mother tree	Breeding value for trait			Cost per seed tree
	Volume produced at age 50	Nut meat quality	Annual nut yield	
	(Bd.ft.)	(Grade)	(No.)	($)
"Wood"	500	5	1100	7
"Meat"	480	10	1020	8
"Nut"	400	8	1200	9

Let us assume that a seed orchard is to be established from grafts of these three mother trees. Furthermore, the three criteria, volume of board feet produced, meat quality, and nut production, are assumed to be additive. The following additional typical conditions are assumed:

1. At least 50 ramets in any variety should be present in the seed orchard.

2. On the average, offspring from this seed orchard should yield at least 20Z more lumber and nuts than the commercial stock (i.e., seed from the average mother tree).

3. On the average, offspring from this seed orchard should yield a grade 6 or better for meat quality.

4. The total cost for the seed orchard should be less than or equal to $10,080.

5. The objective is to maximize annual seed yield from the seed orchard.

The questions are: (1) How many trees in each variety should be plante (2) What are the estimated potential yields for board feet of volume produced, meat quality and annual nut production from the genetically improved seed? and (3) How many improved seed will be available annually from the elite orchard?

In order to solve the problem, the problem was first formulated as follows:

Maximizing $1100X_1 + 1020X_2 + 1200X_3$

Subject to $X_1, X_2, X_3 > 50$

$$500X_1 + 480X_2 + 400X_3 \geqslant 375(1 + .2)(X_1 + X_2 + X_3)$$

$$1100X_1 + 1020X_2 + 1200X_3 \geqslant 1000(1 + .2)(X_1 + X_2 + X_3)$$

$$5X_1 + 10X_2 + 8X_3 \geqslant 6(X_1 + X_2 + X_3)$$

$$7X_1 + 8X_2 + 9X_3 \leqslant 10080$$

where X_1, X_2 and X_3 are the number of clones from "Wood", "Meat", and "Nut" respectively.

The problem was solved by means of the criss-cross method (Zionts 1969). The optimal solutions for questions 1 and 3 are as follows:

Clone name	Ramets needed	Seed yield expected
	(No.)	
"Wood"	1092	1,195,000
"Meat"	248	262,000
"Nut"	50	57,000
Total	1390	1,514,000

The potential performance from the genetically improved seed can be computed as the weighted mean of clonal performances. For example, the potential yield for volume for the average seed would be as follows:

$$\frac{1092(500) + 248(480) + 50(400)}{1092 + 248 + 50} = 493$$

We can also estimate the performance of the seed from a particular clone. Assuming random mating and additive gene action, the seedlings from clone "Wood" have the potential to grow to (500 + 493)/2 = 496.5 bd. ft. at age 50. The performances of seedlings from three clones for three traits are listed in the following table:

Clone name	Performance: Volume produced at age 50	Meat quality	Annual nut yield
	(Bd.ft.)	(Grade)	(No.)
"Wood"	496.5	5.5	1095
"Meat"	486.5	8.0	1055
"Nut"	446.5	7.0	1145
Average	493	6.0	1090

By keeping seed from each clone separate, multiple objective and custom seed orders for multiple objectives can become a reality (Bey and Kung 1973). For example, if a customer's specifications for seed are as follows:

> The average volume per tree produced at age 50 should equal or be greater than 480 bd. ft.
>
> The average meat quality should equal or exceed grade 7.

The seed orchard manager can fill the order by:

> all seed drawn from "Meat".
>
> 40% of seed from "Wood" and 60% from "Meat".
>
> 16% of seed from "Nut" and 84% from "Meat".

The problem of satisfying many customers when each one has a special order may seem complex and difficult. However, the problem can be formulated as "Product Mix Model" and solved by computer in just a few seconds. The record keeping could be quite simple for the orchard manager and nurseryman. Orchard trees selected for rapid growth might be painted red, those selected for nut meat quality white, and those for nut production blue. Seed from each color group would then be kept separate for later planting in the nursery or for shipping seed directly to the customer.

CASE STUDY PROPOSAL

Before the system is in operation, we need to (1) build models, (2) modify models, (3) test models, and (4) develop plans for seed orchard establishment. The development of each phase is very dependent on the previous phase. Some of the important considerations in development are listed below:

I. Model Building

A. Biological, economical and managerial restraints will be identified and assessed.

1. Geographic seed source studies will provide information on adaptability for various traits.

2. Progeny tests will provide information on breeding value of selected trees. Growth, cold hardiness, phenology, form, drought hardiness, seed production, and insect and disease resistance will be evaluated. Heritability and genetic correlation among traits will be obtained.

3. Twin walnut progeny tests will be used to assess variance components.

4. Feasibility of grafting and rooting walnut will be evaluated.

5. Genotype x environment interaction will be evaluated. Effects of wind, irrigation, and cover crops will be included.

6. Economic and managerial restraint information will be developed from field experience of orchard managers.

B. Setting objective functions.--When we maximize gain for a single objective, we automatically reduce gain for another. It therefore becomes necessary to set objective priorities. In addition to ranking the various traits that we want to select for, we need to consider the time it takes to obtain the objective, how many years it will continue, and an estimate of the risk involved.

C. Assessing genetic worth of individual trees.--Whether an individual tree remains in a gene pool depends in part on its breeding value for each of the traits evaluated. The costs and benefits associated with including (or excluding) each candidate in the seed orchard will be determined and incorporated into the various models for testing.

II. Model modification. As new developments occur, it will be necessary to modify the model. The following changes will make it necessary to modify the models:

A. As new biological, economical, and managerial information becomes available, restraints will have to be added or deleted accordingly.

B. As socio-economic behaviors change (such as customer's needs), objective functions will have to be changed.

C. As the techniques in operations research-management sciences are improved, they wi'l be applied to the model building and testing process.

C. Wherever possible, where change can be predicted, it will be incorporated in the model as a dynamic function.

III. Model testing. Based on models that have been built, we plan to establish second generation walnut orchards. Data from trees in these orchards will be compared with expected results from models developed.

IV. Putting the models to work. After the models have been built and verified, recommendations for establishing black walnut seed orchards will be made. The types of trees to include in the orchard, spacing, design, intensity of selection, traits to select for, etc., will be included in the recommendations.

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