Silva Fennica 1990, Vol. 24 N:o 2: 235–247

Use of linear programming in land use planning in the Ethiopian highlands

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TIIVISTELMÄ: LINEAARISEN OHJELMOINNIN KÄYTTÖ MAANKÄYTÖN SUUNNITTELUSSA ETIOPIAN YLÄNKÖMAALLA

Pukkala, T. & Pohjonen, V. 1990. Use of linear programming in land use planning in the Ethiopian highlands. Tiivistelmä: Lineaarisen ohjelmoinnin käyttö maankäytön suunnittelussa Etiopian ylänkömaalla. Silva Fennica 24(2): 235–247.

Linear programming was used to analyze the land use alternatives in the Debre Birhan Fuelwood Plantation area, in the central highlands of Ethiopia. The region represents a rural, high-altitude area, where the main land uses are grazing and cultivation of barley, wheat and pulses. To alleviate fuelwood shortage, large plantations of *Eucalyptus globulus* Labill. have been established. Livestock has traditionally used the major part of the production capacity of the sites. A decrease in the number of cows, sheep, goats, horses and donkeys would facilitate a considerable increase in the production of cereals, pulses, fuelwood and construction timber. The optimal share of the land for arable crops, grazing and tree plantations would be about 40, 45 and 15 % respectively.

Etiopian keskusylängöllä sijaitsevan Debre Birhanin polttopuun viljelyalueen maankäyttövaihtoehtoja analysoitiin lineaarista ohjelmointia käyttäen. Alueen perinteisesti tärkeimmät maankäyttötavat ovat laidunnus sekä ohran, vehnän ja papujen kasvatus. Polttopuupulan lievittämiseksi alueelle on perustettu laajoja eukalyptusviljelmiä *(Eucalyptus globulus* Labill.). Aluetta laiduntava karja käyttää valtaosan maan tuotantokapasiteetista. Mikäli lehmien, lampaiden, vuohien, hevosten ja aasien pääluku alenisi, viljan ja puun tuotanto voisi nousta olennaisesti. Optimaalisessa maankäytössä viljelymaan osuus olisi noin 40 %, laitumen 45 % ja puuntuotannon 15 % maa-alasta.

Keywords: mathematical models, arable crops, grazing, fuelwood, plantations, *Eucalyptus globulus*.
ODC 911

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Accepted September 6, 1990

1. Introduction

When planning fuelwood or other tree plantations for densely populated tropical areas one particular question regularly arises: how to select the sites for the proposed plantations? Should the trees be planted on fertile sites where trees grow well, or, because the fertile sites are also the most productive for food crops, should the trees be planted on poor sites? As land resource usually is scarce, planning faces the general land allocation problem in agriculture and forestry: how to combine arable crops, grazing and tree crops in a particular area.

The optimal share of land for arable crops, grazing and forests is related to the proportions of different site fertility classes and how the growth of food, grass and tree crops varies with changes in soil fertility. Land allocation also depends on the species composition of crops, trees and livestock growing or grazing in the area.

Land use planning often deals with complicated situations. It may be difficult to reach the optimal land use without efficient calculation means. Because different regions are not similar, and the situation also changes with time within one region, there are no standard solutions for land use problems. Therefore, what is needed is a general land use planning method that works in a variety of different situations.

The differences between regions lie in the proportions of different sites and in the needs of the people living in the area. The requirements of the people are reflected in the objectives and constraints concerning the production. Usually, there are several objectives and constraints at the same time. It may be required that the land should produce enough food, fuelwood and construction timber for a particular town, while at the same time it should sustain a fixed amount of livestock for draught and transport power, meat and hides. Within these restrictions the land should give the maximal income.

These kinds of problems can be solved by using mathematical programming. Mathematical programming is an easy and flexible method for assessing different ways to use limited resources under variable objectives and constraints.

This study used linear programming in a typical land use planning problem in the Ethiopian highlands. The Debre Birhan Fuelwood Plantation site (Establishment … 1985), 125 km north of Addis Ababa is used as a case study area.

2. Methods

Linear programming is commonly used for selecting the most favorable combination of different products of an enterprise (Danzig 1963). In forestry it is a common practice to optimize the cutting schedule of compartments using this method (Curtis 1962, Kilkki and Pökälä 1975, Kilkki et al. 1975, Siitonen 1983, Pukkala and Pohjonen 1987, Pohjonen and Pukkala 1988a, Pukkala 1988, Pukkala et al. 1990). Linear programming can also be used for a more general land allocation problem in agriculture and forestry: in searching for the best combination of different production alternatives.

Linear programming presupposes that each production alternative, called an activity, is described by those parameters which are used as objective or constraining variables. These variables include inputs and outputs of the production process. It is assumed that the utility of the decision maker depends on the objective and constraining variables: such a solution is selected which gives the best value combination for these variables.

Land use planning is typically strategic and static. It is not restricted by or based on the current crop, grassland and forest cover but searches for such a pattern of land use which is optimal for the needs of the population in the long run. Production alternatives may therefore be described on a static annual basis.

When linear programming is applied in this kind of static problem, the following data are needed: (1) areas of different site productivity classes, (2) inputs and outputs of different production alternatives in each site class, and (3) objectives and constraints. A typical objective variable is the total net income obtainable from the combination of production alternatives, whereas a constraint variable may determine that food production

must exceed a certain value.

The areas of site classes can be surveyed in the field or measured from the map, provided there exists a site classification system. The yield level of arable crops is usually known from past experience. The productivity of forest stands according to different management schedules can be predicted with yield tables or growth models. The output figures for grazing may be expressed as an annual take-off rate related to the carrying capacity of the site.

The solution of a linear programming problem gives the optimal values of decision variables, i.e. the areas for different production alternatives. The solution of the dual problem associated with linear programming gives the dual prices or shadow prices of constraints (Dykstra 1984). A dual price indicates the change of the objective variable corresponding to a unit change in the constraint. The reduced cost of an activity excluded from the optimal solution indicates how much less or more this activity must consume or produce the objective variable before it enters into the optimal solution. Dual prices and reduced costs can be used for analyzing the sensitivity of the solution to the constraints and objective-function coefficients.

3. Description of the case study area

The Debre Birhan Fuelwood Plantation site is part of the Ethiopia's central highland plateau, its altitude being 2500–3600 meters above sea level. The annual precipitation is about 1200 mm with 70 % falling between July and September.

About 8500 people live in the area. Land use is dominated by agriculture which produces cereals, pulses and livestock. The main cereal, barley, is grown on 72 % of the cropland sown, whereas wheat and pulses account for 8 and 20 % respectively (Gryseels and Anderson 1983).

The contribution of livestock to the agricultural production is essentially based on the use of oxen as draught animals. Milk, meat and hides from cattle are less important byproducts. Cattle manure is collected as the main household fuel.

To sustain the oxen power, a certain number of cows, heifers, bulls and calves are needed. Sheep and goats are raised for meat and cash. Horses, donkeys and mules are used for transport and as pack animals. The total number of livestock is about 7 tropical livestock units (TLU) per farmer (family) (Gryseels and Anderson 1983). The present number of livestock, 15 000 TLU, exceeds the carrying capacity of the pastures. The missing livestock fodder is mainly supplied during the dry season by the arable crop residues.

The lower parts (up to 3000 m) of the Debre Birhan highlands were once covered by mixed deciduous and coniferous forests (mainly of *Juniperus procera* Hocht. ex Endl. and *Olea africana* Mill.). Shortage of fuelwood has lead to serious deforestation. Treeless rangelands for grazing and arable fields have replaced the original forests a long time ago. The upper parts of the area (over 3000 m) are above the original timber limit.

Long-lasting cultivation of cereals without fertilizers has deteriorated the soil and increased erosion. Soil conservation and erosion control are additional reasons, besides acute fuelwood shortage, to reforest the highlands.

The gross area demarcated for the Debre Birhan Fuelwood Plantation site comprises 17 650 ha; out of this 3600 ha is planned to be planted for fuelwood.

The target of the Debre Birhan Fuelwood Plantation is to produce all the fuelwood for the nearby Debre Birhan town and for the people living in the vicinity of the plantation site (Establishment … 1985). The annual fuelwood need is estimated at 50 000 m^3 of stemwood (Pukkala and Pohjonen 1988). The plantation establishment was started in 1984, and by 1988 about 2700 ha were planted. The main species planted is *Eucalyptus globulus* Labill. which was selected based on recommendation from national species trials (Mebratu Mihratu et al. 1983). *E. globulus* and the less planted *Eucalyptus viminalis* Labill. are plantable above the original timber limit and they survive at altitudes up to 3500 m (Pohjonen and Pukkala 1990).

The growing sites of *Eucalyptus globulus* in the central highlands of Ethiopia have been divided into four site fertility classes on the basis of stand age and dominant height (Pukkala and Pohjonen 1990). The land use alternatives were analyzed by using this site classification system. Only the three poorest classes: 2, 3 and 4, are represented in the case study area. Most tree plantations are located in site classes 3 and 4.

The site classes of the established fuelwood plantations have already been measured in the field (Pukkala and Pohjonen 1988). The site classes of the other areas were evaluated with the help of the already classified plantations, using altitude, steepness and aspect of the slope and the proximity of existing plantations as criteria. The boundaries of site classes were demarcated on a base map and their areas were measured on the map.

The highest mountain tops fall outside the poorest site class. These areas can only be utilized as poor grazing areas. They have never held forest cover and the establishment of new plantations would not be economically justified (Pohjonen and Pukkala 1988b). These marginal areas are referred to as site class 5.

4. Production alternatives

41. Agriculture

The two dominating cereals in the case study area are barley and wheat. In addition, pulses (horse beans, field peas and lentils) are commonly grown. For the subsistence of an average family (5.5 persons) the annual cereal production must be at least 1265 kg (230 kg/person) (Gryseels and Anderson 1983). The corresponding need of pulses is 360 kg per family (65.5 kg/person).

In this study it was assumed that it is possible to grow wheat, barley and pulses in all the site classes 2, 3 and 4. The corresponding production figures for each site class were calculated based on the socio-economic study of Tegegnwork and Taddese (1988) which was partly carried out within the case study area (Table 1).

42. Grazing

Grazing is a compulsory production alternative, not only as a source of essential animal protein for the population, but also to provide draught power for plowing. Livestock also provides cash income. The output of grazing is described as the estimated carrying capacity of the site (Table 1), expressed in tropical livestock units (TLU). From the carrying capacity it is possible to calculate the income by assuming an annual take-off rate of 12 % (Furstenberg et al. 1984) and a unit price of 222 EB/TLU (EB = Ethiopian birr; one birr is about 0.483 USD).

The minimum nutritional requirements of livestock products for an average family are 150 kg milk and 50 kg mutton or beef per year. The milk and meat requirements are normally satisfied from cows and other cattle if the farmer has on average one oxen. The number of sheep per family can and does fluctuate according to annual earnings.

43. Forestry

In the case study area it is possible to produce wood in all the site classes 2, 3 and 4. *Eucalyptus globulus* is the only significant species which will be grown on a large scale in the near future. The productivity of forestry activities was therefore calculated for *Eucalyptus globulus* plantations only. For each site class, three different management regimes were considered. They are referred to as short rotation, medium rotation and long rotation forestry:

	Short	Medium	Long
	Rotation (years)		
Seedling stand	10	14	18
Coppice stand	6	12	18

In each regime it was assumed that one seedling rotation and three successive coppice rotations are grown before replanting the area with new seedlings (Pohjonen and Pukkala 1988b). Short rotation forestry did not include thinning treatments. With the medium rotation the coppice stand was thinned two years (site class 2) or three years (classes 3 and 4) after coppicing by removing 30 % of stand basal area. With the long rotation the seedling stand was thinned when the basal area median diameter exceeded 13 cm. The coppice stands were harvested twice: first after two years (site class 2) or three years (classes 3 and 4) since coppicing, and the second time when the basal area median diameter exceeded 13 cm (this never happened in site class 4). Each thinning removed 30 % of stand basal area.

Table 1. Mean production, net income and land expectation value in agriculture and grazing.

Production regime and variable	Site class 2	3	4	Unit
Wheat production				
Net income	767	364	157	EB
Land expectation value				
– discounting rate 4 %	19.1	9.1	3.9	1000 EB
– discounting rate 8 %	9.6	4.6	2.0	1000 EB
Production	1.35	0.64	0.28	ton
Barley production				
Net income	694	658	637	EB
Land expectation value				
– discounting rate 4 %	17.4	16.5	15.9	1000 EB
– discounting rate 8 %	8.8	8.2	8.0	1000 EB
Production	1.29	1.22	1.19	ton
Pulse production				
Net income	358	175	130	EB
Land expectation value				
– discounting rate 4 %	9.0	4.4	3.3	1000 EB
– discounting rate 8 %	4.5	2.2	1.6	1000 EB
Production	1.10	0.54	0.40	ton
Grazing				
Net income	53	37	19	EB
Land expectation value				
– discounting rate 4 %	1.33	0.93	0.48	1000 EB
– discounting rate 8 %	0.66	0.46	0.24	1000 EB
Number of heads	2.00	1.40	0.70	TLU
Annual take-off	0.24	0.17	0.08	TLU

The net income, land expectation value and mean annual wood production were calculated by a simulation technique for each forest management regime (Table 2). Each simulation began with plantation establishment. The stand growth was simulated by predicting the diameter distribution of trees at a desired age by using the stand models of Pukkala and Pohjonen (1990, also Pohjonen and Pukkala 1987). All the stand characteristics were computed from the diameter distribution. The simulation method is described in Pohjonen and Pukkala (1988b) and in Pukkala and Pohjonen (1990).

During the seedling rotation and the first coppice rotation the development of dominant height followed the models of the site classification system. In the second and later coppice crops the height development was assumed to be 10 % slower than in the preceding crop. This was due to the impoverishment of the soil after several cuttings without any fertilization, and also because of the expected dying and deterioration of stools.

For each cropped tree the amounts and monetary values of the following assortments were computed: transmission line pole volume, construction pole volume, volume of stem fuelwood, dry mass of branches and leaves. The stumpage price of transmission poles was taken as 45 EB/m^3, or, in other computations, as 20 EB/m^3. The corresponding unit prices of construction poles, stem fuelwood and biomass of branches and leaves were 18 EB/m^3, 15 EB/m^3 and 27 EB/ton, respectively (Pohjonen and Pukkala 1988b). The cost of plantation establishment was 2000 EB/ha (Pohjonen and Pukkala 1988b).

Table 2. Mean production, net income and land expectation value in forestry with different treatment regimes. The bigger income and land expectation value were calculated using a unit price of 45 EB/m^3 for transmission poles and the lower figures with a price of 20 EB/m^3.

	Site class			
Production regime and variable	2	3	4	Unit
Short rotation				
Net income (45/20 EB)	493/421	274/260	147/147	EB
Land expectation value				
– discounting rate 4%	9.8/7.7	4.5/4.1	1.5/1.5	1000 EB
– discounting rate 8%	3.4/2.3	0.9/0.7	–0.5/–0.5	1000 EB
Total removal	24.0	16.0	9.7	m^3
Transmission pole harvest	2.9	0.6	0.0	m^3
Construction pole harvest	12.1	6.2	1.9	m^3
Branch and leaf harvest	3.1	2.7	2.4	ton
Medium rotation				
Net income (45/20 EB)	770/558	417/357	207/199	EB
Land expectation value				
– discounting rate 4%	15.3/9.8	7.3/5.5	2.5/2.2	1000 EB
– discounting rate 8%	5.1/2.6	1.8/0.9	–0.3/–0.4	1000 EB
Total removal	29.0	19.0	11.2	m^3
Transmission pole	8.5	2.4	0.3	m^3
Construction pole	16.0	11.4	5.3	m^3
Branch and leaf harvest	2.6	2.3	2.0	ton
Long rotation				
Net income (45/20 EB)	956/620	529/398	218/202	EB
Land expectation value				
– discounting rate 4%	17.1/9.9	8.7/5.6	2.5/2.0	1000 EB
– discounting rate 8%	4.8/2.2	1.9/0.7	–0.4/-0.6	1000 EB
Total removal	32.0	20.3	11.0	m^3
Transmission pole harvest	13.7	5.0	0.6	m^3
Construction pole harvest	14.7	11.8	6.8	m^3
Branch and leaf harvest	2.4	1.9	1.5	ton

5. Results

51. Production possibilities

The production possibilities of the case study area are summarized graphically in Figure 1. It is possible to produce annually either 143 000 tons of above-ground biomass in tree plantations (point **a** in Fig. 1) or 14 000 tons of grain and pulses (point **b**), if the number of cattle is minimal, 659 heads. The annual fuelwood production target, 50 000 m^3 or about 30 000 tons of dry mass, facilitates an annual food production of almost 12 000 tons, if cattle are excluded from site classes 2–4 (point **c**). Points **d** and **e** in Figure 1 indicate that increasing the number of cattle drastically decreases the crop harvests. Therefore, the key factor for increasing the production of food and wood is the decrease in the number of cattle.

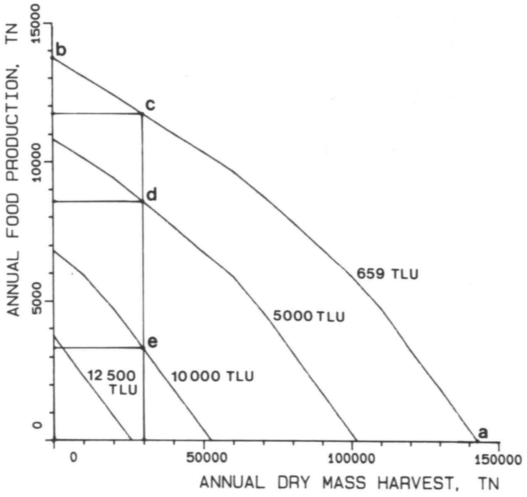

Fig. 1. Production frontiers of food (grain and beans) and fuelwood with varying number of cattle units.

52. Optimal land use

In all the alternative land use plans the objective variable was the land expectation value with a discounting rate of 8%. The land expectation value of the whole case study area was maximized with different sets of constraints.

In the first case, referred to as Alternative 1, there were no restrictions concerning the species composition of agricultural crops or the growing sites of tree plantations. The annual food production in agriculture had to be at least 2500 tons to sustain the population living in the area. The wood production target was set to 50 000 m^3 of small-sized stemwood (smaller than transmission pole size). It was further stated that the maximum annual production of big transmission poles is 2000 m^3, because of the small demand. The number of livestock was to be at least 5000 TLU for sustaining enough draught animal power and for providing variation in the diet.

In the optimal land use plan the average site class 3 should be used entirely for tree plantations and site class 4 almost entirely for barley (Fig. 2). The best sites are to be used for wheat production and grazing. There would be no area under pulses and the forest area in site class 4 would be minimal.

Because it is unlikely that the production of pulses could be excluded – it provides necessary proteins in the diet – a new constraint was set: the annual production of pulses must be at least 500 tons. It was further stated that the area of tree plantations in site class 4 must be at least 1000 ha. This was supposed to be necessary for a compact location of plantations and for providing erosion control on the steepest slopes in site class 4. The land use plan corresponding to these additional constraints is referred to as Alternative 2.

The new requirements decrease the annual net income from 4.7 mill. EB to 4.4 mill. EB (Table 3). The annual food production decreases from 6745 tons to 6383 tons. The fields of pulses should be located in the best site class 2 as their productivity drastically decreases in poorer sites (Fig. 2).

The dual prices of constraints of land use alternatives 1 and 2 (Table 4) show clearly that the restriction that no more than 2000 m^3/a of big-sized wood can be produced, has

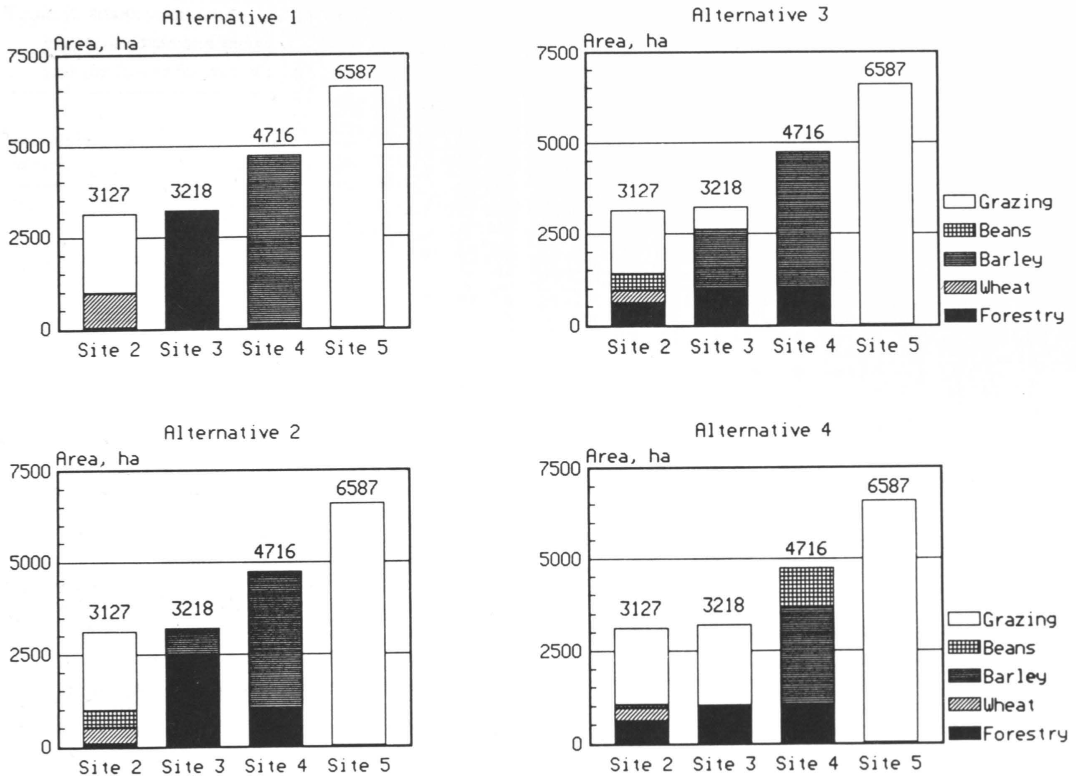

Fig. 2. Optimal land use with different sets of constraints when the land expectation value with a discounting rate of 8% is maximized. The constraints of alternatives 1–4 are explained in the text.

a very strong adverse effect on the land expectation value of the case study area. In Alternative 1 one more allowed cubic meter of transmission poles would increase the land expectation value by 4130 EB. This is because, as a result of the imposed constraint, too short rotations must be used in forestry. The constraint also excludes tree plantations from site class 2.

Although the comparisons of the dual prices of Table 4 are difficult, due to the different units, it can be deduced that the requirement of 5000 TLU of livestock is very detrimental for the land expectation value, too. One livestock unit less would allow the land expectation value to increase by 4460 EB. There are not, however, realistic possibilities to decrease the number of cattle from 5000 TLU since the rural life and the agricultural traditions heavily rely on big herds. In addition, some oxen are necessary in the cultivation of agricultural fields.

Because of the small transmission pole demand, it is possible that the unit price sharply decreases if transmission poles are offered in big quantities. In this case the biggest poles would perhaps go for construction purposes or fuelwood, and the unit price would be near to these assortments. For this reason, it was assumed that the unit price of transmission poles would be only 20 EB/m^3, instead of the 45 EB/m^3 in the previous calculations, if the production clearly exceeds 2000 m^3/a.

The land use plan where the transmission pole production is not limited is referred to as Alternative 3. It corresponds to Alternative 2 except that in Alternative 3 the annual stemwood harvest of any assortment must be at least 50 000 m^3 and the minimum plantation area both in site class 3 and 4 is 1000 ha.

In the resulting plan there are tree plantations in all the site classes 2, 3 and 4 (Fig. 2) and the applied rotations are longer, as can be seen from the following comparison:

	Alternative 2	Alternative 3
Site class 2		
– short rotation	71 ha	–
– average rotation	–	–
– long rotation	–	576 ha
Site class 3		
– short rotation	2491 ha	–
– average rotation	–	–
– long rotation	–	1000 ha
Site class 4		
– short rotation	–	–
– average rotation	1000 ha	1000 ha
– long rotation	–	–

Compared to Alternative 2, the mean annual income and the land expectation value are higher in Alternative 3, even though the price of big poles is considerably lower (Table 3). Because of the more productive management regimes of forestry, the area of tree plantations can be decreased (Fig. 3) which allows the food production to increase (Table 3).

Alternative 3 was further illustrated by calculating the reduced costs of those production alternatives which were not selected to the optimal plan (Table 5). The results indicate that it is more or less the same whether forestry applies long (18 years) or average rotations (14 years in seedling stand and 12 years in coppice stands), but short rotations (10 years for seedling stands and 6 years in coppice stands) are considerably poorer, especially in the best site classes. The cultivation of wheat and pulses in the poorest site classes also have high reduced costs which means that such practice should be avoided.

In the last alternative (Alternative 4) it was assumed that the amount of livestock cannot be reduced below 8000 TLU. In this case the additional grazing areas should be located in the best site classes (Fig. 2). As can be seen from Figure 1, the increase in the herd size causes a considerable reduction in food production, annual income and land expectation value (Table 3). This land use may, however, be near to what happens in the case study area in the future.

Table 3. Annual income, land expectation value, and mean production in different land use alternatives.

Variable	Alternative 1	2	3	4	Unit
Net income	4.7	4.4	4.9	3.3	mill. EB
Land expectation value					
– discounting rate 4%	110	101	113	72	mill. EB
– discounting rate 6%	70	64	72	45	mill. EB
– discounting rate 8%	50	46	51	31	mill. EB
Forest products					
– Drymass (all biomass)	37	37	33	33	1000 ton
– Stemwood volume	52	52	50	50	1000 m^3
– Transmission poles	2	2	13	13	1000 m^3
– Construction poles	21	22	26	26	1000 m^3
Agricultural products					
– Wheat	1275	585	500	500	ton
– Barley	5469	5297	6349	3136	ton
– Pulses	0	500	500	500	ton
– Total grain and beans	6745	6383	7349	4136	ton
Cattle					
– Heads	5000	5000	5000	8000	TLU
– Annual take-off	560	560	560	920	TLU

Table 4. Dual prices of constraints in production alternatives 1 and 2. The dual price expresses the change in land expectation value corresponding to a unit change of constraint.

Constraint	Alt. 1	Alt. 2	Unit
Small-sized stemwood prod. ≥ 50 000 m^3/a	–0.87	–0.56	1000 EB/m^3
Transmission pole prod. ≤ 2000 m^3/a	4.13	1.92	1000 EB/m^3
Cattle ≥ 5000 TLU	–4.46	–4.46	1000 EB/head
Bean prod. ≥ 500 tn/a	–	–4.63	1000 EB/ton
Forest area ≥ 1000 ha in site class 4	–	–2.66	1000 EB/ha

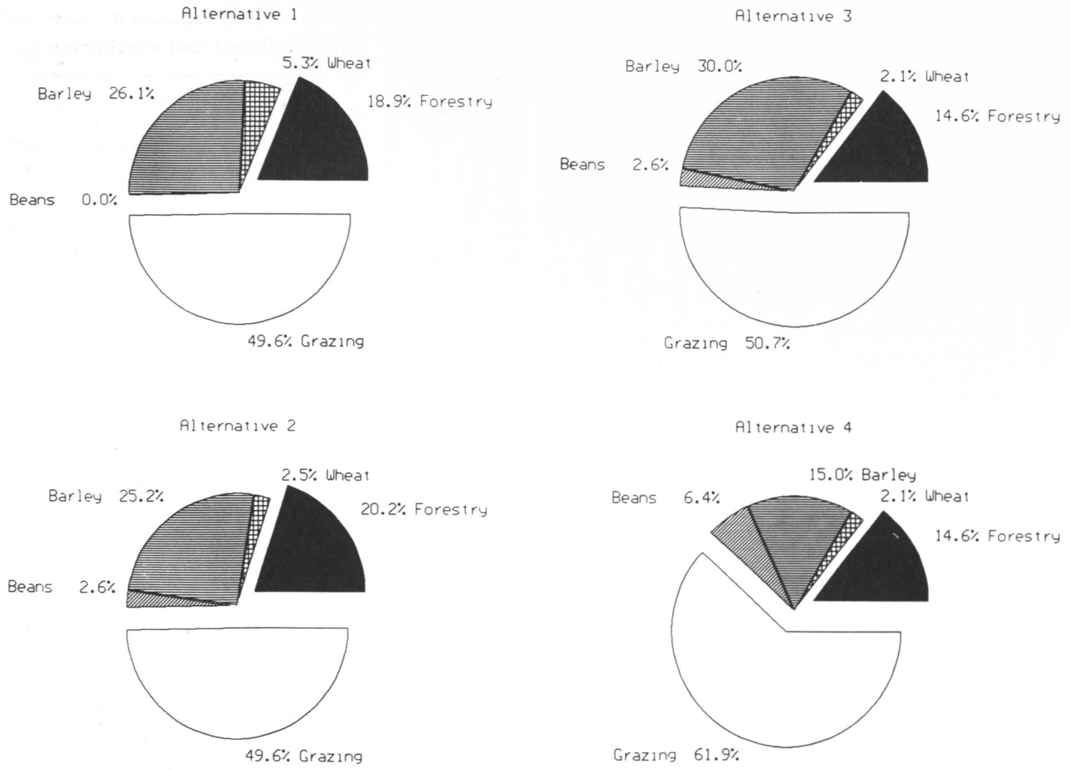

Fig. 3. Share of agricultural fields, tree plantations and pastures in land use alternatives 1–4.

6. Discussion

61. Analysis of the method

The land use planning method used in this study was based on linear programming. The method helps the decision maker to analyze complicated land use problems and find out efficient production alternatives. The applied method gives the optimal allocation of land area for fields of crops, grazing areas and forests, optimal proportions of different species, and the best rotation and thinning regime in forestry. The method thus promises to solve a lot of interrelated problems at the same time. Agroforestry and silvopastoral production methods could be handled without difficulty by adding such production alternatives to the linear programming model.

Even though it may be difficult to change the land use practice of rural people, the analysis is valuable when planning tree plantations and other development activities. Although the linear programming model often is a simplified description of reality, it can give significant insight to the problem. It may reveal that the optimal way to allocate land is not always similar to the common or traditional practice. In the case study area, for example, it was found out that trees should not be planted systematically on the poorest sites and agricultural crops on the best sites.

Linear programming presupposes that the objective function and all the constraints are linear over the domain of each activity (Dykstra 1984). In land use planning this requirement of the linear programming model is the most difficult to meet. In the case study, for example, the objective-function coefficients of forestry activities were not constant since the unit price of transmission poles depended on demand. This difficulty was avoided by changing the model when the pole production exceeded a definite limit. This method, although quite cumbersome, can be used also in other corresponding situations, e.g. when the cost of an activity is not a linear function of the area.

Table 5. Reduced costs of those production regimes which were not used in land use alternative 3. The reduced cost indicates how much greater the land expectation value of the regime should be for being included into the optimal land use plan (in EB/ha, discounting rate 8%).

	Area in the land use plan Activity (ha)	Reduced cost (EB/ha)	Corresponds to annual net income (EB/ha)
Site class 2			
Forestry			
– short rotation	–	2166	173
– mean rotation	–	267	21
– long rotation	576	–	–
Agriculture			
– wheat	370	–	–
– barley	307	–	246
– pulses	453	–	–
Grazing	1728	–	–
Site class 3			
Forestry			
– short rotation	–	1522	122
– mean rotation	–	214	17
– long rotation	1000	–	–
Agriculture			
– wheat	–	2649	212
– barley	1585	–	–
– pulses	–	2472	198
Grazing	632	–	–
Site class 4			
Forestry			
– short rotation	–	540	43
– mean rotation	1000	–	–
– long rotation	–	280	22
Agriculture			
– wheat	–	5557	445
– barley	3716	–	–
– pulses	–	3687	295
Grazing	–	3843	307
Site class 5			
Grazing	6587	–	–

The land expectation value of forestry was computed with the assumption that forestry always starts with planting. If there are already plantations in each age class over the whole rotation, it is possible to use the mean annual income of the plantations as the objective variable or as the basis of the land expectation value. In this case existing plantations and the possible new ones should be treated as separate activities.

This study considered the production alternatives of a land area independently of the neighboring areas. Usually different areas are not independent but can change products. If the site class distribution is different in different areas, their production possibilities are different as well. One could therefore ask whether it is more profitable to concentrate on food production in one area and on timber and fuelwood production in the adjacent area. The studying of these kinds of problems needs the optimization model to be enlarged to include the new areas as additional sets of activities, and the specific needs of these areas as new constraints.

Another possibility to solve land use planning problems of several areas, is to carry out the optimization in two stages (Kilkki 1985). The first stage is similar to that presented in this study except that several solutions with varying production targets are computed. These solutions are then the activities (or production alternatives) of the second stage. This latter optimization gives the optimal land use for each area when the situation is considered in a larger context. In the first stage the constraints assure that some minimum requirement is produced within each area. The proportion that should be produced within each area may be higher for food and fuelwood than for poles. In the second stage the constraints assure that each product is obtained sufficiently within some large area; a subarea may produce just enough a particular product, or buy or sell it.

62. Analysis of the results

In the case study area the share of forests should be 4000 hectares at maximum. This is enough for satisfying the demand of the area and the Debre Birhan town. Additional plantations cannot be justified by economics. The maximum area compares well with the planned area of fuelwood plantations, 3600 ha (Establishment ... 1985, Pukkala and Pohjonen 1988). If the area is increased, the justification should be found from such reasons as soil and water conservation and erosion control.

The reason for the low profitability of plantation forestry is the high altitude and thence poor growth of trees. At lower latitudes, e.g. near to the towns of Addis Ababa and Nazret, the profitability of plantation establishment is much better (Pohjonen and Pukkala 1988a, 1988b).

In the case study area most tree plantations should be established on average sites (site class 3). At the highest points, grazing is the only way to utilize the land. Below the highest areas, in site class 4, cultivation of barley is the most profitable land use alternative as the productivity of other crops and trees decreases more sharply with altitude. The required amount of wheat and pulses should be produced on the best sites.

The possibilities to produce wood and agricultural crops greatly depend on the amount of cattle. The easiest way to increase production and income is to reduce the number of animals. This may be difficult in practice, since big family herds traditionally belong to the Ethiopian rural lifestyle. The reason why these herds have evolved may be that in the past, only a minor part of the production capacity has been needed to produce the required food. The rest of the capacity has been left for cattle. These cattle act as an asset which can be sold when money is needed.

Some animals are necessary in agriculture, in the plowing of the fields. The upkeeping of these animals could be decreased from the income of agriculture, e.g. as an opportunity cost of the pasture which is needed to sustain the draught animals of one hectare of agricultural fields.

The benefits of the optimization depend on the accuracy and reliability of the data on which the calculation is based. In the present study, the areas of site classes and their production figures are perhaps about the correct magnitude. The production of agricultural crops is based on a study carried out within the case study area (Tegegnwork and Taddese 1988) and the wood production was predicted with models which were partly based on the existing stands within and in the vicinity of the area. The unit prices of different products are by far the most unreliable data. Happily enough, the optimal land use under the applied constraints seems to be rather insensitive to the assumptions on unit prices.

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