

Introducing a New Approach in Stand Tending Planning and Thinning Block Designation by Using Mixed Integer Goal Programming

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Abstract

Long-term management plans have been developed for nearly all of the forests in Turkey. These plans are applied at a sub-district management unit level and may contain guidance for both intermediate yield and final yield harvests. To implement an intermediate yield plan, which involves the scheduling of forest thinnings (stand tending), consideration in Turkey is given to the advantages of working in the same terrain and the same general area each year. Therefore, compartments are often clumped together to create thinning blocks, taking into consideration the thinning priority of the stands, road conditions, site index, age, and proximity of the compartments. Further, when preparing annual budgets and planning to meet the market's needs, forest enterprises require an even flow of intermediate wood volume each year. In this paper, we introduce a new approach in stand tending planning designed to schedule an equal amount of intermediate wood volume each year and to create thinning blocks by minimizing the distance to pre-defined ramps (landings). We developed both linear and nonlinear goal programming models to minimize both the deviations from a harvest volume (annual intermediate yield allowable cut) target and the deviations from a target value determined for the distances (total and average) of the centroid of each compartment to the hypothetical forest ramps. By using the extended version of Lingo 16, we solved the problem with different weights for the deviations in volume and distance that ranged from 0.0 to 1.0, in 10% intervals, which created 11 scenarios. We carefully analyzed the results of each scenario by taking into consideration the wood volume and distance of compartments to the ramps. The best scenario using the linear model produced a deviation in volume scheduled for the entire decade of 6 m³, while the deviation in total distance between harvest areas and ramps was 59.7 km. Scenario 5, with weights of 0.6 for volume and 0.4 for distance, produced these results, where compartments were closest to one another. The best scenario using the nonlinear model also produced a deviation in volume of 0 m³ and the total average deviation in distance between harvest areas and ramps was 8.7 km. Scenario 3, with weights of 0.8 for volume and 0.2 for distance, produced these results. The approach and models described through this study may be appropriate for further integration into forest management planning processes developed for the planning of Mediterranean forests.

Keywords: linear goal programming, nonlinear programming, mixed integer goal programming, optimization, thinning schedule intermediate yield planning

1. Introduction

Forests, as major components of terrestrial ecosystems, provide to society many economic, environmental and socio cultural services. Forests provide favour-

able mid-term green growth opportunities, they also facilitate the attainment of long-term ecosystem services that include the mitigation of climate change and the production of clean air and water (United Nations Food and Agriculture Organization 2016). In order to

ensure these services are available in the long-run, the use of sustainable forest management principles becomes more important. Forest management plans can be developed to illustrate how the outcomes that represent measurable achievement of these services can be obtained through management activities. While a forest management plan has been developed for nearly all of the forests in Turkey, long-term forest management plans have been developed for only about 54% of the world's forests (United Nations Food and Agriculture Organization 2020).

In Turkey, forest management plans are developed for sub-district management units, and they can provide guidance for both final (regeneration harvest) and intermediate (thinning/stand tending) management activities. One of the main considerations for intermediate harvest activities is that they are placed in close proximity during each year of a management plan, so that workers conduct activities in similar terrain and in the same general area. In this sense, compartments (collections of stands) are combined to create operational thinning blocks. In addition, the thinning blocks do not include stands that have a final harvest scheduled, during the first period (10 years). The scheduled thinning activities take into consideration the silvicultural need for thinning stands, marketing opportunities, and road system conditions. Finally, the yield from intermediate harvests would ideally be consistent from year to year to facilitate the market's needs (Eraslan 1982).

In conducting this research, the harvest scheduling aspects related to wood flow and location of intermediate harvest management activities were recognized. The total and average distances of the scheduled intermediate harvest compartments to the forest ramps (areas where logs are loaded for transport to a woodyard or mill) were also included. The forest ramps were hypothetical and located throughout the planning unit. They are typically developed when they are needed, thus they were randomly located, yet checked for plausibility by the lead author based on his expertise as a forest engineer and his familiarity with the landscape. The total distance of the compartments to the ramps was used for the linear model, and the average distance, which was obtained by dividing the total distance by the number of scheduled compartments, was used for the non-linear model. From the suite of operations research techniques that have been used in management planning, goal programming (GP) is suitable for addressing this type of complex forestry problem that has more than one consideration in the objective function (Demirci and Bettinger 2015). And since we assume that entire compartments will be scheduled for intermediate harvests, a mixed integer approach is needed to ensure that activities within compartments are fully scheduled

within a single year. In accommodating the distance to ramps, goal problem formulations were designed using both linear GP and nonlinear GP.

GP has been widely used in many different fields of commerce. The process was initially described by Charnes et al. (1955) as an alternative use of linear programming. The term »goal programming« was attributed to this process by Charnes and Cooper (1961). Rustagi (1973) and Field (1973) provide the first demonstrations of GP in forest management. A number of other works have demonstrated how GP can be applied to traditional forest management objectives that have commodity production, economic, and other objectives (Porterfield 1973, 1974, Lyon 1974, Romesburg 1974, Bell 1975, Dress 1975, Schuler and Meadows 1975, Bare and Anholt 1976, Schuler et al. 1977, Kahalas and Groves 1978, Kao and Brodie 1979, Field et al. 1980, Köse 1986, Kangas and Pukkala 1992, Diaz-Balteiro and Romero 1998, Misir 2001, Bertomeu and Romero 2001, 2002, Diaz-Balteiro and Romero 2003, Misir and Misir 2007, Silva et al. 2010, Gómez et al. 2011, Chen et al. 2011, Aldea et al. 2014, Chen and Chang 2014, Zengin et al. 2015). The features within an objective function of a GP problem can be weighted using several approaches and schemes to emphasize the importance of objective function components or to normalize the values of disparate outcomes such as wood flow and wildlife habitat (Hotvedt et al. 1982, Hotvedt 1983, Hossain and Robak 2010). The spatial location of harvest activities has also been recognized in GP problems to control the timing and placement of management activities (Demirci and Bettinger 2015, Augustynczyk et al. 2016, Bagdon et al. 2016).

The aim of this study is to develop two mixed integer GP models that address the intermediate harvest activities typical of the Turkish forest management problem in a different manner for each period in this area (e.g., Demirci and Bettinger 2015). A linear thinning model (LTM) and a nonlinear thinning model (NLTM) were developed to minimize deviations from the wood flow target and the distance to the forest ramp (total and average) target. To be clear, the problem-solving method involves mixed integer GP, although a portion of the problem formulation involves either linear or nonlinear functions to represent the spatial constraints.

2. Materials and Methods

2.1 Case Study

Located in the Mediterranean region of Turkey (Fig. 1), the study area is a sub-set of the Akoren Planning Unit of the Adana Forest Regional Directorate.

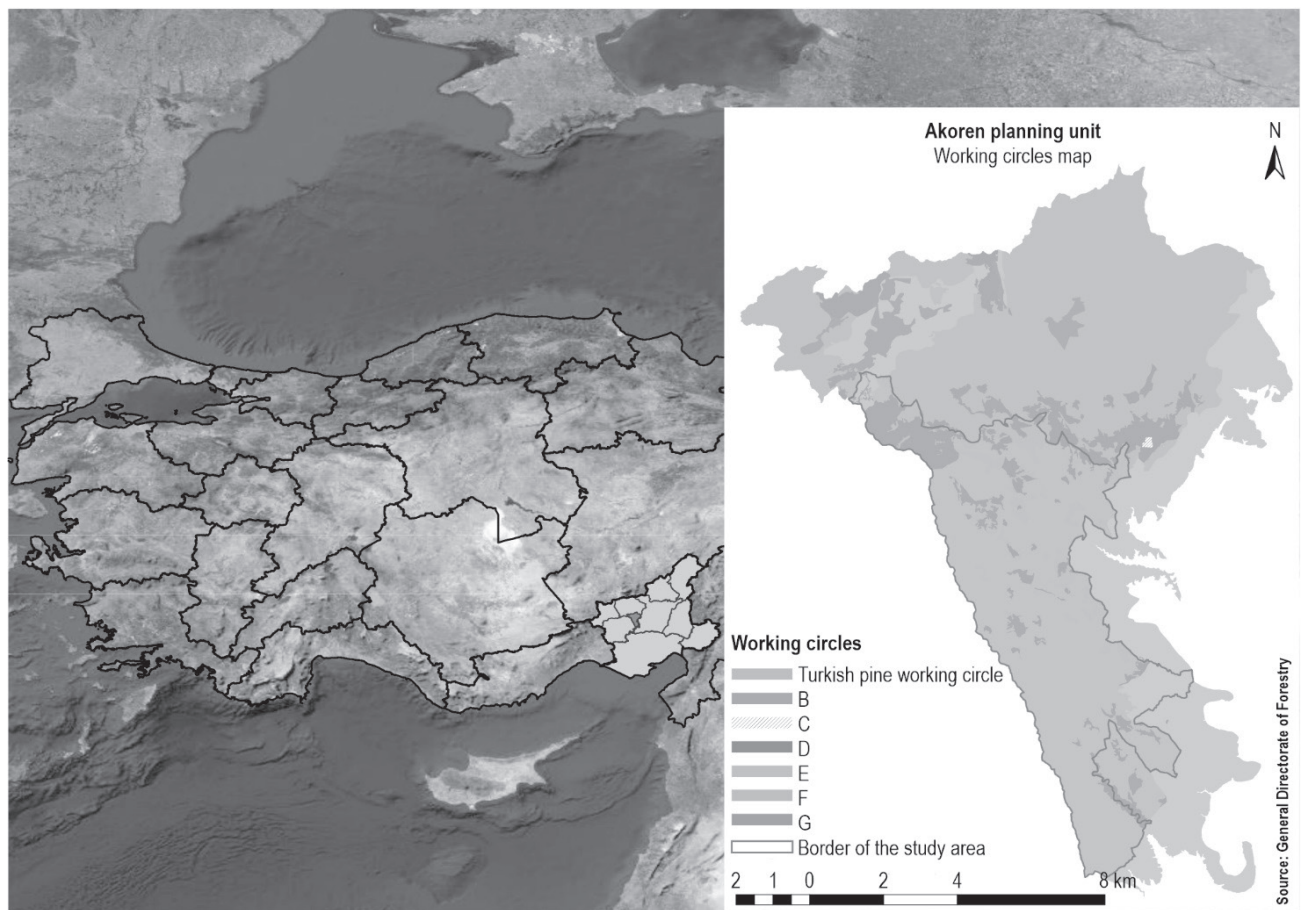


Fig. 1 Location of Akoren Planning Unit and study area (Turkish pine working circle)

The study area contains about 5380 ha of coniferous forests. Turkish pine (*Pinus brutia* Ten.) is the dominant coniferous tree species, and other coniferous species include Anatolian black pine (*Pinus nigra* Arn. subsp. *pallasiana* (Lamb.) Holmboe var. *pallasiana*), fir (*Abies cilicica* Carr.), cedar (*Cedrus libani* A. Rich.), and juniper (*Juniperus* spp.). The estimated growing stock of the study area is 559,006 m³ and the annual increment of the growing stock is 22,422 m³ (increment of thinning stands is 8324 m³). The production of pine wood volume is the main management objective of the study area. Plans are developed for the study area every 20 years, and the length of the thinning cycle is 10 years.

Thinning operations during the first decade are conducted within compartments that do not have other stands scheduled for a final harvest during that decade. For comparison and use in this analysis, the area, increment, growing stock, and allowable cut information for the planned thinning compartments were obtained from the Forest Plan of the Akoren Planning Unit (General Directorate of Forestry 2014).

This information was developed using spreadsheet-based analysis of forest information. The number of thinning compartments in the study area is 84, and the estimated annual allowable cut for these compartments is 2628 m³ per year (about 32% of the 8324 m³ increment of thinning stands) (Table 1).

In this research, the objective was to schedule for harvest a set of thinning compartments in such a way that they were physically close to each other each year. This arrangement would in effect ease the work organization for the foresters and reduce losses in labour time, and cost for moving machinery and equipment. For this work, 10 hypothetical forest ramps (landings) were located throughout the study area (Fig. 2). Using the Calculate Geometry tool within ArcMap, the latitude and longitude positions of the ramps and the centroid of each compartment were determined. The Euclidian distance from each ramp to each compartment was then calculated. In sum, 840 ramp-compartment distance combinations were produced between the 84 compartments and 10 ramps.

Table 1 Stand tending compartments and their annual allowable cuts

Compartment number	Allowable cut, m ³	Compartment number	Allowable cut, m ³	Compartment number	Allowable cut, m ³	Compartment number	Allowable cut, m ³
97	766	215	288	255	48	290	857
132	8	220	180	256	28	291	529
168	123	222	32	258	16	292	102
169	59	225	574	262	305	293	992
170	187	226	526	263	471	297	353
188	43	227	364	264	491	298	78
191	39	228	560	265	58	299	417
194	84	229	116	266	294	300	22
195	904	235	154	268	735	302	730
196	230	236	18	270	804	305	155
197	156	237	1297	273	132	306	411
204	50	239	170	274	398	307	374
205	333	241	140	275	403	311	544
207	132	242	526	276	10	312	550
208	127	243	572	282	184	313	232
209	408	244	130	284	265	319	372
210	302	246	102	285	422	320	26
211	8	251	146	286	188	322	660
212	66	252	32	287	256	323	672
213	12	253	352	288	254	330	152
214	502	254	344	289	547	337	580

2.2 Problem Formulation

To address the scheduling of thinnings throughout the study area, it is desired to minimize both the deviations from a desired harvest volume (annual intermediate yield allowable cut) and the distances (total and average) from each compartment to a ramp over a 10-year time horizon. The foresters also want to thin the forests within each compartment as a whole when they are entered; therefore, the decision for a compartment is discrete (to harvest or not to harvest). Given this management situation, mixed integer GP may be useful in scheduling the thinning activities. We designed both a mixed-integer linear GP model and a mixed-integer nonlinear GP model to address this thinning problem. The mathematical formulation of the mixed-integer linear thinning GP model (LTM) is as follows:

$$\text{Min } Z = \sum_{i=1}^{10} \sum_{j=1}^2 (w_{ij}^- d_{ij}^- + w_{ij}^+ d_{ij}^+) \quad (1)$$

Subject to

$$\sum_{i=1}^{10} (X_{ki}) = 1 \quad \forall k \quad (2)$$

$$\sum_{k=1}^K (V_{ki} X_{ki}) - VC_i = 0 \quad \forall i \quad (3)$$

$$X_{ki} - D_{kpi} \geq 0 \quad \forall i, k, p \quad (4)$$

$$\sum_{p=1}^P (D_{kp}) = 1 \quad \forall k \quad (5)$$

$$\sum_{k=1}^K \sum_{p=1}^P (S_{kp} D_{kpi}) - SPR_i = 0 \quad \forall i \quad (6)$$

$$\sum_{k=1}^K (X_{ki}) - N_i = 0 \quad \forall i \quad (7)$$

$$N_i \geq 7 \quad \forall i \quad (8)$$

$$N_i \leq 10 \quad \forall i \quad (9)$$

$$VC_i + d_{i1}^- - d_{i1}^+ = VT_i \quad \forall i \quad (10)$$

$$SPR_i + d_{i2}^- - d_{i2}^+ = DT_i \quad \forall i \quad (11)$$



Fig. 2 Locations of hypothetical forest ramps

$$X_{ki} \in \{0,1\} \quad (12)$$

$$D_{kpi} \in \{0,1\} \quad (13)$$

Where:

- i years
- j objectives: 1 = volume scheduled for harvest, 2 = distance of compartments to a forest ramp
- w_{ij}^- weight for negative deviations in objective j , year i
- w_{ij}^+ weight for positive deviations in objective j , year i
- d_{ij}^- negative deviation in objective j , year i
- d_{ij}^+ positive deviation in objective j , year i
- K total number of compartments within the planning unit
- k a compartment within the planning unit
- X_{ki} binary (0, 1) decision variable representing the harvest of compartment k during year i
- V_{ki} volume available for harvest in compartment k during year i

- VC_i total volume scheduled for harvest in year i
- P total number of forest ramps
- p a forest ramp
- D_{kpi} a binary (0,1) variable representing the distance of compartment k to forest ramp p , in year i
- S_{kp} distance between the centroid of compartment k and forest ramp p
- SPR_i total distance of the centroids of scheduled compartments in year i
- N_i number of scheduled compartments in year i
- VT_i volume target in year i
- DT_i distance target in year i .

Eq. 1 represents the objective function, which minimizes the deviations from volume and distance targets. The harvest target for Eq. 11 was 2628 m³, and the distance target for Eq. 10 was assumed to be 7 km. Eq. 2, together with Eq. 12, forces a compartment to be scheduled for harvest. Eq. 3 represents the accounting rows that sum harvest volumes each year. Eq. 4 determines the pairs of compartments and forest ramps in the same year. Eq. 5, together with Eq. 13, forces only one »scheduled compartment-forest ramp« pair to be considered in the same year. Eq. 6 represents the accounting rows that sum the distances between scheduled compartments and forest ramps. Eq. 7 counts the compartments scheduled for harvest for each year. Eqs. 8 and 9 limit the number of compartments scheduled for harvest for each year, since foresters want to manage roughly the same number of compartments each year. Since it was not possible to equalize the numbers of the compartments scheduled for harvest each year, Eqs. 8 and 9 were used to limit the maximum and minimum number of the compartments scheduled for harvest. These levels (minimum 7 and maximum 10) were determined based on the results of previous (trial) model runs. Eq. 10 calculates the deviations in volume scheduled for harvest from the volume target. Eq. 11 calculates the deviations in distances of scheduled compartments to ramps from the distance target.

The mathematical formulation of the mixed-integer nonlinear GP model (NLTM) is similar to the LTM model with a few exceptions. To make the above linear mathematical formulation nonlinear, we added the following equation:

$$\left(\frac{SPR_i}{N_i} \right) - AVD_i = 0 \quad (14)$$

Where:

- AVD_i the average distance between scheduled compartments for harvest and forest ramps in year i .

Table 2 Total number of variables and constraints used in two models (LTM and NLTM)

Variables and constraints	LTM	NLTM
Variables	1750	1760
Nonlinear variables	0	20
Integer variables	1680	1680
Constraints	1079	1089
Nonlinear constraints	0	10

In this nonlinear case, in Eq. 11, AVD_i replaces SPR_i and DT_i represents the desired average distance between scheduled compartments for harvest and forest ramps. In this case, the deviation from the average distance replaces the total distance in the objective function. Here, we assumed a 1 km target for the distances between harvest units in a year. In effect, these changes attempt to clump thinning harvests together regardless of their distance to a ramp.

LINGO 16.0 (Lindo Systems, Inc. 2016) was used to solve these problems, where an unlimited number of continuous value, integer, and nonlinear variables were accommodated. Some data was exported from a geographic information system (GIS) to text files to address the need for distances amongst landscape features, and Lingo syntax was developed in a spreadsheet and text editor. The total number of variables and constraints within these models was moderately

Table 3 Weights for two objectives

Scenario	Volume weight w_{11}^+ and w_{11}^-	Distance weight w_{12}^+ and w_{12}^-
1	1.0	0.0
2	0.9	0.1
3	0.8	0.2
4	0.7	0.3
5	0.6	0.4
6	0.5	0.5
7	0.4	0.6
8	0.3	0.7
9	0.2	0.8
10	0.1	0.9
11	0.0	1.0

large (Table 2). The problems further used different weights in the objective function to represent the importance of deviations in harvest volume and compartment distance. The weights ranged from 0.0 to 1.0, in 10 percent intervals, and thus 11 scenarios were created for each of the two models (Table 3). Weights were applied to the objective function variables in order to observe how sensitive changes in volume and distance outcomes were when the emphasis between

Table 4 Total solver iterations and elapsed runtime seconds for linear and nonlinear models

Scenario	LTM		NLTM	
	Total solver iterations	Elapsed runtime	Total solver iterations	Elapsed runtime
Scenario 1	36,327	0 hrs 0 min 2 sec	535,166	0 min 8 sec
Scenario 2	100,000,001	2 hrs 58 min 24 sec	100,016,293	22 min 2 sec
Scenario 3	100,000,001	10 hrs 1 min 28 sec	100,001,658	23 min 52 sec
Scenario 4	100,000,001	3 hrs 29 min 49 sec	100,007,747	21 min 29 sec
Scenario 5	100,000,001	1 hrs 56 min 24 sec	100,006,066	23 min 42 sec
Scenario 6	100,000,001	2 hrs 8 min 54 sec	100,000,146	31 min 9 sec
Scenario 7	100,000,001	2 hrs 10 min 18 sec	100,003,010	20 min 1 sec
Scenario 8	100,000,001	0 16 min 5 sec	100,002,673	27 min 37 sec
Scenario 9	100,000,001	2 hrs 18 min 58 sec	100,002,271	29 min 26 sec
Scenario 10	100,000,001	2 hrs 32 min 27 sec	100,000,006	2 min 19 sec
Scenario 11	873	0 hrs 0 min 1 sec	486,123	0 min 5 sec

these two was altered. Either method (weighting or normalizing) can be used to reduce unintentional bias towards the parts of the objective that have a larger magnitude, and weighting has been put forward as one way to normalize outcomes (Tamiz et al. 1998, Ketani et al. 2004). A PC with a 2.60 GHz Intel® Core™ i7 processor and 16 GB of RAM was used to run LINGO. If the optimum solution was not located prior to about 100 million iterations of the LINGO model, the best solution located during the branch and bound search was reported (Table 4).

3. Results

3.1 Results of Linear Thinning Model

Scenarios 1 and 11 are the reference scenarios for volume and distance, respectively, because they represent the greatest weights applied to the volume deviations (scenario 1) and the distance deviations (scenario 11). For these two reference scenarios, the deviation in volume was 0 m³ (scenario 1) and the deviation in total distance was 25.7 km (scenario 11). In addition to scenario 1, there was no deviation from the target wood flow value in scenarios 2 and 3. Other than the two reference scenarios, the best three results for deviations in volume were achieved, respectively, from scenarios 2, 3, 4 and 6. The best three results for deviations in total distance were achieved from scenarios 10, 9 and 8 (Table 5). When we evaluated the volume and distance deviations together looking for a compromise between objectives, scenario 5, where the weights were 0.6 for volume and 0.4 for total distance, seemed to provide the best results. The maximum positive deviation from the target value was 11 m³ (2639 m³) in the 10th year of scenario 10 and the maximum negative deviation was -11 m³ (2617 m³) in the 10th year of scenario 9 (Table 6). In other words, the maximum deviation from the volume target was only 11 m³ (0.42% of the volume target). In Turkish forestry, this deviation in annual harvest volume for a planning unit is reasonable. The total distance between compartments ranged from 7 km (in year 7) to 13.8 km (in year 1) under scenario 11. For scenario 5, the distance ranged from 7.3 km (in year 6) to 21.4 km (in year 1) (Table 7). In this case, trade-offs were made in the timing and location of stand tending activities within compartments in order to address the notion that the timber volume target was also of some importance. Fig. 3 (a) shows the distribution of the compartments scheduled for harvest for scenario 11, and Fig. 3 (b) shows the distribution for scenario 5. As can be seen in Fig. 3 (a), the compartments scheduled for harvest during the

same harvest year would be perfectly clumped together under scenario 11. The compartments scheduled for harvest for the same harvest year under scenario 5 are also often clumped together, with a few exceptions, in spite of the reduced emphasis on this goal.

3.2 Results of Nonlinear Thinning Model

With respect to the NLTM, where now the deviation in the average distance between scheduled compartments and forest ramps was to be minimized, the results were as good as the results from the LTM. Here, a 1 km distance was set as average distance target between scheduled compartments and forest ramps. The total deviation from the target for the distance reference scenario (scenario 11) was 1.17 km (Table 8). The total deviation from the wood flow target was 0 m³ for seven scenarios (scenarios 1, 2, 3, 4, 5, 6 and 7) (Table 8 and 9). When the volume and distance deviations are evaluated together, scenario 3, where the weights were 0.8 for volume and 0.2 for average distance, seemed to have provided the best results. Interestingly, the NLTM provided better scheduled volume results (minor deviations from its target) than the LTM. The average distance between scheduled compartments under scenario 3 ranged from 1.5 km (in year 8) to 2.5 km (in year 1), or 50 to 150% greater than the target value (Table 10). Across all scenarios and for all years, the actual average distance between scheduled compartments and forest ramps indicated that in only one case the results of the NLTM were better than those ob-

Table 5 Outcomes achieved by linear thinning model

Scenario	Objective value	Deviations from goals		Actual average distance between compartments, km
		Volume, m ³	Total distance, km	
1	0.00	0.0	354.9	5.12
2	8.39	0.0	83.9	1.84
3	15.00	0.0	75.0	1.74
4	25.84	4.0	76.8	1.74
5	27.48	6.0	59.7	1.55
6	38.00	4.0	72.0	1.70
7	41.48	14.0	59.8	1.55
8	41.74	22.0	50.2	1.44
9	44.24	24.0	49.3	1.44
10	47.67	42.0	48.3	1.43
11	25.70	5669.0	25.7	1.16

Table 6 Volume scheduled and deviations from volume target when using LTM (m³)

Year	Scenario										
	1	2	3	4	5	6	7	8	9	10	11
1	2628	2628	2628	2628	2629	2628	2624	2629	2629	2621	1237
2	2628	2628	2628	2628	2628	2626	2628	2628	2628	2631	2366
3	2628	2628	2628	2629	2628	2628	2625	2628	2628	2621	2805
4	2628	2628	2628	2628	2628	2628	2628	2630	2630	2630	3195
5	2628	2628	2628	2629	2627	2628	2628	2626	2632	2622	1953
6	2628	2628	2628	2628	2626	2628	2628	2633	2631	2627	3041
7	2628	2628	2628	2628	2628	2628	2628	2628	2627	2628	2791
8	2628	2628	2628	2628	2629	2628	2629	2631	2628	2633	2123
9	2628	2628	2628	2627	2628	2629	2628	2628	2630	2628	3933
10	2628	2628	2628	2627	2629	2629	2634	2619	2617	2639	2836
Total	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280
1	0	0	0	0	1	0	-4	1	1	-7	-1391
2	0	0	0	0	0	-2	0	0	0	3	-262
3	0	0	0	1	0	0	-3	0	0	-7	177
4	0	0	0	0	0	0	0	2	2	2	567
5	0	0	0	1	-1	0	0	-2	4	-6	-675
6	0	0	0	0	-2	0	0	5	3	-1	413
7	0	0	0	0	0	0	0	0	-1	0	163
8	0	0	0	0	1	0	1	3	0	5	-505
9	0	0	0	-1	0	1	0	0	2	0	1305
10	0	0	0	-1	1	1	6	-9	-11	11	208
Total ^a	0	0	0	4	6	4	14	22	24	42	5666

^a Absolute value of annual deviations

tained through the LTM. However, the processing time of the NLTM was much shorter. In order to graphically illustrate the results of the NLTM, the scheduled compartments and forest ramps within each year of scenario 11 (reference for distance goal) and 3 (best results), are noted in Fig. 4.

3.3 Comparison of Actual Stand Tending Plan with Model Results

An intermediate harvest plan (stand tending plan) was prepared by the General Directorate of Forestry (2014). The local forester was responsible for creating thinning blocks on the condition of scheduling annu-

ally 1/10th of the planned decadal intermediate allowable cut. Since stand tending blocks were not created in the management plan, we could not fully compare the results of our thinning models with the actual forest management plan data. Therefore, we obtained the actual annual cutting plans for 2014–2018, prepared by local foresters (Pos Forest District Directorate 2017). We reconstituted a 5-year cutting plan table for the study area based on the annual plans (Table 11). However, we were only able to compare the total (and average) distances between the centroids of scheduled compartments within the same thinning block.

Table 7 Actual distance of compartments to ramps and deviations from distance target when using LTM (km)

Year	Scenario										
	1	2	3	4	5	6	7	8	9	10	11
1	62.8	26.5	26.1	23.4	21.4	23.4	20.8	21.4	21.4	17.5	13.8
2	45.0	16.6	10.3	11.2	10.3	9.5	10.6	10.3	10.3	11.2	9.0
3	43.5	11.8	11.9	16.9	14.9	13.3	14.9	14.9	14.9	12.6	11.6
4	25.7	8.9	10.8	12.3	11.5	13.3	11.1	11.0	10.7	10.7	8.8
5	34.6	17.3	15.9	16.0	16.6	13.1	18.6	14.8	12.4	18.5	9.5
6	29.7	12.8	12.3	17.2	7.3	14.9	10.0	9.3	7.3	8.5	9.3
7	47.4	13.6	12.2	8.2	8.7	10.7	9.3	9.3	12.3	8.7	7.0
8	44.3	11.1	15.1	15.4	12.4	9.7	13.0	8.8	8.7	8.3	7.7
9	27.6	19.8	14.9	10.7	10.6	18.1	10.6	10.6	12.0	10.6	10.2
10	64.3	15.5	15.5	15.5	16.0	16.0	10.9	9.8	9.3	11.7	8.8
1	55.8	19.5	19.1	16.4	14.4	16.4	13.8	14.4	14.4	10.5	6.8
2	38.0	9.6	3.3	4.2	3.3	2.5	3.6	3.3	3.3	4.2	2.0
3	36.5	4.8	4.9	9.9	7.9	6.3	7.9	7.9	7.9	5.6	4.6
4	18.7	1.9	3.8	5.3	4.5	6.3	4.1	4.0	3.7	3.7	1.8
5	27.6	10.3	8.9	9.0	9.6	6.1	11.6	7.8	5.4	11.5	2.5
6	22.7	5.8	5.3	10.2	0.3	7.9	3.0	2.3	0.3	1.5	2.3
7	40.4	6.6	5.2	1.2	1.7	3.7	2.3	2.3	5.3	1.7	0.0
8	37.3	4.1	8.1	8.4	5.4	2.7	6.0	1.8	1.7	1.3	0.7
9	20.6	12.8	7.9	3.7	3.6	11.1	3.6	3.6	5.0	3.6	3.2
10	57.3	8.5	8.5	8.5	9.0	9.0	3.9	2.8	2.3	4.7	1.8
Total	354.9	83.9	75.0	76.8	59.7	72.0	59.8	50.2	49.3	48.3	25.7

Using scenario 5 of the linear model, the average (for 5 years) deviation from annual allowable cut volume was only 0.4 m³, and the average of total distances (for 5 years) between the centroids of scheduled compartments within the same thinning block was 89.6 km (Table 12). Using scenario 3 of the nonlinear model, there was no deviation from annual allowable cut volume in 5 years, and the average of total distances between tended units was 105 km. In the actual plan, the deviations in scheduled volumes over the 5-year period were 660.4 m³ per year. Considering that the average intermediate yield allowable cut is 2,628 m³ per year for the study area, this deviation is noteworthy (25% of the volume target). Further, the distances between the centroids of scheduled compartments in the actual plan totaled 122.2 km. This will

result in loss of time and money in the transport of cutting and skidding equipment from one compartment to another, and will also make it difficult to control the harvesting operations.

4. Discussion

The contribution of this work has been to illustrate alternative methods for addressing a timber production program conducted in the thinning compartments of a forest district within a government-controlled European/Asian forested landscape. This work expands upon the work of others (e.g., Demirci and Bettinger 2015) to show that a nonlinear method for the development of an intermediate harvest plan can effectively be developed to provide reasonable results

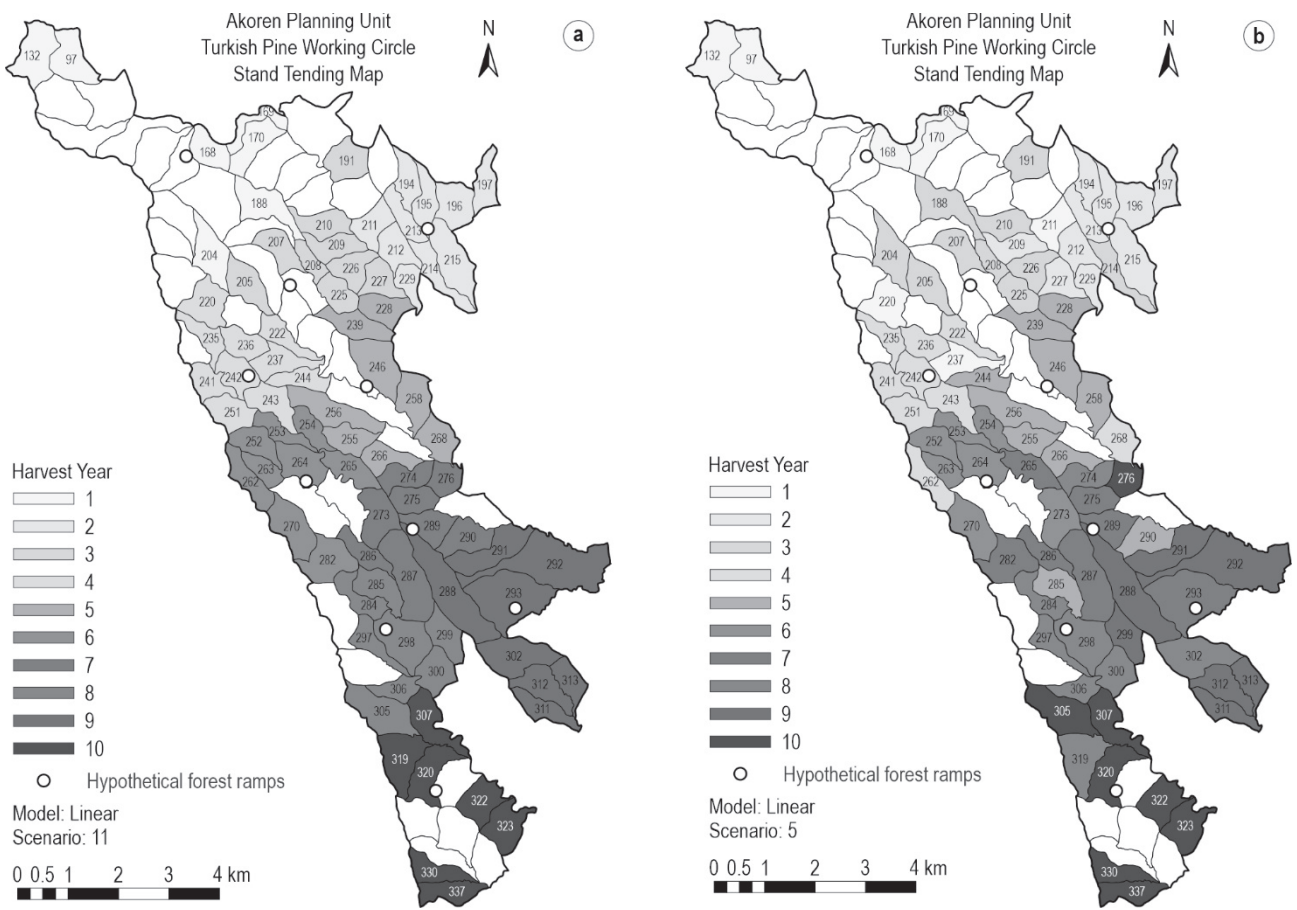


Fig. 3 Stand tending map produced by linear thinning model (a – scenario 11, b – scenario 5)

that form the basis of a management plan. To model the intermediate harvest plan, consideration was given to the advantages of working in the same terrain, and thus through the recognition of distance to ramps, compartments are often clumped together to create thinning blocks. Further, when preparing annual budgets and planning to meet the market's needs, forest enterprises desire the annual intermediate harvest yield to be nearly equal each year. However, decision support systems have not been used by the Turkish foresters so far in order to designate the location of the stand tending blocks and to harvest an equal amount of wood every year from the thinning compartments. Thus, as can be seen from the comparison of the study with the actual plan, the volume deviation at the time of implementation can be up to 25% of the average annual allowable cut. Moreover, the distances between scheduled thinning compartments can be more than 100 km, which makes it difficult to control the harvesting operations. Without modeling this problem mathematically, it seems impossible to develop a plan with an equal amount of harvest each year and thinning

Table 8 Outcomes achieved by nonlinear thinning model

Scenario	Objective value	Deviations from goals		Actual average distance between compartments, km
		Volume, m ³	Average distance, km	
1	0.00	0.0	39.2	4.92
2	0.97	0.0	9.7	1.97
3	1.74	0.0	8.7	1.87
4	2.88	0.0	9.6	1.96
5	3.52	0.0	8.8	1.88
6	5.02	0.0	10.0	2.00
7	6.66	0.0	11.1	2.11
8	8.11	2.0	10.7	2.07
9	7.07	4.0	7.8	1.78
10	7.37	10.0	7.1	1.71
11	1.93	7074.0	1.7	1.17

Table 9 Volume scheduled and deviations from volume target when using NLTM (m³)

Year	Scenario										
	1	2	3	4	5	6	7	8	9	10	11
1	2628	2628	2628	2628	2628	2628	2628	2628	2628	2631	1237
2	2628	2628	2628	2628	2628	2628	2628	2628	2628	2626	2397
3	2628	2628	2628	2628	2628	2628	2628	2628	2627	2628	2806
4	2628	2628	2628	2628	2628	2628	2628	2628	2627	2630	3195
5	2628	2628	2628	2628	2628	2628	2628	2628	2628	2628	1218
6	2628	2628	2628	2628	2628	2628	2628	2627	2628	2628	3009
7	2628	2628	2628	2628	2628	2628	2628	2628	2628	2627	3526
8	2628	2628	2628	2628	2628	2628	2628	2628	2628	2628	2123
9	2628	2628	2628	2628	2628	2628	2628	2629	2629	2628	3933
10	2628	2628	2628	2628	2628	2628	2628	2628	2629	2626	2836
Total	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280	26,280
1	0	0	0	0	0	0	0	0	0	3	-1391
2	0	0	0	0	0	0	0	0	0	-2	-231
3	0	0	0	0	0	0	0	0	-1	0	178
4	0	0	0	0	0	0	0	0	-1	2	567
5	0	0	0	0	0	0	0	0	0	0	-1410
6	0	0	0	0	0	0	0	-1	0	0	381
7	0	0	0	0	0	0	0	0	0	-1	898
8	0	0	0	0	0	0	0	0	0	0	-505
9	0	0	0	0	0	0	0	1	1	0	1305
10	0	0	0	0	0	0	0	0	1	-2	208
Total^a	0	0	0	0	0	0	0	2	4	10	7074

^a Absolute value of annual deviations

blocks that are not too far from one another. We have demonstrated a tractable process to develop efficient plans that can be used as guidance to field foresters for implementation of intermediate harvests.

Our stand tending problem (creation of stand tending blocks) is a forest level spatial optimization problem that aggregates compartments. In Scandinavian countries, a commonly modeled aggregation problem is the minimization of the fragmentation of mature forests (Öhman 2000, Öhman and Eriksson 2002). Minimizing older forest fragmentation can be achieved, for example, by having a certain core area for each of the first period and minimizing the differ-

ence between the total amounts of old forest and the total amount of core area (Öhman 2000) or maximizing the boundary between adjacent natural old forest stands. In spatial forest planning, minimizing and maximizing operations such as these (not deviations from the target value) are usually performed using mixed-integer programming methods since the integer assumption of decision variable values facilitates tracking adjacent conditions (Bettinger and Chung 2004). When decision variables are assigned continuous real numeric values in a mathematical programming problem, the resulting size of an older forest (or final harvest) is uncertain, since one cannot assume

Table 10 Actual distance of compartments to ramps and deviations from distance target when using NLTM (km)

Year	Scenario										
	1	2	3	4	5	6	7	8	9	10	11
1	6.0	2.6	2.5	3.0	3.0	2.6	2.7	2.6	3.0	2.6	2.0
2	5.4	1.8	1.6	1.1	1.2	1.7	1.4	1.6	1.3	1.4	1.0
3	5.7	1.7	1.7	2.0	1.5	2.0	2.2	2.7	1.6	1.3	1.2
4	5.9	1.8	1.6	1.2	1.8	1.5	1.6	1.3	1.2	1.1	0.9
5	2.6	3.0	2.1	2.8	1.9	1.9	1.9	2.6	2.8	1.9	1.1
6	3.1	1.1	1.6	2.3	2.0	1.4	2.2	1.4	1.4	1.5	1.0
7	2.8	1.6	1.8	1.4	1.5	2.1	1.7	1.6	1.0	1.3	1.0
8	6.5	1.4	1.5	2.0	1.7	1.5	1.3	1.7	1.2	1.9	1.0
9	6.1	2.2	2.4	1.9	1.5	2.2	2.7	2.0	2.0	2.4	1.3
10	5.2	2.4	2.0	1.9	2.7	3.1	3.5	3.3	2.4	1.7	1.3
1	5.0	1.6	1.5	2.0	2.0	1.6	1.7	1.6	2.0	1.6	1.0
2	4.4	0.8	0.6	0.1	0.2	0.7	0.4	0.6	0.3	0.4	0.0
3	4.7	0.7	0.7	1.0	0.5	1.0	1.2	1.7	0.6	0.3	0.2
4	4.9	0.8	0.6	0.2	0.8	0.5	0.6	0.3	0.2	0.1	-0.1
5	1.6	2.0	1.1	1.8	0.9	0.9	0.9	1.6	1.8	0.9	0.1
6	2.1	0.1	0.6	1.3	1.0	0.4	1.2	0.4	0.4	0.5	0.0
7	1.8	0.6	0.8	0.4	0.5	1.1	0.7	0.6	0.0	0.3	0.0
8	5.5	0.4	0.5	1.0	0.7	0.5	0.3	0.7	0.2	0.9	0.0
9	5.1	1.2	1.4	0.9	0.5	1.2	1.7	1.0	1.0	1.4	0.3
10	4.2	1.4	1.0	0.9	1.7	2.1	2.5	2.3	1.4	0.7	0.3
Total	39.2	9.7	8.7	9.6	8.8	10.0	11.1	10.7	7.8	7.1	1.7

that the partial assignment of activity within one stand touches the partial assignment of activity in another adjacent stand. Unfortunately, when integer or binary decision variables are assumed in a problem formulation, a branch and bound or cutting plane method (or both) problem-solving process is typically employed, which can dramatically increase the computational effort. With a total of 1760 variables, including 20 nonlinear variables and 10 nonlinear constraints, NLTM presents a somewhat more difficult problem than LTM. However, the processing time of the NLTM was much shorter. While it took almost 28 hours to run all 11 scenarios of the LTM, it took only 3 hours, 21 minutes and 50 seconds to run all NLTM scenarios. The longest computing time was 10 hours and 1 minute and 28 seconds (LTM scenario 3).

Ultimately, both models (linear and nonlinear) developed to solve the intermediate harvest problem produced reasonable results both in aggregating thinning compartments and in scheduling equal amounts of harvest volume each year. The models can be further enhanced by including other important management issues, such as road availability, silvicultural priorities, and availability of labour into the objective function or constraints. In incorporating a road system into the planning model, for example, a reduction in road density might be suggested, which may help contribute to improvements in ecological goals. Further, there may exist other silvicultural priorities, such as management actions that would improve forest health, which may contribute to sustainable forest management goals. These may be seen as intermediate activi-

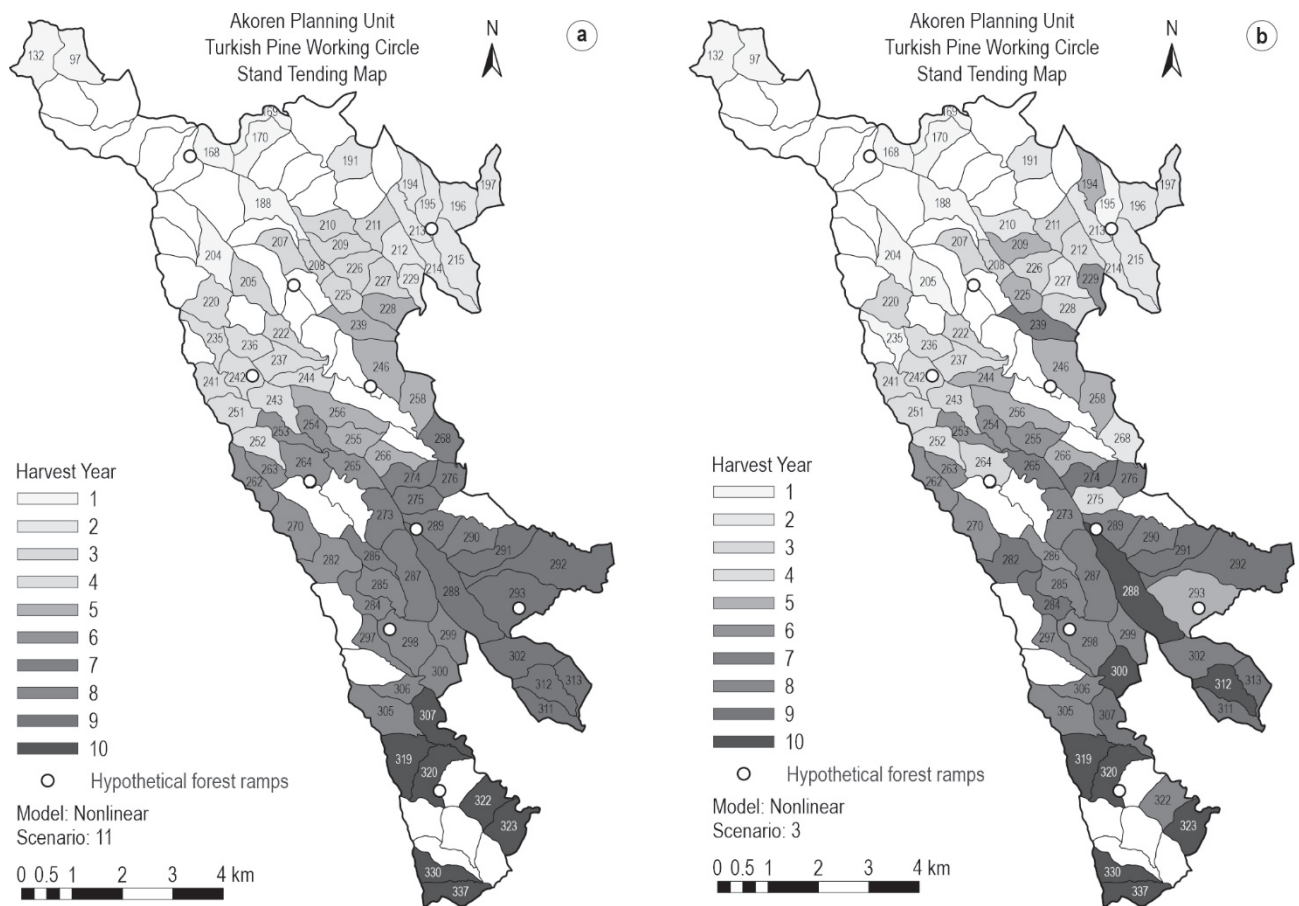


Fig. 4 Stand tending map produced by nonlinear thinning model (a – scenario 11, b – scenario 3)

ties that can be scheduled alongside the thinnings to assist in meeting wood flow targets. Since sustainable forest management could include economic, ecological, and social goals, the management of forests to minimize large deviations in these factors could become quite complex. If a goal can be quantified, GP seems to be an appropriate technique to address these management issues, rather than representing them as constraints within a management model (Demirci and Bettinger 2015).

The sensitivity of the models described here was assessed by evaluating how the results (harvest volume and distance of compartments to ramps) might change when the weights applied in the objective function varied. One challenge of the planner is to determine the appropriate weights to be applied to the components of the objective function (Demirci and Bettinger 2015), such as seeking the opinion of experts and attempting to find a consensus. The issue of normalization is important when attempting to overcome the incommensurability that occurs when deviational variables are represented by different units (ha, m³,

km, etc.). Either normalizing or weighting the values of disparate outcomes in the objective function can place them on common ground. We chose the weighting approach, since each of the outcomes (differences in timber produce from a target and differences in distances between treatments from a target) was expected to approach zero in the ideal case and the closer they were to the ideal, the less need there was to normalize their values, especially when scenarios 9 and 10 are considered (weighting distances by 0.7 or 0.8 and volumes by 0.2 or 0.3). However, the simple summation of different units in an objective function may cause an unintentional bias towards those with a larger magnitude, such as wood flow in our case (as compared to distance to a forest ramp). To overcome this problem, one may have to locate weights that ensure all objectives have roughly the same magnitude in the objective function. Alternatively, normalization constants can be developed through percentage, Euclidean, summation, or zero-one normalization processes (De Kluyver 1979, Masud and Hwang 1981, Wildhelm 1981, Romero 1991, Jones 1995, Tamiz et al. 1998).

Table 11 Actual intermediate harvest plan of the study area (stand tending plan)

Year	Block no	Compartment no	Allowable cut, m ³	Year	Block No	Compartment No	Allowable cut, m ³
2014	I	97	766	2017	IV	214	251
2014	I	132	8	2017	IV	215	144
2014	I	242	279	2017	IV	268	735
2014	I	243	286	2017	IV	297	295
Total			1339	2017	IV	298	49
2015	II	195	904	2017	IV	299	389
2015	II	262	238	2017	IV	306	411
2015	II	270	773	2017	IV	337	290
2015	II	282	184	Total			2564
2015	II	322	660	2018	V	229	58
2015	II	323	672	2018	V	253	176
Total			3431	2018	V	254	172
2016	III	196	230	2018	V	263	471
2016	III	228	280	2018	V	264	484
2016	III	239	85	2018	V	265	29
2016	III	286	188	2018	V	291	529
2016	III	288	127	2018	V	293	968
2016	III	289	423	2018	V	305	155
2016	III	290	857	2018	V	307	374
2016	III	302	501	Total			3416
2016	III	311	295	GENERAL TOTAL			13,736
Total			2986				

However, the use of these normalization processes cannot guarantee that the outcomes will be consistent with their goals (Jadidi et al. 2014). Therefore, with regard to the forestry problems described here, this area of investigation is still open.

5. Conclusions

In this study, we described how mixed-integer GP might be used within a Turkish forest management planning system to recognize important issues related to stand tending (intermediate harvests). Our work illustrated a new approach to temporal and spatial scheduling of intermediate yield harvests, which provided an enhancement on previous research related to this management concern. Although the process was

accommodated through spreadsheet and manual manipulation of data, decision-makers should evaluate if this is a useful process for thinning planning purposes, and a matrix generator should be developed to solve these (and similar) problems. Alternatively, processes to address these issues within commercial forest planning software might be explored. Further research can be conducted to address the limitations of this study, such as the excessive computer processing time of mixed-integer models that use branch and bound search processes, and the large number of iterations necessary to arrive at the optimal solution. Finally, while this methodology was demonstrated on a relatively small case study landscape, it could be applied to larger problems and different planning units worldwide to assess the temporal and spatial scheduling of forests intermediate planning.

Table 12 Comparison of actual stand tending plan data with study results

Harvest year	Linear thinning model (scenario 5)			Actual plan		
	Allowable cut, m ³	Deviation, m ³	Distance, km	Allowable cut, m ³	Deviation, m ³	Distance, km
2014	2629	−1	110.4	1339	1289	32.4
2015	2628	0	66.6	3431	−803	93.0
2016	2628	0	87.1	2986	−358	160.9
2017	2628	0	73.4	2564	64	145.5
2018	2627	1	110.7	3416	−788	179.2
Average	2628	0.4^a	89.6	2747	660.4^a	122.2
Harvest year	Nonlinear thinning model, scenario 3			Actual plan		
	Allowable cut, m ³	Deviation, m ³	Distance, km	Allowable cut, m ³	Deviation, m ³	Distance, km
2014	2628	0	158.0	1339	1289	32.4
2015	2628	0	87.5	3431	−803	93.0
2016	2628	0	88.3	2986	−358	160.9
2017	2628	0	71.6	2564	64	145.5
2018	2628	0	119.7	3416	−788	179.2
Average	2628	0	105.0	2747	660.4^a	122.2

^a Absolute value of deviations

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