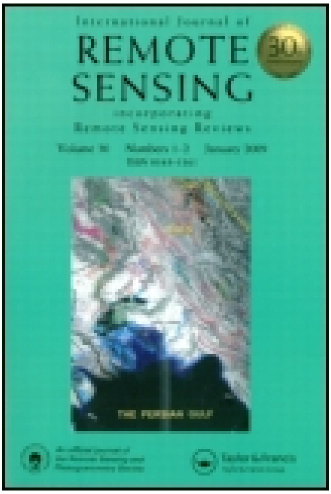

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Thinning-caused change in reflectance of ground vegetation in boreal forest

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Abstract. Ground reflectances were measured in the blue, green, red and near infrared (NIR) regions of the spectrum in a set of recently thinned pine- and spruce-dominated stands near Umeå, Sweden. Compared with the untouched reference stands, the change in ground reflectance of the thinned stands was approximately linearly related to the thinning grade and to the coverage of the cutting waste left on the ground. Typically, thinning resulted in a reflectance increase in the red and decrease in the NIR band. The major effects of the presence of cutting waste on the ground reflectance can be simulated following a rather simple theoretical analysis. It appeared to be more difficult to quantitatively describe the effects on reflectance caused by the successional changes in the ground and field layer vegetation.

1. Introduction

The detection of areas subject to recent cuttings by use of remote sensing methods is of interest to, among others, the National Forest Inventories (NFIs) in Scandinavian countries. Since one important task of the NFIs is to estimate changes in timber volume, prior knowledge of potentially changed areas would help to direct a portion of the ground sample studies directly to these areas.

Clearfelling of pine-dominated or mixed pine and spruce stands in the boreal forests of northern Scandinavia causes changes in the values of the stand reflectance factor from approximately 0.02 to 0.05 in the visible and NIR spectral bands, and even larger changes in the short wave infrared bands (Olsson 1994). It has long been known that these changes are easily detectable when multitemporal satellite images are compared (Colwell and Weber 1981, Wastenson *et al.* 1981). On the other hand, normal thinning cuttings in these forests cause changes in reflectance from only 0.0015 to 0.015 and the respective change for pure spruce stands might be even less (Olsson 1994). Still, on limited test sites in pine-dominated areas, thinning cut areas have been automatically delineated in satellite images with an accuracy of more than

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80% (Olsson *et al.* 1994). It is, however, not known whether these results can be extrapolated to areas of less pine.

The summary effect of reflectance change due to a thinning is caused by the direct removal of trees, resulting in a change in proportions of scene components (sunlit and shaded canopy and background) as well as by a change in background reflectance and illumination. By simulation with a forest reflectance model, Nilson and Olsson (1995) tried to separate the cutting-caused reflectance changes into contributions from the canopy and background. They assumed that the ground reflectance was a linear function of the thinning grade, which was obtained by interpolation between ground reflectance in undisturbed forest and the reflectance for clear-cut areas. The reflectances were determined by a parameter fitting and from the satellite images respectively. The simulations showed that the change in the background reflectance essentially contributed to the total stand reflectance change.

Any kind of thinning or clear cutting in a managed forest introduces a disturbance in the forest ecosystem. In addition to the direct removal of overstorey trees, the disturbance mainly concerns the understorey vegetation. From the point of view of remote sensing, at least three different co-effects of thinning on the understorey should be considered:

(i) mechanical damage caused by the cutting machinery resulting in partial or full destruction of the ground and field layer vegetation and, in some cases, the appearance of bare soil;
(ii) appearance of cutting waste on the ground;
(iii) successional changes in the ground and field layer vegetation due to changed micrometeorological conditions (irradiance at the ground level, regimes of water and nutrition) resulting in changes of abundance and composition of dominating species.

The aim of the present paper is to study the effects of thinning on background reflectance and to derive quantitative relations between the background reflectance change and thinning grade. Ground reflectance values have also been sought by those concerned with modelling forest stand reflectance. The measured values of ground reflectance of the studied stand type as presented below can thus also be used in modelling stand reflectance.

2. Materials and methods

Measurements were taken in thinning cuttings near Umeǎ, Sweden (latitude 64° N, longitude 20° E). Cuttings were made between the summers of 1994 and 1995 mostly by harvesters. Only cuttings from operational forestry, without any experimental treatment, were used.

Two groups of forest stands were chosen for detailed investigation, i.e. stands dominated by Scots pine (*Pinus silvestris*) and Norway spruce (*Picea abies* (L.) Karst). For the ground reflectance measurements, two or three representative stands were chosen from the classes of unthinned reference, light thinning, heavy thinning, extremely thinned seed tree and clear-cut stands. According to the management practice for Norway spruce stands, no representatives of the heavily thinned and seed tree stands could be found, since extremely sparse spruce stands are not wind-resistant. In most of the stands, the ground layer vegetation was of mesic moss type with a field layer dominated by blueberry (*Vaccinium myrtillus*).

In each of the stands, a minimum of six sample plots with a 50 m separation were established. At each plot forestry parameters were measured within a radius of 10 m. The NFI measurement standard (Anonymous 1995) was followed, but only a subset of the variables was collected. Basal areas and vegetation types for the stands are summarized in table 1.

Breast height diameters (DBH, measured in centimetres) of all trees on each plot were measured and the respective mean basal areas of all stands calculated. For thinned and clear-cut stands, diameters of all stumps within the plots were also measured. The stump diameter (D_{STUMP}, in centimetres) was related to DBH by regression functions computed from approximately 7000 sample trees from the region, available in the NFI database ($DBH = -0.201 + 0.8176\ D_{STUMP}$ for pine and $DBH = 0.223 + 0.7955\ D_{STUMP}$ for spruce). Using these functions, the basal area of the stand before thinning could be estimated. The intensity of thinning was characterized by the thinning grade (THGR) defined as the basal area of the trees removed divided by the basal area before thinning. Thus, for extreme cases THGR = 0 for unchanged reference stands and THGR = 1 (100%) for clear-cut stands.

Radiometric measurements were taken at the same sample plots as the forestry measurements. A series of radiometric measurements of ground reflectance was made from 12 to 23 July 1995. The measurements were repeated on the same plots the

Table 1. Basal area of the studied stands before and after thinning, thinning grade (THGR) and a description of the ground and field layer vegetation. Codes for ground layer vegetation: 2, mosses of genus *Sphagnum*, rich in lichens; 3, lichen-rich type; 4, mosses of genus *Sphagnum*; 5, swamp moss type; 6, mesic moss type. Codes for field layer vegetation: 2, tall herbs with *Vaccinium myrtillus*; 3, tall herbs with *Vaccinium vitis-idaea*; 4, low herbs without dwarf shrubs; 5, low herbs with *Vaccinium myrtillus*; 9, thin grasses, 11, low *Carex*; 13, *Vaccinium myrtillus*; 14, *Vaccinium vitis-idaea*; 15, predominantly *Calluna* and *Empetrum*; 16, predominantly *Vaccinium uliginosum* and *Ledum palustre*.

	Basal area ($m^2\ ha^{-1}$) before thinning			Basal area ($m^2\ ha^{-1}$) after thinning					
Stand id	Pine	Spruce	Total	Pine	Spruce	Total	THGR (%)	Ground layer	Field layer
Pine-dominated stands									
1101	21.1	0.1	22.8	21.1	0.1	22.8	0	6 (2)	13
1102	16.3	4.1	20.5	16.3	4.1	20.5	0	6 (3)	14
1103	15.2	0.2	15.4	15.2	0.2	15.4	0	6 (3,4)	14 (13)
2102	16.8	0.1	17.1	13.0	0.1	13.3	22.2	6	14,13
2103	19.8	2.7	24.6	15.7	1.7	17.6	28.5	6	13
3102	15.2		16.3	4.2		4.9	69.9	6	15 (14,13)
3103	11.0	6.7	19.7	2.8		3.0	84.8	6	13
4101	17.0	0.8	18.2	3.3	0.6	4.0	78.0	6	13 (14)
4102	16.9	2.5	19.6	3.9		3.9	80.1	6	13 (14)
5101	15.6	4.4	20.1			0	100	6	13 (14,16)
5102	15.1	6.4	21.7		0.1	0.2	99.1	6	13 (14)
Spruce-dominated stands									
1201	2.1	24.4	28.5	2.1	24.4	28.5	0	4 (5,6)	5, 13 (11,2)
1202	2.0	20.8	25.5	2.0	20.8	25.5	0	6 (5,4)	5 (13,4)
2201	12.0	17.0	37.9	7.4	11.0	22.2	41.4	6	13 (9)
2202	4.8	18.3	28.2	4.8	16.5	23.9	15.2	6	13 (5,9)
5201	12.8	13.8	26.6	0.4		0.4	98.5	6	13
5202	1.5	26.4	28.8			0.3	99.0	6	13

following year, from 25 July to 6 August 1996. A four-channel field radiometer KFM-4M designed at the Tartu Observatory was used. The radiometric head was mounted with a Cardan joint at one end of a horizontal rod fixed on a photographic tripod. The radiometer had four spectral bands corresponding to blue (maximum transmission wavelength of the filter, $\lambda_{max} = 487$ nm, transmission half-width, $\Delta\lambda_{0.5} =$ 10 nm), green ($\lambda_{max} = 556$ nm, $\Delta\lambda_{0.5} = 14$ nm), red ($\lambda_{max} = 650$ nm, $\Delta\lambda_{0.5} = 9$ nm) and NIR ($\lambda_{max} = 791$ nm, $\Delta\lambda_{0.5} = 11$ nm) regions of the spectrum. These bands corresponded approximately to Landsat Thematic Mapper (TM) bands TM1, TM2, TM3 and TM4 respectively. Unfortunately, many of the measurements in the blue band appeared be unreliable because of technical problems with the sensor. In all the spectral bands, the radiometer measured irradiance at a height of approximately 1.5 m from the ground level and radiance from the nadir direction with 13° field of view.

Radiometric measurements were made at five points on each 10 m radius sample plot: at the plot centre and 5 m to the north, east, south and west from the centre. When choosing the timing of measurements, we avoided rapid changes of illumination from full sunlight to shade or vice versa caused by movement of clouds. During a measurement sequence that lasted 50 s, the radiometer was manually scanned by rotating the radiometric head on the tripod along a circle of approximately 1 m radius. As a result, at each measurement point, an average of ground radiance over approximately 2 m^2 and irradiance along a circular line 3 m in length was recorded.

Measurement of ground surface reflectance factors under the forest canopy is a complicated task because of the high variability of irradiance at the forest floor. Despite the averaging resulting from the scanning technique used, it is still possible to obtain biased and unrealistic reflectance factors at some of the measurement points. A typical problematic case is when the ground surface in the field-of-view of the radiometer occurs in the sun fleck, but the radiometric head itself at 1.5 m above the ground is in the shade or vice versa. To reduce the influence of these extreme situations, the radiances and irradiances were averaged over all five measurement points on each sample plot before calculating the reflectance factors. Thus, on each sample plot the measured reflectance factors represent averages over 10 m^2 of ground area.

The ground reflectance factors for each of the sample plots were calculated as the ratio of the average measured radiance to the average irradiance. The radiometer was calibrated using measurements of a reference panel in an open area taken before and after the measurement sequence. The reflectance factors of the panel were determined earlier in the laboratory.

As a result of thinning, the ground surface was partly covered by cutting waste. The relative ground coverage of the cutting waste was visually estimated in the field-of-view of the radiometer at each measurement location. The visual estimate was classified into one of five classes (0, 25, 50, 75 or 100%). In addition, the average cutting waste coverage for each stand was determined on linear transects through the plot centres.

3. Results and discussion

3.1. *Empirical relations between ground reflectance and thinning grade*

Figure 1 shows the stand average ground reflectances in the green, red and NIR bands plotted against the thinning grade of the stand for pine- and spruce-dominated stands. Unfortunately, in the set of stands chosen we have almost no representatives

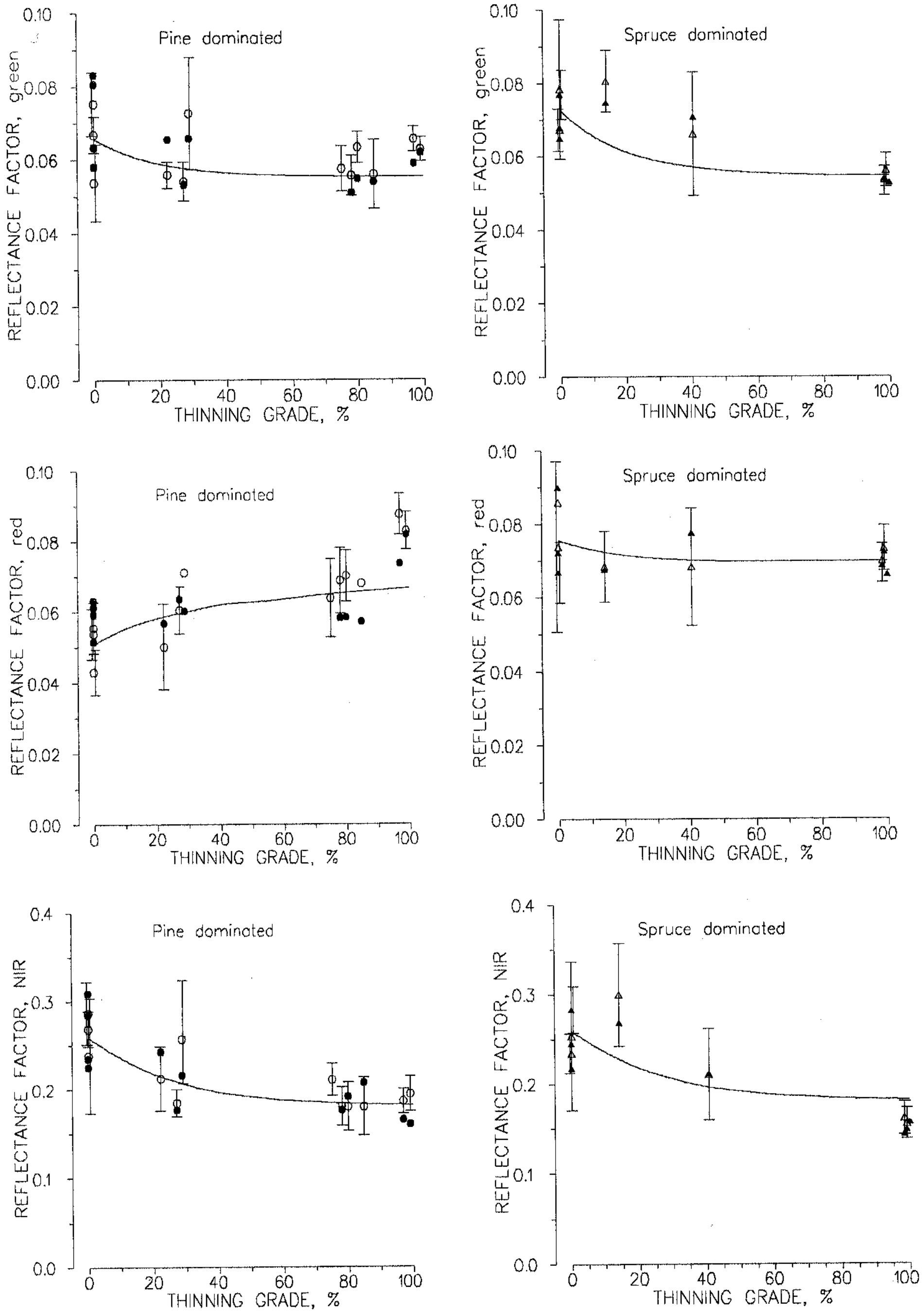


Figure 1. Measured and simulated (solid lines) relations between ground reflectance and thinning grade of the studied pine-dominated and spruce-dominated stands in green, red and NIR bands. Error bars show the standard deviation of reflectance on a single 10 m radius sample plot. Measurements: pine-dominated ○, 1995, ●, 1996; spruce-dominated △, 1995, ▲, 1996.

of the medium thinning grade (50%). Most measurements from 1995 are supplied with error bars to show the standard deviation of reflectance among the six plots within the same stand. Note that the standard deviation of the mean ground reflectance for a stand is by $\sqrt{6} \approx 2.45$ times less. The errors indicate the magnitude of horizontal variability of ground reflectance as well as the variability caused by instrumental and methodological (e.g. limited averaging) effects.

In an analysis of figure 1, considerable variability in the measured ground reflectance can be noted. However, some systematic trends are also evident. For the pine-dominated stands in the green band, the ground reflectance is relatively insensitive to the thinning grade. However, an increase in reflectance in the red band and a decrease in the NIR can be noted as the thinning grade increases. For the spruce-dominated stands, surprisingly, the red band reflectance shows little dependence on the thinning grade. A decreasing trend, similar to that in the pine stands, appears in the NIR band. As a first approximation, all of these relations can be considered as linear (table 2). Thus, the linear assumption made by Nilson and Olsson (1995) seems to be realistic. The values of average ground reflectances for the extreme cases—untouched reference stands and clear-cut stands—are shown in table 3.

For the pine-dominated stands in figure 1, the differences in ground reflectance between the reference and clear-cut stands are generally as expected. Adding cutting waste and decreasing the green leaf area and chlorophyll content of leaves should just result in some reflectance decrease in the green and NIR regions and a concurrent increase in the red band. The only problematic case is the difference in the ground reflectance of clear-cut stands when compared to visually similar seed trees or heavily thinned stands (red and green bands). For spruce-dominated stands, the measured

Table 2. Parameters of linear regression $R = b\text{THGR}/100 + a$ of ground reflectance factors (R) on visual estimates of the thinning grade (THGR); s, standard error of the estimate; R^2, coefficient of determination.

Spectral band	b	a	s	R^2 (%)
Pine, 1995				
Blue	0.0120	0.0104	0.0124	14.1
Green	−0.0017	0.0641	0.0088	0.7
Red	0.0284	0.0518	0.0093	62.3
NIR	−0.0875	0.2535	0.0289	61.9
Spruce, 1995				
Blue	0.0129	0.0123	0.0041	73.0
Green	−0.0209	0.0758	0.0060	76.6
Red	0.0056	0.0756	0.0068	15.1
NIR	−0.1041	0.2632	0.0303	76.1
Pine, 1996				
Blue	0.0198	0.0105	0.0056	69.0
Green	−0.0149	0.0724	0.0051	77.2
Red	0.0101	0.0576	0.0069	27.4
NIR	−0.0849	0.2543	0.0296	59.6
Spruce, 1996				
Blue	0.0176	0.0112	0.0040	83.3
Green	−0.0183	0.0724	0.0051	77.2
Red	−0.0061	0.0753	0.0081	13.0
NIR	−0.1058	0.2560	0.0231	84.8

Table 3. The average (m) and standard deviation (s) of ground reflectances in the reference and clear-cut stands, and on mechanically undisturbed subplots in heavily thinned stands (an average over all plots having CW = 0, without cutting waste, in heavily thinned, seed tree and clear-cut stands).

		1995				1996			
Stand type		Blue	Green	Red	NIR	Blue	Green	Red	NIR
Pine									
Reference	*m*	0.009	0.065	0.051	0.264	0.011	0.071	0.059	0.263
	s	0.005	0.009	0.006	0.020	0.003	0.011	0.004	0.034
Clear-cut	*m*	0.034	0.064	0.085	0.191	0.037	0.060	0.078	0.163
	s	0.008	0.002	0.002	0.004	0.003	0.002	0.004	0.003
CW = 0,	*m*	0.018	0.058	0.065	0.243	0.019	0.056	0.060	0.203
Heavy thin	*s*	0.004	0.007	0.012	0.028	0.006	0.006	0.007	0.015
Spruce									
Reference	*m*	0.016	0.073	0.080	0.244	0.013	0.070	0.076	0.248
	s	0.002	0.006	0.006	0.010	0.003	0.005	0.010	0.027
Clear-cut	*m*	0.026	0.055	0.072	0.159	0.029	0.053	0.069	0.150
	s	0.000	0.001	0.002	0.003	0.003	0.001	0.003	0.006
CW = 0,	*m*	0.021	0.053	0.065	0.174	0.022	0.049	0.059	0.184
Heavy thin	*s*	0.006	0.013	0.017	0.040	0.006	0.004	0.003	0.012

reflectance behaviour in the red and green bands is different from that observed in the pine stands. The ground reflectance in the green and red bands is surprisingly high among the studied reference and light thinning stands, and the respective average reflectance in clear-cut stands is even smaller than in the reference stands. This effect could possibly be due to some differences in field (and ground) layer vegetation type (site type) between the reference and cut stands (see table 1). If we could compare the ground vegetation reflectance changes in more similar sites, the resulting effects would, hopefully, be more alike those in pine-dominated stands.

Comparing the ground reflectances of the same plots on the first (1995) and second (1996) year after cutting, contrary to our expectation, no significant changes can be noted. In heavily thinned, seed tree and clear-cut pine-dominated stands, some decrease in the red band and a minor decrease in the NIR band is apparent. Changes could be expected due to changes in the appearance of the pine cutting waste on the second year after cutting (reddish needles having been dropped from cut branches) and by a decrease in the Leaf Area Index (LAI) of dominant field-layer species (mostly *Vaccinium myrtillus*). Soil scarification, carried out on most of the clear-cuts in summer 1996, has certainly had an effect on the 1996 reflectances. Some differences of ground vegetation reflectance could also be caused by possible minor differences in the phenological time during the measurement series of these two years.

In addition to the measured values, simulated curves are presented in figure 1. Details of the simulation are explained below. Here, it is important to note that the simulated curves are not linear, while the main non-linearity effects are present at lower thinning grades.

The empirical (linear) relations between the ground reflectance and thinning grade that were derived from our datasets (table 2) could be sufficient for several practical applications in interpretation and simulation of cutting effects on stand reflectance in boreal forests of the same type. However, in the following sections we will try to apply some quantitative theoretical analysis of the influence of the main factors responsible for the ground reflectance change. First of all we consider the influence of cutting waste. If the cutting waste exposed on the ground was the only cutting-caused reason for the change of ground and field layer vegetation reflectance, then it would be better to express the reflectance and its change in terms of cutting waste coverage rather than in terms of the thinning grade. Note that the thinning grade is a relative measure of cutting intensity, however, the total amount (coverage) of thinning waste should be closely related to the amount (area) of branches of cut trees.

3.2. *Relations between cutting waste coverage and thinning grade*

More trees cut implies more cutting waste covering the ground after the thinning. It was possible to derive an empirical relation between thinning grade and cutting waste coverage. This relation appeared to be non-linear—at higher thinning grades (more than 50%) cutting waste coverage became saturated (figure 2). According to our data, it was possible to approximate the relation between the thinning grade (THGR, in %) and cutting waste coverage (CW, in %) by means of the formula

$$CW = 55.4[1 - \exp(-0.0360\ \text{THGR})], \qquad s = 5.13,\ R^2 = 95.3\% \qquad (1)$$

where s is the standard deviation of the estimate and R^2 is the coefficient of determination of the non-linear regression.

Let us now try to derive theoretical formulae to predict cutting waste coverage. Different management practices result in different effects of cutting on the ground vegetation. They determine how much of the ground and field layer vegetation is mechanically damaged and how the cutting waste is left on the ground (either randomly or in piles on/at the cutting roads).

Cutting waste is mainly composed of the branches of cut trees. The simplest case is if the cutting waste is left in the form of distinct and thick piles of branches, while the rest of the ground surface remains uninfluenced. Then we simply need to know

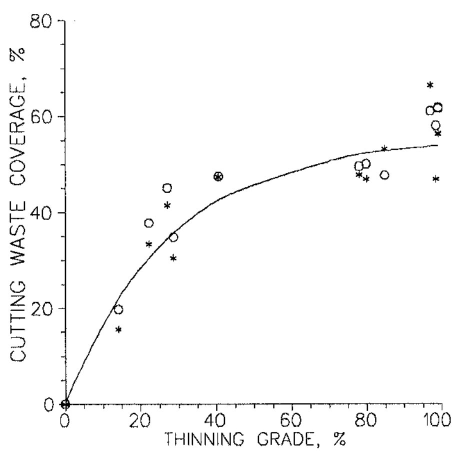


Figure 2. Relation of the coverage of cutting waste on the ground surface of thinned or cut stands with the thinning grade: *, measured data on the linear transects the first year after cutting; ○, simulated values; ———, empirical relation, equation (1).

the number and dimensions of typical piles. However, in the majority of the thinned or cut stands we studied, the cutting waste was distributed more or less randomly on the ground. In this case it is possible to derive a theoretical estimate for the cutting waste coverage (CW) in the form

$$CW = 1 - \exp(-2k\mathrm{BAI}_{cut}/\pi) \tag{2}$$

where BAI_{cut} is the branch (woody part) area index of the cut trees defined as half of the total surface area of branches per unit ground area, the coefficient k is introduced to account for the effects of the angular distribution of branches laid on the ground and their clustering (mutual overlapping) effects and the term $2/\pi$ takes into account the relation between the projected and one-sided branch area.

Supposing that all branches are horizontal, i.e. parallel to the ground and randomly dispersed, then $k = 1$. For instance, if, before cutting, a pine stand had a one-sided BAI equal to 1.0, then the cutting waste coverage for the respective clear-cut stand would be 0.47. For a clustered dispersion of branches on the ground, $k < 1$ and the cutting waste coverage is less than in the case of a random dispersion.

We tried to produce a rough estimate of the BAI_{cut} of the removed trees by using the regression of branch area against DBH (cm) and tree height h (m) of trees and density of the removed trees (N_{cut}, trees m^{-2}) in the following form:

$$\begin{aligned}\mathrm{BAI}_{cut} &= 1.355N_{cut}\exp[12.1095\mathrm{DBH}/(\mathrm{DBH}+7)\\ &\quad +0.0413h - 1.565\ln(h) - 3.4781] \text{ for pine}\\ \mathrm{BAI}_{cut} &= 0.792N_{cut}\exp[9.7809\mathrm{DBH}/(\mathrm{DBH}+12)\\ &\quad -0.4873\ln(h) - 1.8551] \text{ for spruce}\end{aligned} \tag{3}$$

These equations originate from Marklund's (1988) regressions of the tree needle mass on DBH and height. The needle mass was converted to needle area and the area of branches was assumed to be proportional to needle area with coefficients of 0.18 for pine and 0.12 for spruce. Equations (1) or (2) together with (3) enable us to estimate the cutting waste coverage if information about the parameters of cut trees is available.

We estimated the cutting waste coverage of our study stands by means of equations (2) and (3). When we compared the simulated estimates of the cutting waste coverage to the measured values, it appeared that these formulae clearly underestimated the cutting waste coverage for the pine-dominated stands. This problem was most probably caused by the pine needles that remained on cut branches for the first year after cutting. In visual estimates of the cutting waste coverage, the needles on cut pine branches made an important contribution. We thus added the contribution of the needles on cut branches of pine as a factor of 2, i.e. the projected needle area index was twice the area of cut branches. As a result, a reasonable agreement between the measured and simulated cutting waste coverage was achieved (figure 2).

3.3. *Empirical relations between ground reflectance and cutting waste coverage*

Since visual estimates of cutting waste coverage were made on each subplot, it was possible to relate the measured ground reflectance factors to the coverage of cutting waste on the same subplot. The reflectance factors were averaged over all subplots with no (0%), 25%, 50%, 75% and 100% of cutting waste respectively.

The results obtained (figure 3) are rather similar to those in figure 1. For pine-dominated stands, a statistically significant reflectance increase in the red band and a decrease in the NIR band could be noted with an increase in the cutting waste coverage, while in the green band the reflectance was found to be almost insensitive to the presence of cutting waste. Hence, typical cutting waste should have higher reflectance than mechanically undisturbed ground vegetation in the red region and lower in the NIR. In the green band the reflectances of cutting waste and typical ground vegetation should be similar.

For the spruce stands studied, a decrease of reflectance in the NIR band was found. However, in the green and red bands the dependence of the reflectance factor on the cutting waste coverage was small. Here, again, the problem could be that on the plots with no cutting waste in the spruce-dominated reference and clear-cut stands there are some differences in the field and ground layer vegetation type (table 1).

As a first approximation, the relation between the ground reflectance factors and cutting waste coverage can be described by linear functions. On the basis of figure 3, the reflectances of typical cutting waste (100% cutting waste in the field-of-view of the radiometer) of the first and second year can also be compared. With the exception of spruce in 1996, the cutting waste reflectances for pine and spruce were nearly the same in the green and red spectral bands. For the NIR band, evidently, the presence of pine needles in 1-year old (1995) cut branches had an effect on NIR reflectance, even though they had turned reddish. The differences between pine and spruce cutting waste in the second year was also considerably diminished in the NIR band.

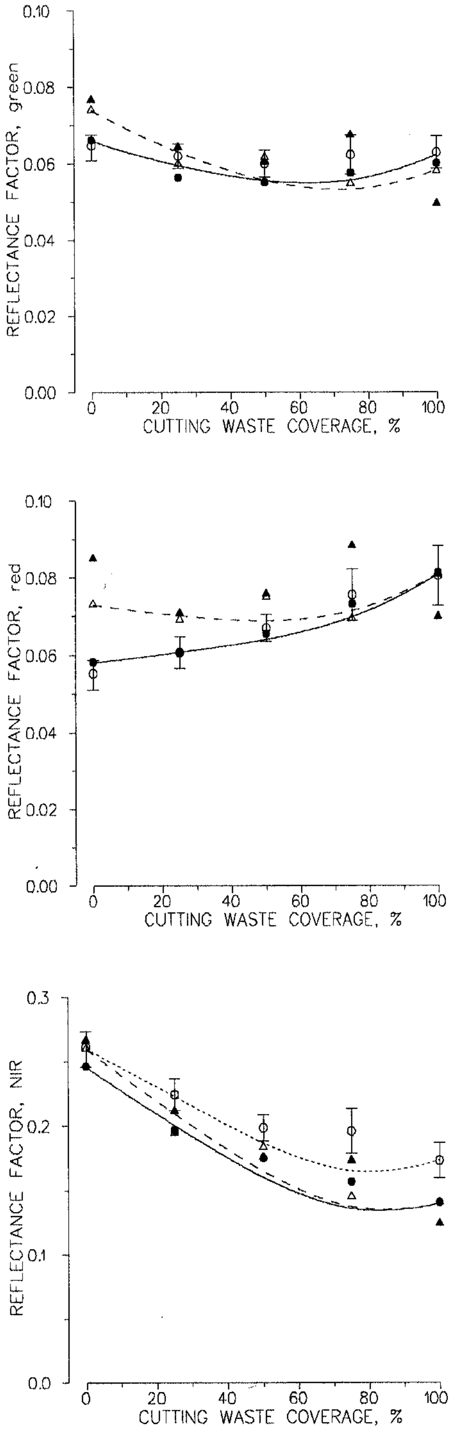
3.4. *Simulated cutting waste coverage effect on ground reflectance*

In order to create a simulation, first a certain optical model of the medium (consisting of undisturbed ground and field layer vegetation as the background and pine or spruce branches forming the 'upper' layer) is needed. It is relatively simple to simulate the situation when the cutting waste is left in distinct piles. While the undisturbed surface and a pile of cut branches generally have different spectral signatures, a linear relation is expected between the ground surface reflectance and coverage of the cutting waste. The linear approximation would clearly work rather well at approximating the measured data shown in figure 3.

Another possibility is to simulate the layer of cut branches as more or less randomly dispersed above the ground and field layer vegetation. For this kind of optical medium, plant canopy reflectance models can be applied. We used the Nilson–Kuusk (1989) canopy reflectance model. The input parameters needed to run the model were determined in the following way.

- For background reflectance, the average measured values on plots having no cutting waste were used.
- Hemispherical reflectance of a canopy element (branch bark in our case) was adjusted so that the simulated reflectance factor of an infinitely thick layer of

Figure 3. Measured and simulated dependence of ground reflectance in the green, red and NIR bands on the coverage of cutting waste on a subplot. For measurements in 1995 on pine-dominated stands, in addition to the average values, 95% confidence limits of the mean are given. Simulated curves: . . . . ., pine-dominated stands (1995); ———, pine-dominated stands (1996); – – – –, spruce-dominated stands (1995). Measurements: pine-dominated ○, 1995; ●, 1996; spruce-dominated △, 1995; ▲, 1996.


REFLECTANCE FACTOR, green
CUTTING WASTE COVERAGE, %
REFLECTANCE FACTOR, red
CUTTING WASTE COVERAGE, %
REFLECTANCE FACTOR, NIR
CUTTING WASTE COVERAGE, %

branches would coincide with the measured average reflectance on the plots of 100% cutting waste coverage.

- Transmittance of an element (branch) was set to zero.
- The element size needed in the reflectance model and medium total height ratio was assumed to be 0.3 (the average diameter of cut branches is one third of the height of the 'layer' of branches).
- The two parameters of the elliptical distribution describing the angular distribution of canopy elements were fixed at $\theta_m = 0$ (modal angle) and $\varepsilon = 0.9$ (eccentricity), which means that the cut branches are preferably horizontal.
- The one-sided (cutting waste) area index ($= BAI_{cut}$) was calculated from the given coverage of cutting waste (CW) by equation (2).

With the latter method relations between the ground reflectance and cutting waste coverage were simulated and the respective curves added to the measured points on figure 3. For the pine-dominated stands, simulations in the NIR band were made separately for the first year (1995) and second year (1996, when the branches were without needles). We see that the simulated relations are non-linear. On average, the random canopy model seems to agree better with the measured values than the simple linear model. The random canopy model somewhat underestimates the ground reflectance at medium and high cutting waste coverages (CW = 75%). However, with the present experimental material, it is difficult to judge which of the theoretical simulations, the simple linear model or the random canopy model, is preferable.

An alternative scenario to a random distribution of cutting waste is the sometimes used technique where cutting waste is left in piles on the cutting roads. The model could then be used on cutting roads, which are well exposed in the nadir view direction and almost fully covered with the cutting waste, and intermediate thinned areas in which the ground surface remains almost uninfluenced by the cutting waste.

3.5. *Simulation of reflectance and thinning grade relation*

Another series of calculations was made to simulate the relation between ground reflectance and thinning grade (figure 1). For this purpose, first a set of thinning grades (0, 10, 20, ..., 100%) was chosen and equation (1) was used to calculate the respective cutting waste coverage. From formula (2) the cut branch area index BAI_{cut} was calculated and further, the ground reflectances were calculated by means of the Nilson–Kuusk (1989) canopy reflectance model. The same set of optical parameters was used as above when the relation between the cutting waste coverage and ground reflectance was simulated. However, in addition, it was assumed that the background reflectance linearly changed with increasing thinning grade. Thus, we also tried to simulate the effect of successional change in the ground and field layer vegetation on ground reflectance.

From these simulations, the main conclusion that can be drawn is that the most remarkable reflectance changes should be expected at lower thinning grades. At higher thinning grades, the saturation of the level of cutting waste coverage causes a smaller ground reflectance dependence on the thinning grade. Comparing the simulated curves with the measured points (figure 1), a reasonable agreement can be noted. The only effect that cannot be simulated with the present model is the significant difference in the ground reflectance between the clear-cut and heavily thinned/seed tree stands in the red band.

Is it possible to separate the effects of cutting waste and bare soil appearance on the ground reflectance from the effect of successional change? Detailed measurements of the species composition and LAI change were not made. However, on the first summer after cutting the dominant species in the field layer, blueberry, had turned brownish-reddish in heavily thinned, seed tree and clear-cut stands. During the next summer, the abundance of blueberry was considerably reduced on these plots. With the present available data, it is rather difficult to quantify the possible effects of successional changes in the ground and field layer vegetation on reflectance. Here, we need a reflectance model for the ground vegetation, which can be developed on the basis of existing canopy reflectance models, such as the Nilson-Kuusk (1989) model or its multispectral analogue (Kuusk 1994). However, the most difficult problem would be the introduction of quantitative overstorey–understorey relations, e.g. expressing ground vegetation green LAI as a function of overstorey canopy closure, LAI, etc. In addition, the transition processes of the degradation of blueberry—the changes in leaf pigmentation (destruction of chlorophyll) and the corresponding changes in leaf reflectance in the visible region—would need to be simulated.

We tried to compare the reflectances of mechanically undisturbed plots from heavily thinned, seed tree and clear-cut stands to those from the reference stands (table 3). A reflectance decrease in the NIR band and the concurrent increase in the red band in pine-dominated stands could well be a result of a decrease of abundance of *Vaccinium myrtillus*. However, there were too few mechanically undisturbed plots among the studied plots for the radiometric measurements in heavily thinned stands to draw final conclusions. Also, at present we have not quantified the effect of mechanical damage of ground and field layer vegetation by cutting machinery, neither have we presented reliable reflectance factors of the bare soil.

By comparing the reflectances on plots with no cutting waste, one can conclude that there are systematic differences between the pine-dominated and spruce-dominated stands in the red and green bands: in the spruce stands the ground vegetation reflectance is higher than in the pine stands.

4. Conclusions

The change in ground reflectance caused by thinning is important for the elaboration of methods for optical detection and monitoring of all types of cutting in forests. The following conclusions can be drawn from this particular study.

1. An increase of ground reflectance in the red and a decrease in the NIR regions of the spectrum were found to be concurrent with recent thinning in *Vaccinium*-type pine-dominated boreal forest stands. The higher the thinning grade, the larger the change in ground reflectance. As a first approximation, the reflectance change can be considered to be linear with respect to the thinning grade. No considerable differences between ground reflectances during the first and second year after cutting were found.
2. The coverage of cutting waste left on the ground surface appeared to be the most important factor determining the cutting-caused reflectance change.
3. A simple theoretical formula was proposed for calculating the cutting waste coverage, provided that the stem density and some dimensions of the removed trees are known and the cutting waste has been more or less randomly dispersed on the ground surface.

4. Canopy reflectance models can be used to simulate the effect of cutting waste on ground reflectance. Thus, together with the theoretical estimates of cutting waste coverage, the expected cutting-caused change in ground reflectance can be simulated.
5. Further studies are needed to quantify the successional effects in the ground reflectance change as well as more systematic measurements of ground reflectance in forests of different site types.

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References

ANONYMOUS, 1995, Instruktion för fältarbetet vid Riksskogstaxeringen år 1995. Swedish University of Agricultural Sciences, Department of Forest Survey, Umeå (in Swedish).

COLWELL, J. E., and WEBER, F. P., 1981, Forest change detection. *Proceedings of the 11th International Symposium of Remote Sensing of Environment, Ann Arbor, Michigan, USA, 11–15 May 1981* (Ann Arbor, MI: Environmental Research Institute of Michigan), pp. 839–859.

KUUSK, A., 1994, A multispectral canopy reflectance model. *Remote Sensing of Environment*, **50**, 75–82.

MARKLUND, L. G., 1988, Biomass functions for pine, spruce and birch in Sweden. Report 45, Department of Forest Survey, Swedish University of Agricultural Sciences, Umeå.

NILSON, T., and KUUSK, A., 1989, A reflectance model for the plant canopy and its inversion. *Remote Sensing of Environment*, **27**, 157–167.

NILSON, T., and OLSSON, H., 1995, Effect of thinning cutting on boreal forest reflectance: a comparison of simulations and Landsat TM estimates. *International Journal of Remote Sensing*, **16**, 2963–2968.

OLSSON, H., 1994, Changes in satellite measured reflectances caused by thinning cuttings in boreal forest. *Remote Sensing of Environment*, **50**, 221–230.

OLSSON, H., NÄSHOLM, B., and HAGNER, O., 1994, Detection of cuttings using segmentation of multitemporal SPOT-satellite images. Monitoring of local reflectance changes in boreal forests using satellite data, edited by H. Olsson, Report 7, Remote Sensing Laboratory, Swedish University of Agricultural Sciences, Umeå.

WASTENSON, L., ARNBERG, W., BORESJÖ, L., and IHSE, M., 1981, Computer analysis of multitemporal Landsat TM data for mapping of land-use, forest clearcuts, and mires. Methododological studies. *Geografiska Annaler* A, **63**, 325–337.