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REMOTE SENSING OF OFF-ROAD VEHICLE IMPACTS TO SOIL AND VEGETATION ON THE LAC DU BOIS RANGELANDS, KAMLOOPS, BRITISH COLUMBIA

by

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B.A., University of Winnipeg, 1977

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

REMOTE SENSING / FORESTRY

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October 1980

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ABSTRACT

Land use management to provide areas for off-road vehicle (ORV) recreational activity, and to control and reduce the ORV impacts, requires information on the rapidly changing conditions. The objective of this study was to develop a remote sensing method to monitor ORV impacts to soil and vegetation on the open lands of British Columbia.

To complement available aerial photographs of the Lac du Bois rangeland study area for 1971, 1975 and 1977, two scales and formats of aerial photographs were flown in the summer of 1979. A ground survey program was designed to support the aerial photograph interpretation of ORV impacts.

The ORV trails, which were mapped from the aerial photographs, had an increase in bulk density and a decrease in moisture content and organic carbon. Regression analysis of the soil variables versus optical density values from the 1979 aerial photographs failed to provide consistent results to permit the identification of variations in soil conditions within areas of ORV activity.

The monitoring program was developed as a multistage remote sensing approach. The first stage utilizes large scale (1:4000) aerial photographs to map and measure ORV trails and associated zones of secondary disturbance within a study area. The second stage utilizes very large scale (1:600) aerial photographs to sample the study area and assess the erosion conditions. The third stage collects ground information to assist the aerial photograph interpretation of the first two stages and to provide quantitative measures of the changes to selected soil and vegetation variables.

To consolidate the monitoring program information, an ORV impact condition scale was developed. The simple five point scale summarizes the varying impact conditions within a study area and can be used to assess general changes over time within land management units.

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ACKNOWLEDGEMENTS

The author expresses sincere appreciation to Dr. Peter A. Murtha, Faculty of Forestry and Department of Soil Science, University of British Columbia, for his guidance during this project, his assistance in acquiring the necessary aerial photographs, and his encouragement and support throughout my entire graduate program.

Sincere thanks for their time and assistance are extended to the thesis committee members, Dr. Robert J. Woodham, Faculty of Forestry and Department of Computer Science, University of British Columbia; Dr. Leslie M. Lavkulich, Department of Soil Science, University of British Columbia; and Dr. Peter J. Dooling, Faculty of Forestry, University of British Columbia.

The funding for the fieldwork of this project, provided by a University of British Columbia Natural and Applied Sciences research grant under the supervision of Dr. Peter A. Murtha, and the use of the laboratory facilities at the Agriculture Canada Research Station, Kamloops, British Columbia, is gratefully acknowledged.

Final thanks to my mother, Helen, for her continual encouragement and her typing skills.

1.0 INTRODUCTION

The popularity of off-road vehicle (ORV) recreation in North America grew rapidly during the 1960s and maintained its popularity throughout the 1970s. The impact of ORV activity on natural resources and the conflicts between ORV enthusiasts and other users of the land was seen by the United States Council on Environmental Quality as

> "... one of the most serious public land use problems that we face.
> Therefore, ways must be found to accommodate off-road vehicles without sacrificing the integrity of the natural environment or the rights of those who choose non-motorized forms of recreation." (Sheridan, 1979, p.iii).

The popularity of ORVs in several regions of British Columbia has prompted the recognition of a problem on both local and provincial levels. At Kamloops, the 1976 Lac du Bois Coordinated Resource Management Plan (CRMP) identified the uncontrolled use of the area by motorized vehicles as a major problem to be solved (CRMP, 1976). The Greater Vancouver Regional District (GVRD) established a task force on motorized recreation in October 1978 to assess potential sites for trail bikes and to develop a plan for motorized recreation vehicles in the Lower Mainland region (GVRD, 1978). At the provincial level, an 'off-highway vehicle' coordinator was appointed and the Environment and Land Use Committee (ELUC) Off-Highway Vehicle policy was formulated to provide for cooperative efforts by governmental agencies and private groups and individuals to overcome specific problems which may be identified in the various resource management regions of the province (ELUC, 1978).

The objective of the ELUC Off-Highway Vehicle policy is to control environmental and property damage associated with improper vehicle use and to resolve conflicts between vehicle operators and other resource users. Meeting this requires a good source of information on the past, present and future ORV environmental damages. The utility of remote sensing techniques for informa-

tion collection is recognized in the development of the environmental impact statement process and the assessment of change over time (Rosen, 1976). Historical aerial photographs provide an objective record of past baseline conditions. Subsequent changes can be efficiently and objectively recorded with repetitive aerial photographic coverage. Previous ORV studies in the United States to measure quantitatively past and present ORV environmental impacts (Davidson and Fox, 1974; Webb et al., 1978; Wilshire et al., 1978) have not fully utilized information content of aerial photographs. Systematic monitoring programs have not been developed (Sheridan, 1979).

1.1 Objective

The objective of this thesis is to develop a remote sensing method to monitor ORV impacts to soil and vegetation on the open lands of British Columbia.

2.0 LITERATURE REVIEW

This thesis concerns the environmental impact to soil and vegetation by ORVs, other than snowmobiles. The literature on ORV environmental impacts dates to 1948 (Hill and Kirby, 1948: as cited by Sheridan, 1979) but did not become a popular subject until the late 1960s when the use of ORVs in the United States began to boom. The early papers on ORVs were popular, non-scientific articles which drew attention to the environmental impacts and the recreation conflicts caused by ORVs.

The early 1970s saw an increased popularity of ORVs, an increased public awareness of their impacts as a result of the literature, and the official recognition by the United States government that an ORV problem existed. In 1972 the United States Presidential Executive Order 11644 directed agencies with jurisdiction over public lands

> "... to establish policies and provide for procedures that will ensure that the use of off-road vehicles on public lands will be controlled and directed so as to protect the resources of those lands, to promote the safety of all users of those lands, and to minimize conflicts among the various users of those lands." (R. Nixon, 1972, p.2877).

At the time of the Executive Order, Lodico (1973) noted that only by stretching the definition of a 'scientific study', which she defined as

> "... any report of research which planned in advance to measure any environmental impact by an ORV and which included a control area where the ORV was not used" (Lodico, 1973, p.i),

could it be said that a scientific study had been published on the environmental effects of off-road recreation vehicles other than snowmobiles.

As a result of the 1972 Executive Order and the lack of existing knowledge, the Bureau of Land Management (BLM) organized a research strategy to provide necessary information. The six steps of the strategy are listed in Table 1.

Table 1. Bureau of Land Management ORV Research Strategy (McCool and Roggenbuck, 1974, p.6)

1. A systematic identification of the needs of ORV users and the real problems associated with ORV use;

2. A prioritization of the identified needs and problems for evaluation and research;

3. The development of research strategies to resolve those important problems or issues of conflict for which answers are not currently available;

4. The completion of the necessary research;

5. The development of comprehensive ORV policy and managerial strategies based upon the systematic problem analysis and research findings, and

6. A meaningful on-going feedback system to evaluate programs and policies.

The BLM subsequently contracted Utah State University to complete the first three steps of the research strategy. The major result of the Utah State University study, which has helped to direct ORV research including this thesis, was the identification of ten priority issues concerned with ORV administration, environmental impacts and user behavior.

The ten priority questions, identified and ordered by BLM personnel, other governmental employees, representatives of resource user groups and academicians, during a series of questionnaires and seminars are listed in Table 2. The ten questions have been utilized by the BLM and other land management agencies to direct their research programs prior to the development of management plans for areas with ORV recreation interests. The research programs and the resulting scientific papers (using the term of Lodico, 1973) on the environmental impacts of ORVs have dealt primarily with questions 7 and 1, without careful consideration of the monitoring approach of question 4.

Davidson and Fox (1974) quantified the impact of motorcycles on vegetation and soil but Wilshire and Nakata (1976), Wilshire et al. (1978), Webb et al. (1978) and Stull et al. (1979) quantified changes in soil only. All the above five references studied changes between undisturbed and disturbed areas within ORV activity areas whereas Vollmer et al. (1976), Weaver and Dale (1978), Foster (1977) and Leininger and Payne (1980) studied changes to soil, vegetation and wildlife before, during and after a controlled traffic experiment.

In quantifying the ORV impacts, the research has concentrated on data collection using ground sampling techniques. They have provided land managers with an understanding of the intensity of the environmental effects of ORVs, but management programs still

"... need to monitor the effects of ORV use much more

Table 2. Utah State University Ten Priority ORV Questions (McCool and Roggenbuck, 1974, p.23)

1. What are the relative impacts of various types of ORVs upon the natural environment?

2. What techniques can be used to more effectively communicate with ORV users?

3. What criteria should a land manager use to decide whether an area should be open, restricted, or closed to ORV use?

4. How can the environmental effects of ORV use best be monitored?

5. What kinds of data are needed to give a solid basis for developing an ORV management plan?

6. What kinds of conflicts are occurring between ORV users and other recreationists?

7. How can environmental damage due to ORV use be quantified?

8. How can the land manager decide when ORV use becomes misuse or overuse?

9. How can increased cooperation between federal, state and local governmental agencies be achieved in order to increase ORV opportunities and to reduce ORV impacts and conflicts?

10. How can an ecological and sociological data base be established to increase the effectiveness of ORV management decisions?

> closely and systematically than they have done to date." (Sheridan, 1979, p.57).

The Los Padres National Forest (USFS, 1976) and the Utah Outdoor Recreation Agency (1977) specified annual environmental monitoring programs within their ORV management plans to assist amending the management policies to minimize the adverse effects of ORV activity, but no procedures were developed. The only monitoring program that has been attempted was a non-scientific study by the Tennessee Valley Authority to detect changes in the Land Between The Lakes ORV area. The on-trail locations were measured for changes in erosion transects and tree and shrub mortality over a four year period was noted (McEwen, 1978). Based on the approach of the Tennessee Valley Authority and environmental impact assessment guidelines, the Council on Environmental Quality recommended that

> "In areas regularly used by ORVs a monitoring system should be employed so that land managers can assess the impact of ORVs on wildlife, soil and vegetation. Under such a system, soil loss at key check points would be measured on a regular basis (a relatively simple matter), wildlife counts would be undertaken periodically, and changes in vegetation biomass, species, and the area of coverage would be tracked. The eyeball inspections of land managers on the ground are still vital, but a basic monitoring system would provide objective data on which to base further land use designations and adjustments in existing ORV use plans." (Sheridan, 1979, p.57).

To this point, the review of the literature has drawn solely on United States sources to justify the objective of the thesis to develop a monitoring program. The decision to develop the monitoring program for the open lands of British Columbia was the result of the presence of ORV activity in British Columbia and the lack of specific environmental information.

The attention given to ORVs in British Columbia has dealt with the identification of a variety of problems, the development of plans to control the activity and the provision of special ORV areas (Powers, 1975; CRMP, 1976; GVRD, 1978; ELUC, 1978).

The identification of problems associated with the uncontrolled use of ORVs has varied within the province. The list of ORV problems in published reports for the Greater Vancouver Regional District (Powers, 1975) and for the Lac du Bois rangelands, Kamloops (CRMP, 1976) indicates the variety of concerns and their emphasis (Table 3). The Greater Vancouver Regional District was most concerned with the noise disturbance in residential districts, whereas the Coordinated Resource Management Plan for the Lac du Bois rangelands was most concerned with environmental factors of increased erosion and reduced forage crops for livestock grazing.

The identification of the ORV problems was in conjunction with plans to control the ORV activity and reduce the problems. The plans advocated placement of signs and fences at illegal use areas and the selection of the 'designated ORV use' areas. To assist the implementation of the regional and local plans, the provincial ELUC Off-Highway Vehicle policy was formulated to provide information and education programs, to provide administrative and legal designation of land for ORV use or restriction, and to provide improved enforcement procedures (ELUC, 1978).

The description of the attention given to ORVs in British Columbia can be considered as steps 1 and 5 of the BLM research strategy (Table 1). The intermediate steps of identifying and conducting research have been neglected but are very important to providing a proper program evaluation at step 6 using quantitative information within a pre- and post-plan time framework.

The development of an efficient ORV environmental monitoring system for the open lands of British Columbia can use as a guideline the recommendations by the Council of Environmental Quality of the general needs of a monitoring system (Sheridan, 1979, p.57), which can be developed for each management area based on specific ground conditions.

Table 3. Major Problems Associated with Uncontrolled ORV Activity in British Columbia

A. Greater Vancouver Regional District
(Powers, 1975, p.2-3)

" 1. Noise annoyance occurs when terrain requirements are not optimum and residential areas are nearby;

2. Terrain disturbance occurs when vegetation and surface materials are eroded by overuse;

3. Injuries occur due to lack of supervision and distance to immediate first aid;

4. Fire danger arises when vehicles are not equipped with spark arrestors;

5. Recreation use conflicts occur when vehicles use hiking trails, equestrian lanes, and ski touring trails, and

6. Illegal use often occurs as most vehicles are illegal in most parks and municipalities.

Noise disturbance is by far the most significant problem associated with uncontrolled vehicle use."

B. Lac du Bois Rangelands, Kamloops
(CRMP, 1976)

1. Erosion problems caused by scarring of hillsides;

2. Harassment of wildlife and domestic stock;

3. Spreading of weeds (eg. knapweed);

4. Loss of aesthetic viewing;

5. Noise pollution;

6. Conflicts with range improvements;

7. Destruction of vegetative cover;

8. Conflicts with research projects;

9. Interference with educational pursuits in area;

10. Conflicts with other recreational users, and

11. Increased fire hazard.

Monitoring many forms of environmental conditions and impacts has recently begun to utilize remote sensing techniques to increase the efficiency of information collection. A multistage sampling approach combining ground data sampling with remote sensing information of various sensors and scales has been recognized as a beneficial method of data collection for more intelligent management of resources (Reeves, 1975).

Within the format of a multistage sampling approach for remote sensing, the choice of ground data sampling for the monitoring program was developed from the past experience of quantifying ORV impacts in the western United States. The impacts of ORV activity on soil have been measured for physical and chemical property changes between on-trail and off-trail locations. Varying degrees of change have been measured for surface strength, bulk density, soil moisture, infiltration, soil temperature, organic carbon, pH, and exchangeable calcium and magnesium content (Wilshire et al., 1978; Webb et al., 1978). An additional soil factor, the volume of soil eroded from ORV trails, has been calculated with erosion transects for single trails and for entire hillsides (Wilshire and Nakata, 1978; Stull et al., 1979). The quantification of changes to vegetation have been sampled for changes in plant number, changes in plant cover, changes in percent litter cover and varying degrees of damage to shrubs (Davidson and Fox, 1974; Vollmer et al., 1976; Foster, 1977; Weaver and Dale, 1978; Leininger and Payne, 1980).

Several weaknesses exist in the previous research programs. The first is that the studies have concentrated on the measurement of changes between on-trail and off-trail locations without sampling for a transition zone at the edge of the trail. In addition, the studies measuring vegetation have identified changes to existing plant communities but few areas have had to measure the invasion of undesirable vegetation into the zones of ORV disturbance.

Both of the above weaknesses could be input into the ground data sampling scheme, which could also draw upon information derived from the previous use of remote sensing for ORV studies, or from the previous use or the theory of remote sensing for environmental monitoring.

Five studies represent an initial stage in the utilization of remote sensing for ORV activity monitoring following the 1974 suggestion by Utah State University that a

> "... research program evaluate several potentially useful monitoring systems, which may include remote sensing, ERTS imagery, ground level photography, as well as the more traditional methods of direct observation." (McCool and Roggenbuck, 1974, p.37).

Each of the ORV research projects had utilized remote sensing technology for soil data collection but not to the greatest potential of remote sensing. Schultink (1977) used available aerial photographic coverage to delineate vegetation cover versus ORV barren areas and to calculate the rate of denudation over time. Unfortunately no ground studies on the changes of soil parameters or changes in vegetation species or vigour were done. Whithurst, Blanchard and Doiron (1977) used colour-infrared aerial photographs to locate and measure the linear extent of marsh buggy routes. No ground data collection was reported but the aerial photographs allowed a qualitative estimate of the growth stage of revegetated marsh tracks plus the amount of compaction of the marsh vegetation and soil. A third study utilizing remote sensing for collection of quantitative information was done by Stull et al. (1979). Ground photographs of hillsides allowed measurement of the area of exposed soil, which permitted calculation of soil erosion losses from soil erosion transects and bulk density sampling. The last two studies represent an initial project (Foster, 1977) and its continuation over time (Leininger and Payne, 1980). Their results of the controlled traffic study measured changes to soil and vegetation with ground sampling and indicated that some on the ORV trails

could be seen on 1:6000 scale normal colour and colour-infrared aerial photographs.

The general approach of the first three studies was to identify and measure the exposed soil of ORV trails. More soil information can be obtained from the aerial photographs if the proper scale and date of photography are available. Tueller and Booth (1975) found that large scale (1:600 to 1:1000) 70mm normal colour aerial photographs can be used to detect and inventory soil erosion and movement, plus

> "Aerial photography is not limited by accessibility, allows for a greatly increased sample size at similar cost, provides a permanent record, and is more objective." (Tueller and Booth, 1975, p.709).

For rangeland areas, which receive pressure from cattle grazing and are popular ORV sites (such as the Lac du Bois rangelands), they found that a system of ground observations combined with aerial photograph interpretation keys and guidelines allowed for the evaluation of several soil surface factors, such as: flow patterns, wind erosion, litter movement, vesicular horizons, bare ground and rills and gullies. All these factors are important to range management for the determination of vegetation condition and trend plus each factor can be altered by ORV disturbances.

To complement the soil erosion information, variations in soil properties and conditions may be identified from the spectral reflectance information recorded by the aerial photographs and represented by optical density values (Gaucher et al., 1975; Cihlar and Protz, 1977; Piech and Walker, 1974). Webb et al. (1978) and Wilshire et al. (1978) measured physical and chemical changes in soil properties as an effect of ORV activity. Of the properties measured, alterations to the surface properties of soil moisture, organic matter content and exchangeable magnesium are known to affect soil spectral reflectance (Shields et al., 1968; Schreier, 1977; Hoffer, 1978; Stoner et al., 1980). Although the research has studied soil spectral re-

flectance using spectroradiometers over a wavelength range of 0.5 um to 2.4 um, there are variations in the spectral reflectance of soils within the sensitivity range of colour-infrared film (0.5 um to 0.9 um). The colour-infrared film records the spectral reflectance on three film dye layers instead of the continuous sampling mode of a spectroradiometer. Each ground feature has its spectral signature composed of three optical density values as measured by a densitometer. Therefore the three optical density values or their ratios (Gaucher et al., 1975; Lillesand et al., 1975) may be used to identify variations in ground features which are a result of altered soil properties.

The use of aerial photographs can also assist the vegetation information needs of an ORV monitoring system. ORV induced changes to vegetation species and percent ground cover are among the vegetation parameters which have been studied for the applicability of aerial photography for rangeland inventory and monitoring. For herbaceous vegetation, Carneggie (1968), Carneggie and Reppert (1969) and Tueller (1977) all found that very large scale (1:600) aerial photographs were suited for a wide range of interpretations and measurements, such as:

> "... vegetation and species identification, plant species mapping, vegetation mapping, plant cover determination, plant density counts, biomass or range productivity determinations, vegetation utilization, plant vigor and phenology, range readiness, erosion determinations, rodent activity, off-road vehicle use and/or damage, evaluating herbicide applications, range condition and trend and evaluating and measuring environmental impact." (Tueller, 1977, p.1507).

Large to medium scale (1:4000 to 1:20,000) normal colour and colour-infrared aerial photographs are also useful for vegetation species and community identification and mapping and have been tested on the Lac du Bois rangelands for native climax vegetation and for invading vegetation species (Watson, 1977).

To summarize the literature review, the use of remote sensing

technology to supplement a ground data sampling program should allow for the development of a method to efficiently monitor ORV impacts to soil and vegetation for the open lands of British Columbia.

3.0 METHODS

3.1 Study Area and Site Selection

The Lac du Bois rangelands, Kamloops, British Columbia (Figure 1) were used as a study area representing the open lands of British Columbia. The area was chosen subsequent to the development of a rangeland classification by Watson (1977) which required the inclusion of a 'motorcycle and all terrain vehicle damage' class within the legend.

The rangelands have an irregular topography formed from the thin layer of wind-blown loess covering the drumlinized till which varies in thickness over the bedrock of the interior plateau (Watson, 1977). The Artemisia tridentata Nutt., Agropyron spicatum Pursh var. inerme Heller and Poa secunda Presl climax vegetation (Watson, 1977) does not offer any natural barriers to off-road travel by the motorcycle and 4-wheel drive enthusiasts from the city of Kamloops and its surrounding population.

Within the study area, four study sites (Figure 1) were selected, using existing aerial photographs and a ground reconnaissance, to represent sections of the rangeland which have received varying histories of concentrated ORV activity. Three of the sites were ORV activity areas chosen by the recreationists. The fourth site represents the 1976 Lac du Bois Coordinated Resource Management Plan's 'designated ORV area'.

Study site A represents the area of rangeland which has received the longest and most intensive ORV activity. It is immediately adjacent to a suburban housing development and serves as a first stop for most recreationists. The terrain provides a complete range of topography from gently rolling to very steep and has the greatest concentration of established trails.

Study site B represents the 'designated ORV area' which provides 700 acres of variable topography specifically for concentrated ORV activity and organized ORV competitions.

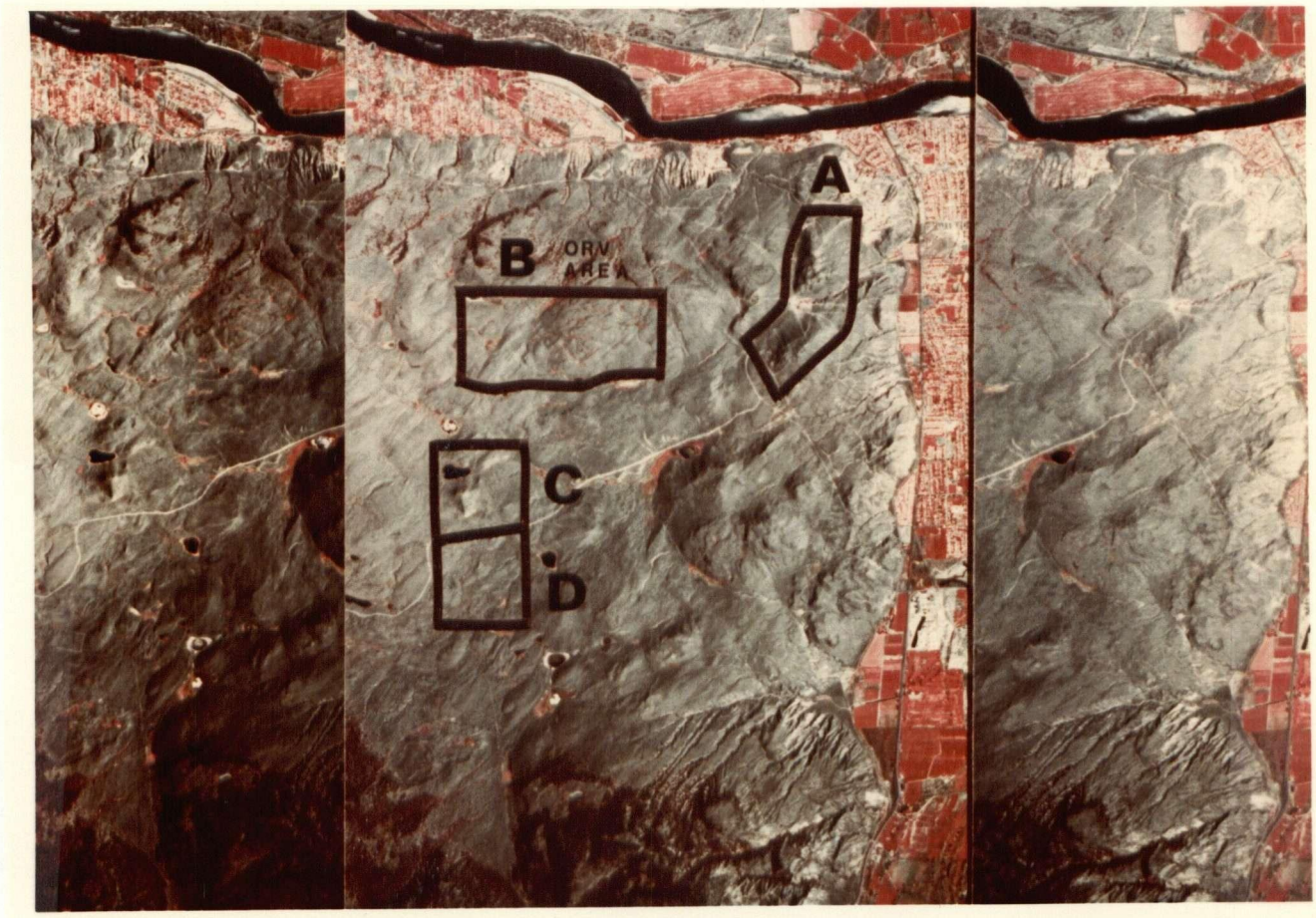
Figure 1. Study Area - Lac du Bois Rangelands, Kamloops, B.C.

Colour Infrared Aerial Photograph Stereo Triplet

North Thompson River

North

To Kamloops



Scale = 1:83,000

Date of Photography = Sept, 1975

Study Site A - Intensive use ORV area

Study Site B - 'Designated ORV area'

Study Site C - ORV Hillclimb area

Study Site D - Light use ORV area

Study site C is a large hill on the rangelands with both moderately steep and very steep slopes. The site is near the middle of the rangelands and requires extra travelling time for access.

Study site D is a gently rolling area adjacent to study site C. The site has received less use than the other sites but had been used for ORV motocross races in its early years of receiving ORV recreational use. It is the only one of the four study sites which is within the restricted use zone for ORV recreation, as designated in 1978 under the Province of British Columbia Land Act.

3.2 Aerial Photography

Two scales and formats of aerial photographs were acquired for all four study sites. Both photographic missions used Kodak Aerochrome Infrared 2443 film which was developed to a positive transparency. The original positive transparencies were used for all interpretations. The first photographic mission on July 28, 1979 photographed the study sites at a scale of 1:1000 using wing-tip mounted, Vinten 70mm cameras. The second mission on August 1, 1979 photographed the study sites at a scale of 1:4000 using a Zeiss 23cm^2 standard survey camera with a 305.3mm focal length lens.

3.3 Ground Data Collection

The ground survey program for soil erosion, selected soil properties and vegetation cover, was completed immediately following the acquisition of the aerial photographs. The sampling scheme consisted of transects across the selected ORV trails. Each transect began and ended in undisturbed areas adjacent to the trails and point sampled for off-trail, trail-edge and on-trail conditions of soil and vegetation plus included a soil erosion transect for the on-trail portions of the transect. Each trail was sampled with a set of

transects ranging in number from two to eight depending on the length and slope changes of the trail. A total of 31 transects represented eight ORV trails within the study area.

The on-trail soil erosion transects were used to estimate the soil removal from the hillsides. The method assumed that the original surface was approximately level across the trail. A thirty meter surveying tape was stretched across the trail and the distance between the hypothetical former surface and the present surface was measured at 50cm intervals along the tape to provide a basis for the calculation of the cross-sectional area of soil removed. The area of soil removed from each cross section represented the erosion condition for a section of the hillslope. The volume of soil removed along a single trail was calculated from the area of soil removed, as measured in the cross-trail transects, and the area of exposed soil, measured with a dot grid on the 1:1000 scale aerial photographs. A final value of the mass of soil removed per trail is the volume of soil removed multiplied by the bulk density of the eroded soil as measured at an off-trail location.

Three standard soil tests were used to determine the surface proportions of off-trail, trail-edge and on-trail sample points at each transect. Bulk density was calculated for the surface 7.5cm. Soil samples were taken using the excavation method because the degree of compaction prevented using a corer, then the volume was measured with air-dried sand. Soil moisture was determined from the bulk density samples following oven drying at $105^{o}C$ for 24 hours at the Agriculture Canada Kamloops Research Station. The third soil property, organic carbon, was measured for each sample site of bulk density and soil moisture using the Leco Analyzer in the University of British Columbia Soil Science Department laboratory.

The vegetation ground cover was determined at each soil sample location using ground photographs of $1m^2$ plots. The vegetation was identified

by species and the surface cover proportions of vegetation, litter and exposed soil were measured with the University of British Columbia Forest Harvesting 9830 digitizer.

The values of each soil property and surface cover were tested by analysis of variance (ANOVA) for significant differences between on-trail, trail-edge and off-trail sample point locations within various groupings of the transects. The transects were grouped three ways based on their location - by study site, by ORV trail, and by soil condition. The transect groupings and a description of the conditions represented is shown in Table 4.

3.4 Aerial Photograph Interpretation

3.4.1 Visual Analysis, Mapping and Measurement

The acquisition of the 1979 aerial photographs was supplemented with existing aerial photographs of various film types and scales to provide a history of ORV activity within the study area. The available aerial photographs, by date, film type, scale and area of coverage are listed in Table 5.

The visual analysis was the interpretation of the aerial photographs for the identification of zones of vegetation and soil disturbance and the invasion of undesirable vegetation species. Combining the vegetation information of the ground photographs and the information on species identification for the Lac du Bois rangelands (Watson, 1977) allowed the identification of disturbed and invading vegetation.

The mapping and measurement of ORV trails recorded the changes between 1971 and 1979. Most ORV trails were easy to identify on the aerial photographs because of the contrast in spectral reflectance between the exposed soil of the ORV trails and the vegetation of the undisturbed rangeland.

Table 4. Ground Survey Transect Groups for the Lac du Bois Rangeland Study Area

Transect Group	Representative Condition	Number of Transects
	By Study Site	
A	study site A. The area of rangeland which has received the longest and most intensive ORV activity.	11
B	study site B. The motocross track within the 'designated ORV area'.	8
C	study site C. A popular hillclimb area of the middle rangeland.	6
D	study site D. A gently rolling area with a previous history of motocross races and infrequent recreational use.	6
	By ORV Trail	
A_1	an intensively used steeply sloping hillclimb area	6
A_2	an intensively used trail accessing the rolling topography of the hilltop area.	2
A_3	a very steep hillclimb area with a large area of invading undesirable vegetation.	3
B_1	same a B of the study site group.	8
C_1	a long steep hillclimb area with a north aspect.	4
C_2	a short steep hilclimb area with a south west aspect.	2
D_1	a section of a flat ORV trail through bunchgrass range.	4
D_2	a section of a flat ORV trail through a Poa secunda swale.	2
	By Soil Condition	
BR	the area of the lower rangeland with the Brown Chernozem soil great group. The soil area corresponds to group A.	11
DKBR	the area of the middle rangeland with the Dark Brown Chernozem soil great group. The soil area corresponds to B_1, C_1, C_2, and D_1.	18
SW	the area of a small Poa secunda swale with Glei Rego Brown Chernozem soil. The soil area corresponds to D_2.	2

Table 5. Available Aerial Photograph Coverage of the Study Area

Film Type	Date	Scale	Study Site Coverage			
			A	B	C	D
Black & White	July 24/71	1:12,000	X	X		
Normal Colour (Kodak 2445)	June 9/75	1:8,000			X	X
Colour Infrared (Kodak 2443)	Sept 6/75	1:63,360	X	X	X	X
Normal Colour (Kodak 2445)	June 10/77	1:12,000	X	X	X	X
Colour Infrared (Kodak 2443)	July 28/79	1:1,000	X	X	X	X
Colour Infrared (Kodak 2443)	Aug 1/79	1:4,000	X	X	X	X

The 1979 1:4000 scale aerial photographs were used as a base map for ORV trail measurement. The trails were mapped at a contact scale using a Bausch and Lomb Zoom Stereoscope. The cultural features visible on the 1979 aerial photographs were also mapped on the base map. The existing aerial photographs from 1971 to 1977 were matched to the base map scale of the 1979 aerial photographs using a Bausch and Lomb Stereo Zoom Transfer Scope and the ORV trails visible at the resolution of the aerial photographs were mapped. For each study site and year of available aerial photographic coverage the length of ORV trails, representing their changes over time, were measured with the 9830 digitizer.

Included as a second step of the mapping and measurement of ORV trails was the calculation of the area of exposed soil for a sample area in study site A. The measurement of trail length does not consider variations in the width of exposed soil on individual trails. The calculation of the area of exposed soil from a four times enlargement of a 1:1000 scale 70mm aerial photograph using a dot grid (329 dots per square inch) was done to demonstrate an alternative procedure.

3.4.2 Optical Densitometry

The last portion of the data collection was the measurement of the film optical density values for each dye layer of the 1:1000 scale aerial photographs. A MacBeth TR-524 spot densitometer with a 1mm diameter aperture measured the yellow, magenta and cyan dye-layer densities of each sample point as an indication of the relative spectral reflectance in the green, red and near infrared regions of the electromagnetic spectrum. Each sample point was accurately identified on the aerial photographs with the aid of field markers and the ground photographs and the optical density values were entered into a computer file at the University of British Columbia. The

optical density value of each dye layer for each sample point was measured three times and averaged to represent the spectral reflectance data of each spectral region of the colour-infrared film. Spectral ratioing of the spectral reflectance data to negate the effect of any extraneous factors in the film exposure acting in all wavelengths of the film sensitivity (Lillesand and Kiefer, 1979) resulted in a spectral signature of six density values for each sample point. The relationships among the densitometer filters, developed film dye-layers, and the spectral sensitivity of the film dye-forming layers are given in Table 6.

Following the calculation of the spectral signatures, the computer was used to analyze the densitometric information and the physical properties of the soil and vegetation. The analysis included a correlation matrix of all variables, a backwards regression of each soil property against the six density value components of each sample point spectral signature, and an analysis of variance between the on-trail, trail-edge and off-trail optical density values.

Table 6. The Composition of the Densitometric Spectral Signature of Each Ground Survey Sample Point

Densitometer Filter	Colour Infrared Film Dye Layer	Film Dye Layer Spectral Sensitivity
Blue	Yellow	Green
Green	Magenta	Red
Red	Cyan	near Infrared
Green / Blue	Magenta / Yellow	Red / Green
Red / Green	Cyan / Magenta	near Infrared / Red
Red / Blue	Cyan / Yellow	near Infrared / Green

4.0 RESULTS AND DISCUSSION

4.1 Ground Survey

4.1.1 Bulk Density

Table 7 shows the results of the ground survey measurements for bulk density. The on-trail, trail-edge and off-trail measurements are grouped for their transect location by study site and by individual ORV trails.

Within each group, the mean bulk density values show an increase for on-trail locations. Only study site A, which has received the longest history of ORV activity, shows a transition from off-trail through trail-edge to on-trail. The impact at the other study sites are confined to on-trail versus off-trail.

The ANOVA for each study site indicates statistically significant increases from off-trail or trail-edge to on-trail for study sites A, B, and C. Study site D, which has received less ORV activity and represents a relatively flat area, does not show a significant change in bulk density following ORV activity.

Table 8 indicates changes in bulk density for the transect groups representing the three soil conditions within the study area. The data was analyzed for differences between on-trail and out-of-trail (trail-edge plus off-trail) only, since Table 7 did not find statistically significant differences between the trail-edge and off-trail measurements. The table shows that different out-of-trail conditions exist for each soil condition and the greatest percent increase in bulk density occurred in the area of greatest ORV activity, the Brown Chernozemic soil great group of study site A.

4.1.2 Soil Moisture

The results of the soil moisture measurements are shown in

Table 7. Bulk Density (g/cc) - By Study Site and ORV Trail

Transect Group	N	Sample Point: On-Trail	Sample Point: Trail-Edge	Sample Point: Off-Trail	ANOVA - Pairwise Strata: Trail-Edge F	Trail-Edge Signif.	Trail-Off F	Trail-Off Signif.	Edge-Off F	Edge-Off Signif.
A	55	1.70	1.41	1.28	12.98	.01	19.51	.01	2.31	--
A_1	30	1.76	1.43	1.35	11.24	.01	15.81	.01	0.69	--
A_2	8	1.76	1.55		1.85	--				
A_3	17	1.51	1.32	1.05	2.24	--	7.52	.01	3.37	--
B	33	1.45	1.01		32.74	.01				
C_1	23	1.29	1.05	1.10	5.71	.05	2.09	--	0.15	--
C_2	5	1.69	1.72		0.03	--				
D	33	1.35	1.17	1.18	2.62	--	2.25	--	0.01	--
D_1	23	1.48	1.31	1.34	2.23	--	1.46	--	0.08	--
D_2	10	0.96	0.86	0.87	0.28	--	0.24	--	0.00	--

Table 8. Bulk Density (g/cc) - By Soil Condition

Transect Group	N	Sample Point: On-Trail	Sample Point: Out-of-Trail	% Change	Signif.
Brown (BR)	55	1.70	1.37	+ 24.09	.01
Dark Brown (DKBR)	84	1.43	1.17	+ 22.22	.01
Swale (SW)	10	0.96	0.87	+ 10.34	--

ANOVA

Pairwise Strata	F	Signif.
On-Trail		
BR		
DKBR	10.11	.01
SW	12.92	.01
DKBR		
SW	5.55	.05
Out-of-Trail		
BR		
DKBR	11.42	.01
SW	22.74	.01
DKBR		
SW	8.88	.01
On-Trail - Out-of-Trail		
BR	16.13	.01
DKBR	17.68	.01
SW	0.20	--

Table 9. There is a general trend of a loss of moisture content from off-trail to on-trail sample points but the high level of variance prevents significant differences. The two areas with significant changes in moisture content can be explained topographically. Transects in group C_1 are located on a steep north-facing slope. The reduced amounts of direct sunlight allows the vegetation to reduce evaporation on the off-trail areas. The same vegetation interaction is occurring at the transect group D_2. The transects are in a small swale with a thick sod layer of Poa secunda which is reducing the amount of soil moisture evaporation at the off-trail sample point locations.

The grouping of the study area transects by soil condition indicates that moisture conditions for the out-of-trail locations in each group are significantly different but significant changes do not occur between on-trail and out-of-trail locations (Table 10).

4.1.3 Organic Carbon

Table 11 shows the results of the organic carbon measurements and indicates the same nonsignificant downward trend that the moisture content had between off-trail and on-trail areas. The two significant areas of decreased organic carbon content occurred in study sites A and B. A significant negative correlation identified between bulk density and organic carbon with a correlation matrix explains the decreased level of organic carbon in the two study sites which have received the greatest amount of soil compaction from ORV activity.

Table 12 indicates the change of organic carbon for each soil condition. Again, the out-of-trail values for each transect group are significantly different but only the Brown Chernozem soil area measured a significant decrease of organic carbon for on-trail conditions.

Table 9. Soil Moisture (% dry wt.) - By Study Site and ORV Trail

Transect Group	N	Sample Point			ANOVA - Pairwise Strata					
		On-Trail	Trail-Edge	Off-Trail	Trail-Edge F	Trail-Edge Signif.	Trail-Off F	Trail-Off Signif.	Edge-Off F	Edge-Off Signif.
A	55	1.75	1.73	1.99	0.00	--	0.04	--	0.06	--
A_1	30	1.25	1.38	1.71	0.03	--	0.35	--	0.22	--
A_2	8	2.41	1.54		0.54	--				
A_3	17	2.28	2.24	2.92	0.00	--	0.26	--	0.40	--
B	33	4.58	4.67		0.02	--				
C_1	23	5.58	8.59	8.28	15.97	.01	7.54	.01	0.10	--
C_2	5	3.80	4.50		0.22	--				
D	33	7.98	10.84	10.40	4.26	.05	2.94	--	0.13	--
D_1	23	5.68	7.38	6.40	3.85	.05	0.66	--	1.50	--
D_2	10	14.85	18.64	18.39	7.10	.01	6.20	.05	0.05	--

Table 10. Soil Moisture (% dry wt.) - By Soil Condition

Transect Group	N	Sample Point: On-Trail	Sample Point: Out-of-Trail	% Change	Signif.
Brown (BR)	55	1.75	1.81	- 3.43	--
Dark Brown (DKBR)	84	5.01	6.46	- 22.46	--
Swale (SW)	10	14.85	18.51	- 19.77	--

ANOVA

Pairwise Strata	F	Signif.
On-Trail		
BR		
DKBR	9.31	.01
SW	25.84	.01
DKBR		
SW	15.60	.01
Out-of-Trail		
BR		
DKBR	41.35	.01
SW	158.63	.01
DKBR		
SW	85.67	.01
On-Trail - Out-of-Trail		
BR	0.00	--
DKBR	3.62	--
SW	1.83	--

Table 11. Organic Carbon (wt. %) - By Study Site and ORV Trail

Transect Group	N	Sample Point			ANOVA - Pairwise Strata					
		On-Trail	Trail-Edge	Off-Trail	Trail-Edge F	Trail-Edge Signif.	Trail-Off F	Trail-Off Signif.	Edge-Off F	Edge-Off Signif.
A	55	1.37	2.07	2.65	3.23	--	7.96	.01	2.11	--
A_1	30	1.27	1.74	2.23	1.09	--	4.13	.05	1.29	--
A_2	8	1.04	1.26		0.09	--				
A_3	17	1.83	2.86	4.06	2.99	--	8.52	.01	3.36	--
B	33	3.15	4.00		5.96	.01				
C_1	23	3.54	3.75	3.50	0.02	--	0.00	--	0.17	--
C_2	5	2.16	2.72		0.38	--				
D	33	2.97	3.46	3.61	0.84	--	1.38	--	0.09	--
D_1	23	2.33	2.59	2.93	0.24	--	1.22	--	0.48	--
D_2	10	4.87	5.41	4.97	0.39	--	0.01	--	0.40	--

Table 12. Organic Carbon (wt. %) - By Soil Condition

Transect Group	N	Sample Point: On-Trail	Sample Point: Out-of-Trail	% Change	Signif.
Brown (BR)	55	1.37	2.26	- 39.38	.05
Dark Brown (DKBR)	84	3.05	3.42	- 10.82	--
Swale	10	4.87	5.19	- 6.17	--

ANOVA

Pairwise Strata	F	Signif.
On-Trail		
BR		
DKBR	19.06	.01
SW	14.17	.01
DKBR		
SW	4.10	.05
Out-of-Trail		
BR		
DKBR	19.98	.01
SW	37.66	.01
DKBR		
SW	14.20	.01
On-Trail - Out-of-Trail		
BR	5.62	.05
DKBR	1.83	--
SW	0.11	--

4.1.4 Soil Erosion Transects

Figure 2 shows a sequence of soil-loss profiles along a single trail in study site A, transect group A_1. The profiles are representative of the ORV trail cross section for the selected slope on the hillside. The total soil mass removed from the area of bare soil of the ORV trail was estimated at 349 metric tons or 114 kg/m^2.

An additional calculation from the soil erosion transects confirms that a positive relationship exists between soil erosion and steepness of slope. The amount of soil removed per unit trail width for all 31 transects correlates to the transect slope with a coefficient of 0.70.

4.1.5 Vegetation and Ground Cover

Table 13 indicates the change in average percent ground cover for on-trail, trail-edge and off-trail locations. The amount of exposed soil decreases with the distance from the centre of the trail and the change in proportions is significant between all three sample points. The percent plant cover is inversely related to the amount of exposed soil, with significant changes in plant cover occurring between on-trail and trail-edge and a trend toward an increase between trail-edge and off-trail locations.

Table 14 indicates the results of separating the ground cover proportions into three categories based on soil condition. The interesting result is the significant difference which exists between the Brown Chernozem and Dark Brown Chernozem soil for the ground cover proportions of litter and plant. The Brown Chernozem soil proportions of litter and plant are the inverse of the Dark Brown Chernozem soil. The change in proportion of litter and plant cover corresponds to a difference in trail-edge vegetation species between the Brown and the Dark Brown Chernozem soil great groups. The areas adjacent to the heavily used trails in the Brown Chernozem soil

Figure 2. Soil Loss Profiles Along a Single Trail - Transect Group A_1

The four soil erosion transects along a single trail (1 = top of trail; 4 = base of trail) were combined with the measured area of exposed soil to compute a total mass soil loss of 349 metric tons or 114 kg/m^2.

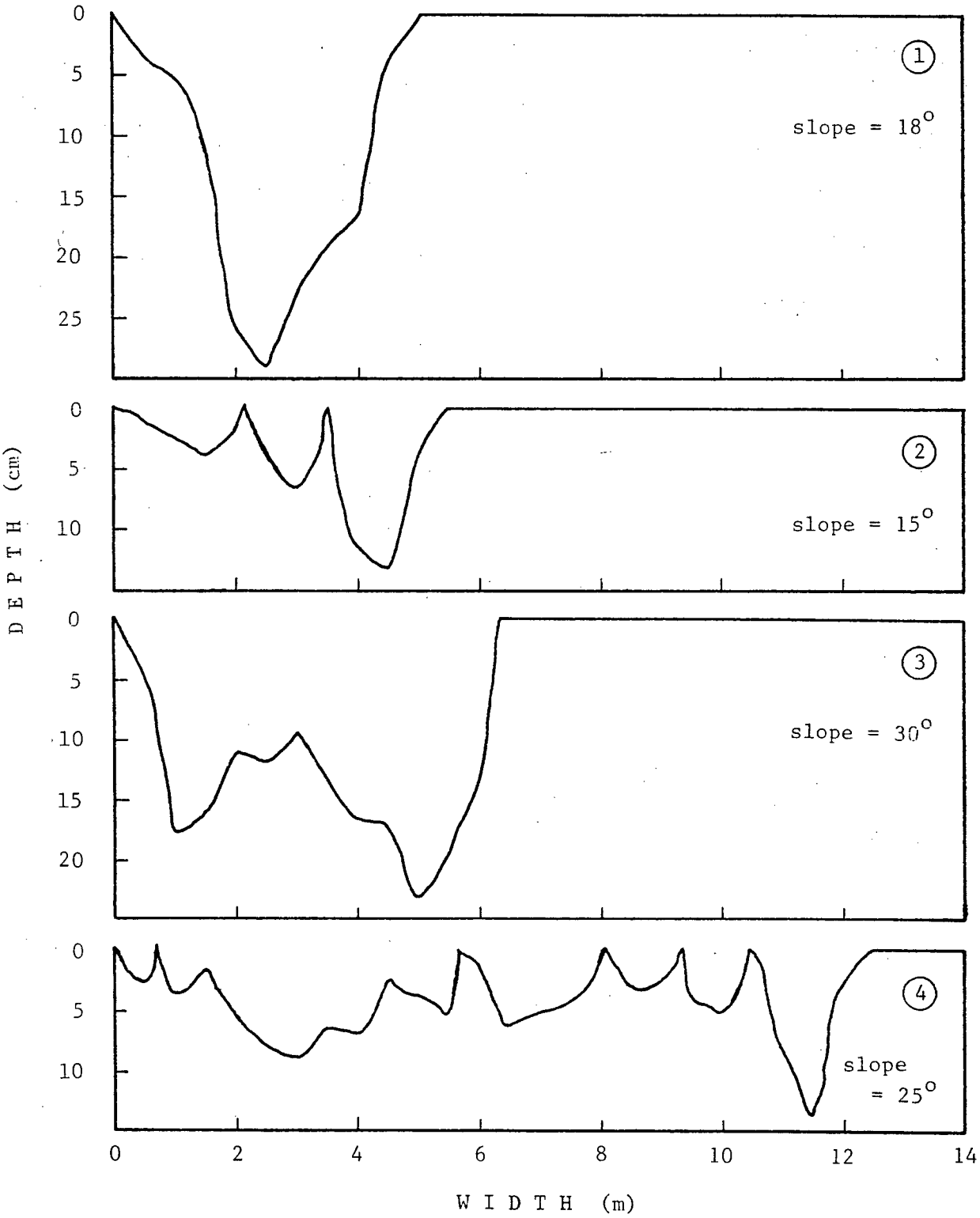


Table 13. Vegetation and Ground Cover Characteristics - By Sample Point Location

Sample Point	N	Ground Cover Proportions			
		Soil	Litter	Plant	Green Plant
On-Trail	50	0.82	0.06	0.06	0.05
Trail-Edge	70	0.25	0.38	0.28	0.09
Off-Trail	29	0.09	0.36	0.38	0.13

ANOVA

Pairwise Strata	Soil		Litter		Plant		Green Plant	
	F	Signif.	F	Signif.	F	Signif.	F	Signif.
On-Trail								
Trail-Edge	135.81	.01	37.68	.01	18.55	.01	0.87	--
Off-Trail	140.34	.01	21.12	.01	25.02	.01	2.36	--
Trail-Edge								
Off-Trail	7.56	.01	0.08	--	2.81	--	0.71	--

Table 14. Vegetation and Ground Cover Characteristics - By Soil Condition

Transect Group	N	Ground Cover Proportions			
		Soil	Litter	Plant	Green Plant
Brown	55	0.44	0.21	0.30	0.049
Dark Brown	84	0.43	0.34	0.19	0.021
Swale	10	0.02	0.00	0.16	0.830

ANOVA

Pairwise Strata	Soil		Litter		Plant		Green Plant	
	F	Signif.	F	Signif.	F	Signif.	F	Signif.
Brown								
Dark Brown	0.01	--	6.35	.01	5.30	.05	2.52	--
Swale	8.97	.01	4.39	.05	2.05	--	450.32	.01
Dark Brown								
Swale	9.06	.01	11.53	.01	0.11	--	508.05	.01

area (Study site A) have a partial vegetation cover of Bromus tectorum L. B. tectorum is an annual grass which grows as a sod-like ground cover with a less obvious proportion of surface litter. Its most significant area of growth is at transect group A_3 (Figure 3). The trail-edge sites in the Dark Brown Chernozem soil areas have maintained the vegetation cover of native bunchgrasses, although the proportions of exposed soil and litter have increased.

4.1.6 Discussion of Ground Survey Results

The results of the soil surface sampling indicate that ORV activity on the Lac du Bois rangelands caused an increase in bulk density and a decrease in soil moisture and organic carbon. Although the three properties are partially correlated, the combined effect can alter the biological productivity of the soil.

Previous research has studied the effect of changes in bulk density, soil moisture and organic carbon on the condition of the soil and on the establishment and development of vegetation in both qualitative and quantitative terms.

The literature on the effect of soil compaction, or increases in bulk density, on agricultural soils and their plant growth was reviewed by the American Society of Agricultural Engineers (Barnes et al., 1971). The impetus of their study was the realization that the

> "Fundamental knowledge of (1) the behavior of soil when subjected to forces, (2) the effect of the soil's behavior on its suitability as a root environment, and (3) the response of plants to this environment is lacking and is needed." (Barnes et al., 1971, p.iii).

Their monograph discusses soil compactions in both beneficial and detrimental terms and provides qualitative and quantitative information on modifications to soil and vegetation. One detrimental effect

Figure 3. Invasion of Bromus tectorum in a Zone of Secondary Disturbance

The colour-infrared ground photograph of transect group A_3 illustrates the visual contrast between three vegetation species - Agropyron spicatum, Bromus tectorum and Centaurea diffusa. On the date of photography, June 9, 1979, the A. spicatum is represented by the dull brown colour at the top of the hillslope. The B. tectorum has invaded the ORV disturbed soil area of the middle and lower slopes and is a light amber colour. The C. diffusa is the magenta colour occurring as narrow strips along the trail edges of the middle slope.

of soil compaction, stated in the review by Harris (in Barnes et al., 1971) is that heavy compaction will reduce soil water infiltration and increase surface runoff and erosion because when a soil is compressed the pore-size distribution tends toward a smaller proportion of larger pores. A second detrimental effect is that soil compaction results in a decrease of the amounts of nutrients mineralized from the soil organic material (Kemper, Stewart and Porter, in Barnes et al., 1971). Both detrimental effects may be induced by the increase in bulk density caused by ORV activity. Unfortunately their focus on agricultural soils restricts the extrapolation of their quantitative results to the rangeland conditions of the Lac du Bois study area. Also their results are qualified by an indication of the complexity of soil and vegetation interactions.

> "In order to fully understand the reactions of a plant growing in a compacted soil it is mandatory that we first understand physiological requirements of the plant and the responses of the plant to other environmental factors. ... A plant can appear to respond normally as long as all its current needs are satisfied. Since soil compaction can alter the ability of the soil to supply the current needs to the roots and the ability of the roots to absorb these current needs from the soil, soil compaction can effectively restrict plant development. What constitutes an effective alteration to the supplying capability of the root system depends upon the requirements of the plant and the aerial environment." (Trouse, in Barnes et al., 1971).

A search of the literature for information on the ability of range vegetation to meet its growth requirements under compacted conditions indicates a lack of specific knowledge. Studies on the effect of grazing on soil compaction (Beke, 1961; Laycock and Conrad, 1967) did not identify changes in vegetation growth or yield under the compacted soils. Studies on seedling emergence, growth and root development as influenced by compaction (Barton et al., 1966; Fryrear and McCully, 1972) failed to provide information relevant to conditions of ORV compaction. Fryrear and McCully (1972) found that fewer roots grew under each plant and that the grass roots were shallower and with

limited development through the soil profile following compaction by a ten ton road roller. The road roller may have simulated surface compaction similar in magnitude to the ORV trails within the Lac du Bois study area but unfortunately the authors did not report any measurements on the amount of compaction causing the changes. Barton et al. (1966) measured the amount of compaction and found that yield of seed and forage was inversely related to compaction but unlike ORV impact conditions, the compacted layer was four inches below the surface and the surface soil provided a seedbed for the emergence of seedlings without any effects from the compacted soil.

As a result, the literature allows speculation that the Lac du Bois range vegetation will not be able to meet its growth requirements along the ORV trails, but leaves in doubt the seriousness of the measured increase in surface compaction due to ORV activity. Will the soil in study site A, compacted to 1.76 g/cc on the surface 7.5cm fail to provide a seedbed for grass species or restrict their development following an ability to establish themselves on the ORV trail? Can the increase in bulk density be termed damage to future vegetation growth or is it just an impact to existing vegetation?

The changes in the soil moisture and organic carbon values on the ORV trails are a cause and effect situation with the change in bulk density. Negative correlations existed between bulk density and organic carbon. The same effect was measured by Laycock and Conrad (1967) during their study of grazing effects on soil compaction. With the removal of vegetation by ORV activity and a resulting increase in surface soil temperature (Brady, 1974), the organic matter of the soil is reduced. A reduced level of organic matter will reduce the supply of phosphorus, sulphur and nitrogen, will decrease the amount of water a soil can hold and the proportion available for plant growth, and will decrease the supply of energy to soil microorganisms

for biochemical activity (Brady, 1974) which can combine to restrict the development of new plant growth.

The decrease of soil moisture as a result of ORV activity can be attributed to several factors previously mentioned. The compaction of the soil alters the pore spaces which increases surface runoff and reduces infiltration (Rauzi and Hanson, 1966), the removal of vegetation by ORV disturbance exposes the soil which increases the temperature and evaporation (Brady, 1974; Voorhees, 1977), and the reduction of organic matter reduces the ability of the soil to hold water (Brady, 1974). A reduction in soil moisture can be a critical factor to plant growth in the semi-arid grassland region of the study area. Laycock and Price (1970) identified an early seasonal drying of soil under drought conditions as responsible for the early drying and maturing of plants which in turn hastens seasonal changes in chemical composition and reduces the nutritive value of the reduced yield.

In addition to the indirect effect of ORV induced soil changes on vegetation, the direct effects are also important. The initial and most obvious direct effect is the mechanical abrasion of ORVs on vegetation, especially during the senescence period of July and August when the grasses are very brittle and easily damaged. Following the abrasion, wind and water erosion can remove plant and litter material and expose the soil to further erosion.

A second effect on the vegetation, caused by the reduced vegetation cover and vigour and the disturbed soil, is the invasion of undesirable vegetation species. The main invaders in the study area are Bromus tectorum, Centaurea diffusa L. and Centaurea maculosa L. All three species are undesirable for grazing and for the semi-arid region of interior British Columbia, all three have similar invasion habits. From research on the rangelands of interior British Columbia, Watson (1972) characterized the invasion

habits of both Centaurea species.

> "The soil analysis indicates that the Centaurea species readily colonize different soils with a wide range of chemical properties. Plant density of C. diffusa and C. maculosa could only be significantly (P= 0.05) correlated with the degree of disturbance of the soil. The greater the degree of disturbance, the higher the plant density of the knapweed species. These results indicate ... that any soil in the dry interior of the province of British Columbia with a disturbed A horizon is subject to knapweed infestation." (Watson, 1972, p.13).

Watson (1972) also indicated that the ability of Centaurea species to invade disturbed sites and withstand competition from other plant species is attributed to its allelopathic effects. This allelopathic effect and their uselessness as a forage plant reduces their desirability as a useful pioneer species for erosion control and organic matter build up on ORV trails.

The invasion habits of Bromus tectorum were described by Harris (1967) for the rangelands of interior Washington. B. tectorum is not as undesirable as the Centaurea species since it does provide a palatable grazing source early in its growing season prior to the development of its spiny seed awls. Harris (1967) indicated that dominance of B. tectorum on Agropyron spicatum sites is only known to occur as the result of some form of disturbance - which has been provided on the Lac du Bois rangelands by ORV activity. Additional results from Harris' study explains the ability of B. tectorum to maintain itself in study site A, especially transect group A_3, yet it is not as prominent in the other study sites. B. tectorum's growth and reproduction occurs in the late fall to early spring when moisture is not limiting. This allows the B. tectorum roots to exhaust the soil moisture supply prior to the needs of the A. spicatum plants at its later maturity date (Harris, 1967). The ability of the B. tectorum plants to reduce the moisture content of the soil was documented during the ground survey program of this thesis. With reference to Table 9, the average moisture content at trail-edge of transect group A_3, which has the largest invasion of B. tectorum

in all the study sites, was reduced below the moisture content of both the on-trail and off-trail sample points. The invasion of B. tectorum in smaller concentrations in study site C, transect group C_1, which has similar site characteristics as group A_3, may be the result of a greater moisture content due to its location in the middle grassland Dark Brown Chernozem soil great group. The reduced moisture stress on the A. spicatum plants provides greater competition to the invading B. tectorum seedlings.

4.2 Aerial Photograph Interpretation

The visual analysis of the 1971 to 1979 aerial photographs provided a history of the areas of ORV impact on the Lac du Bois rangelands. Table 15 summarizes the increase of ORV trail lengths for each study site. The trails were divided into single and double tracks during the mapping stage, although each trail type does not specify use by only motorcycle or 4-wheel drive vehicles. Many double-track trails began as access roads to various regions of the rangelands but were subsequently adopted as ORV trails. This is shown within the table. The early history of the study sites had higher proportions of double-track trails which have decreased over time with increased activity.

From Table 15, study site A received the earliest ORV activity. Presently it has the greatest length of trails, although no increase in trail length occurred between 1977 and 1979, which was the time period of the greatest increase in trail length for study sites B, C, and D. The history of the increasing popularity of sites C and D is shown in Figures 4, 5, and 6. The figures are reductions of the maps used for trail length measurement and the date sequence illustrates the pattern of ORV trail expansion on the steep hill-climb area of the north facing slope in study site C.

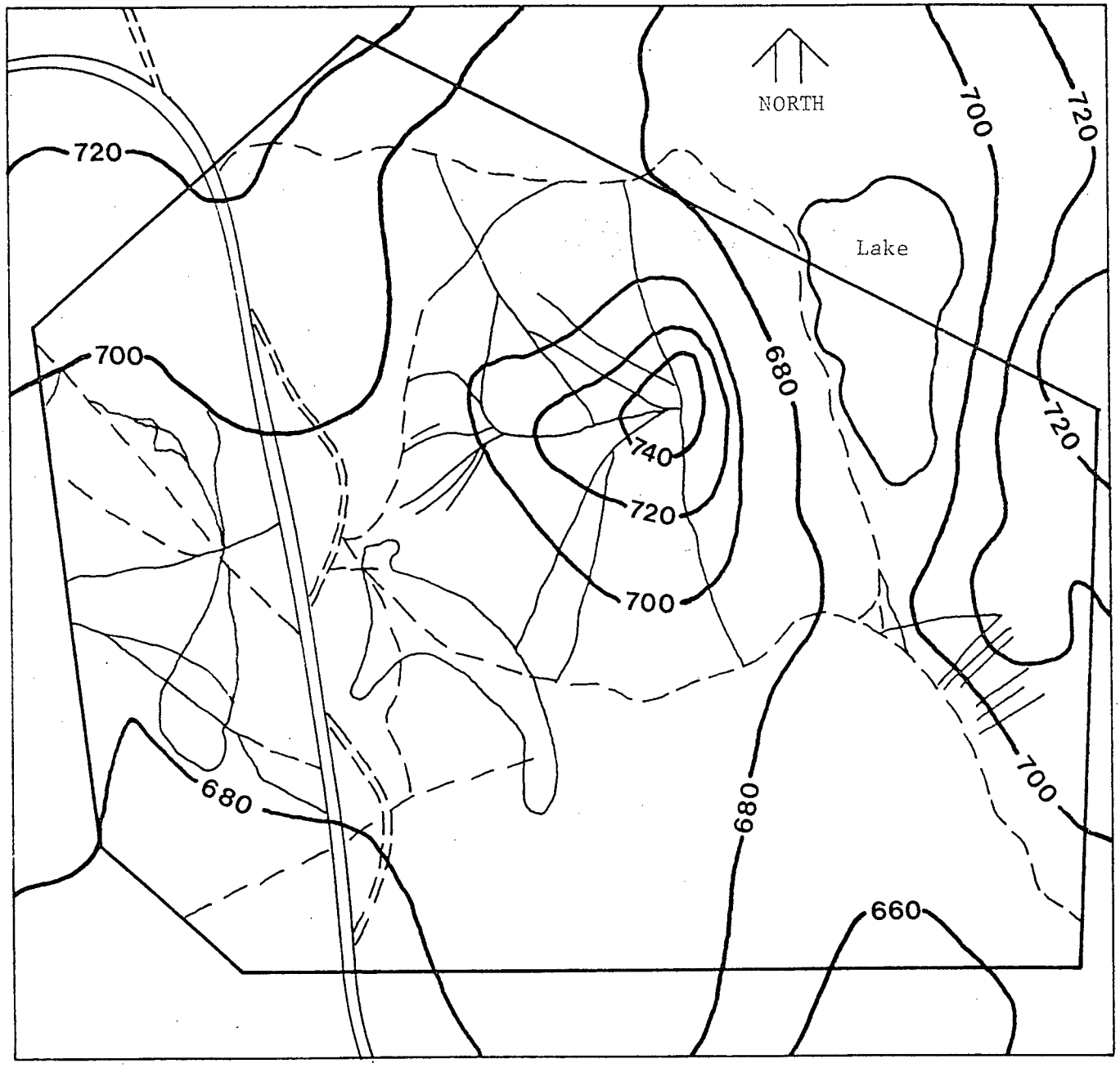
To complement the trail length measurements which do not consider the varying width of the ORV trails, a section of study site A, encompassing

Table 15. Increase of ORV Trail Length (km) - 1971 to 1979

Film Date Scale; Type	Trail Type	Study Site A	Study Site B	Study Site C & D
Aug, 1979 1:4,000 ; CIR	Double	11.4	0.8	1.9
	Single	22.7	19.3	21.7
June, 1977 1:12,000; NC	Double	11.4	3.4	2.2
	Single	22.7	4.0	9.9
June, 1975 1:8,000 ; NC	Double	*	*	3.5
	Single	*	*	6.9
July, 1971 1:12,000; B/W	Double	7.2	0.5	*
	Single	5.9	0.0	*
Study Site Area (km^2)		1.3	1.0	0.8

CIR - Colour Infrared Photographs
NC - Normal Colour Photographs
B/W - Black and White Photographs
* - Aerial Photograph Coverage Not Available

Figure 4. ORV Trails at Study Sites C and D - June, 1975



Scale = 1:7150

Contour Interval = 20m

Area of Aerial Photograph Coverage - 1975, 1977, 1979

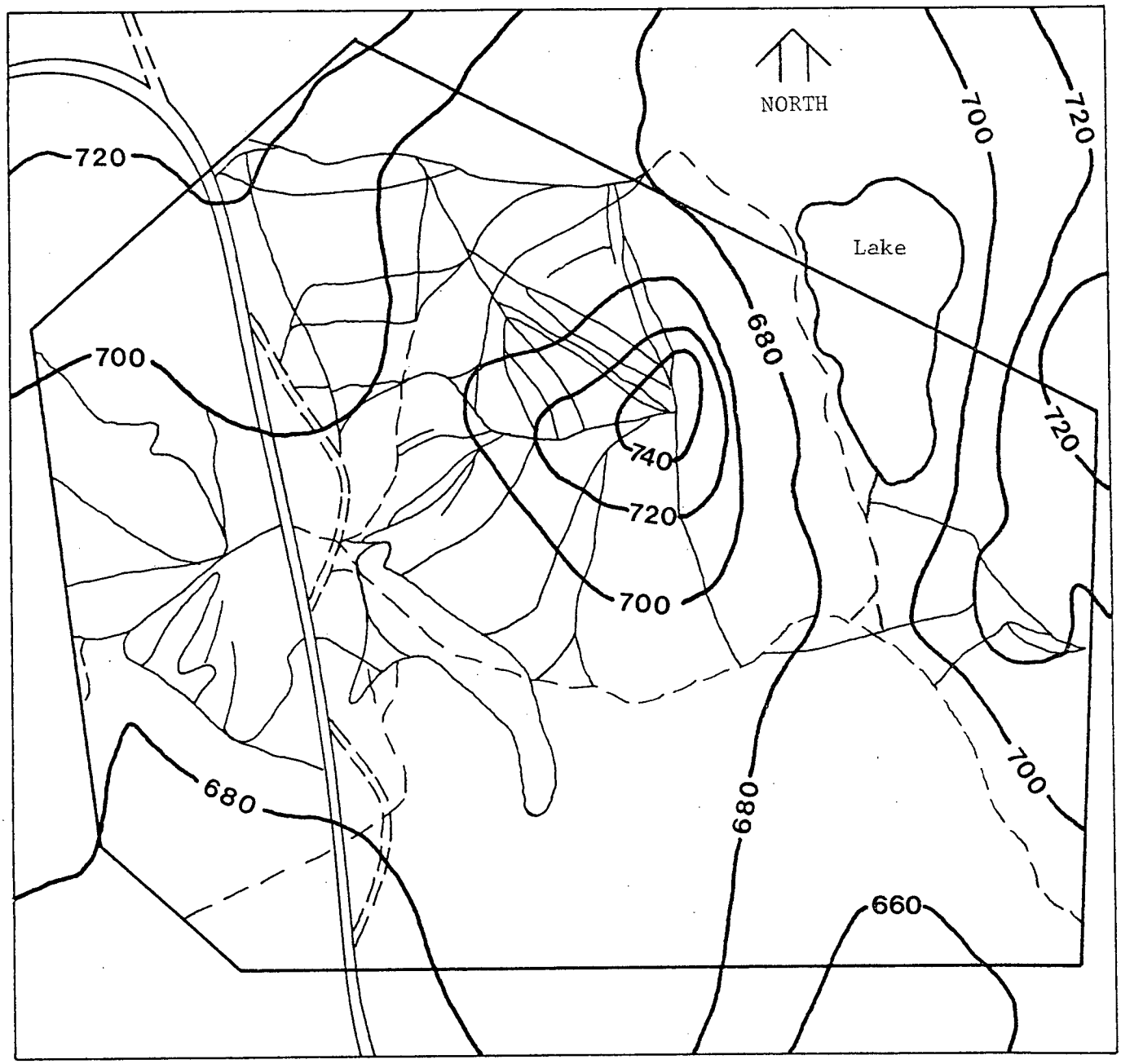
Single Track ORV Trails

Double Track ORV Trails

Access Roads

Main Roads

Figure 5. ORV Trails at Study Sites C and D - June, 1977



Scale = 1:7150

Contour Interval = 20m

Area of Aerial Photograph Coverage - 1975, 1977, 1979

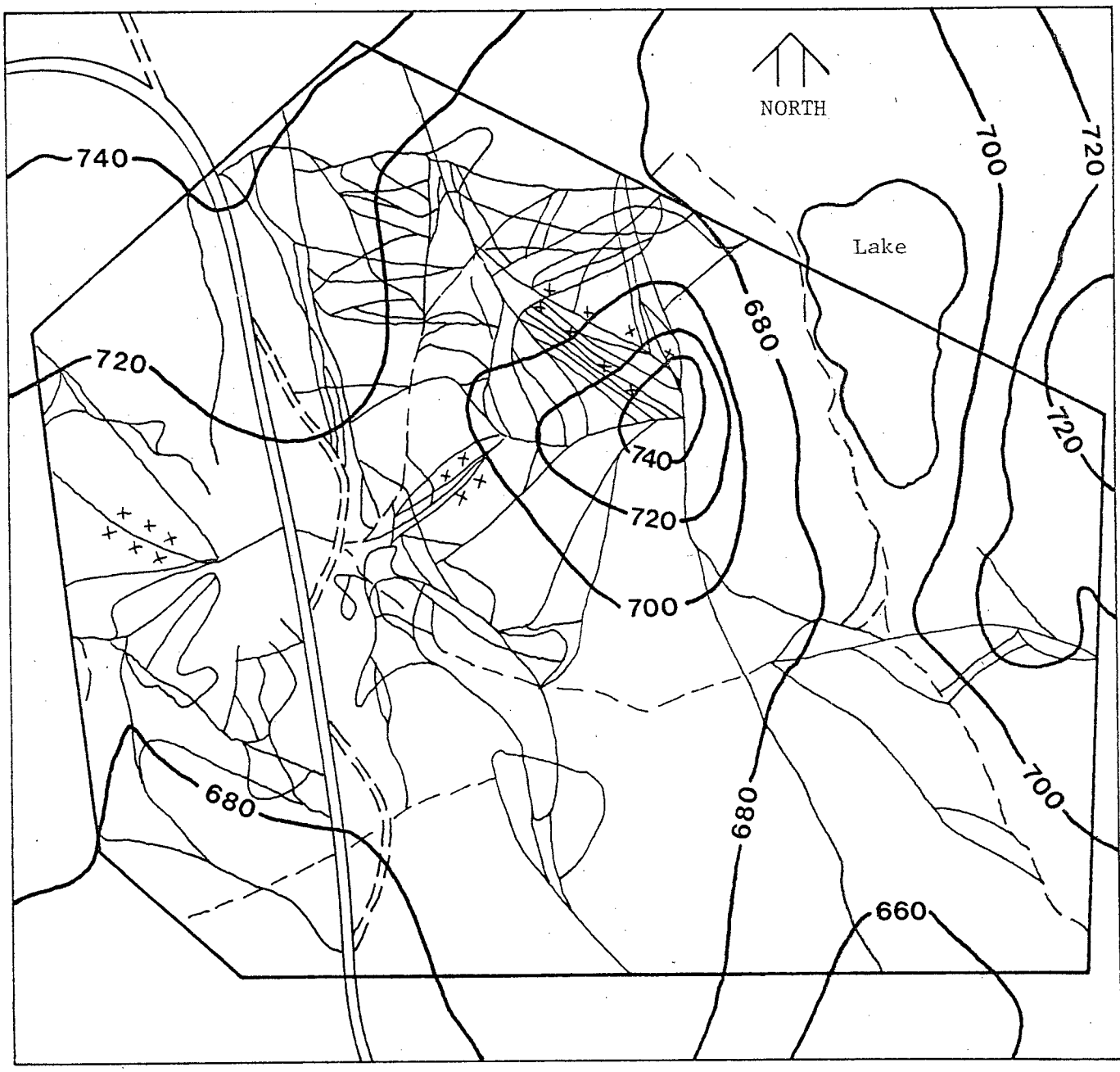
Single Track ORV Trails

Double Track ORV Trails

Access Roads

Main Roads

Figure 6. ORV Trails at Study Sites C and D - August, 1979



Scale = 1:7150

Contour Interval = 20m

Area of Aerial Photograph Coverage - 1975, 1977, 1979

X - 1979 Transect Locations

Single Track ORV Trails

Double Track ORV Trails

Access Roads

Main Roads

transect group A_3, was measured for its area of exposed soil (Figure 7). The dot grid provided a tedious but useful way of measuring the area of exposed soil when the 1:1000 scale aerial photograph was enlarged four times. The enlargement allowed for an easier assessment of exposed soil using a dot grid. The technique can be applied when enlargements are available or when very large scale aerial photographs are available for areas of ORV activity with varying trail widths.

The interpretations of the aerial photographs for vegetation and soil disturbance identified two types of disturbance. The major trails are exposed soil, compacted and with a thin mantle of loess on the surface. They have received the greatest concentration of ORV traffic. The secondary zones of disturbance lie adjacent to or between the major ORV trails and occasionally are major ORV trails which have been abandoned. Not all major trails have a secondary zone of disturbance associated with them. The secondary zones are identified by a trampled appearance of the native vegetation, an invasion of undesirable vegetation species, primarily B. tectorum which is readily visible on the colour infrared aerial photographs as a light yellow to beige hue and also Centaurea species which appear light magenta, plus a rutted soil surface with a reduced litter cover. Ground photographs of transect group A_3, indicates the largest zone of secondary disturbance. This zone is visible on both the 1:1000 and 1:4000 July/August 1979 aerial photographs although not as pronounced as on the June colour infrared ground photograph (Figure 3) which was taken prior to the summer senescence of most grasses. Smaller zones of secondary disturbance are visible on the 1:4000 aerial photographs within study sites A and C, and associated with the hill-climb areas. In study site B the areas adjacent to the major trails and motocross circuit have received considerable impact to the natural vegetation, primarily mechanical abrasion, but it has not resulted in an invasion

Figure 7. Area of Exposed Soil for Transect Group A_3

This photograph is a 1.8 times enlargement of the original 70mm colour infrared aerial photograph which had been enlarged 4.0 times to measure the area of exposed soil using a standard dot grid.

Scale = 1:2470

Date of Photography = July 28, 1979

Area of Exposed Soil = 10,850 m^2

= 16.4 % of the image

of undesirable vegetation species.

4.3 Densitometry

The results of the regression analysis to test the potential of colour infrared photographs to identify variations in ground conditions within areas of ORV activity are shown in Table 16. The R^2 correlation coefficients of regressing the soil physical parameters versus the optical density values and their ratios are listed for each data set group.

For the entire data set, poor correlations, R^2=.247 and R^2=.397, existed between the soil physical parameters of bulk density and organic carbon and the optical density values, with only a slightly better correlation, R^2=.583, existed for the moisture content values.

Grouping of the data set by on-trail, trail-edge and off-trail sample points improved the correlations. Bulk density consistently had the lowest correlation coefficients and the moisture content maintained the better correlation values from the initial analysis of the entire data set. Both moisture content and organic carbon had the best correlation at the off-trail sample points. This result does not support the use of densitometry for ORV areas because the information is most needed for on-trail conditions. In addition, there was no consistent selection of highly correlated optical density values in the regression analysis. A second approach to grouping the data set was tried in an attempt to improve the on-trail correlations.

The data was grouped according to study site but the analysis was restricted to study site B. The choice of study site B was based on the exposure curves on the colour infrared film (Figure 8). The film had been slightly overexposed, with the result that the average optical density values for each study site are not on the straight line portion, but near the toe of the log exposure curve. The range of optical density values for study sites A,

Table 16. Regression Analysis - Soil Physical Variables versus Optical Density

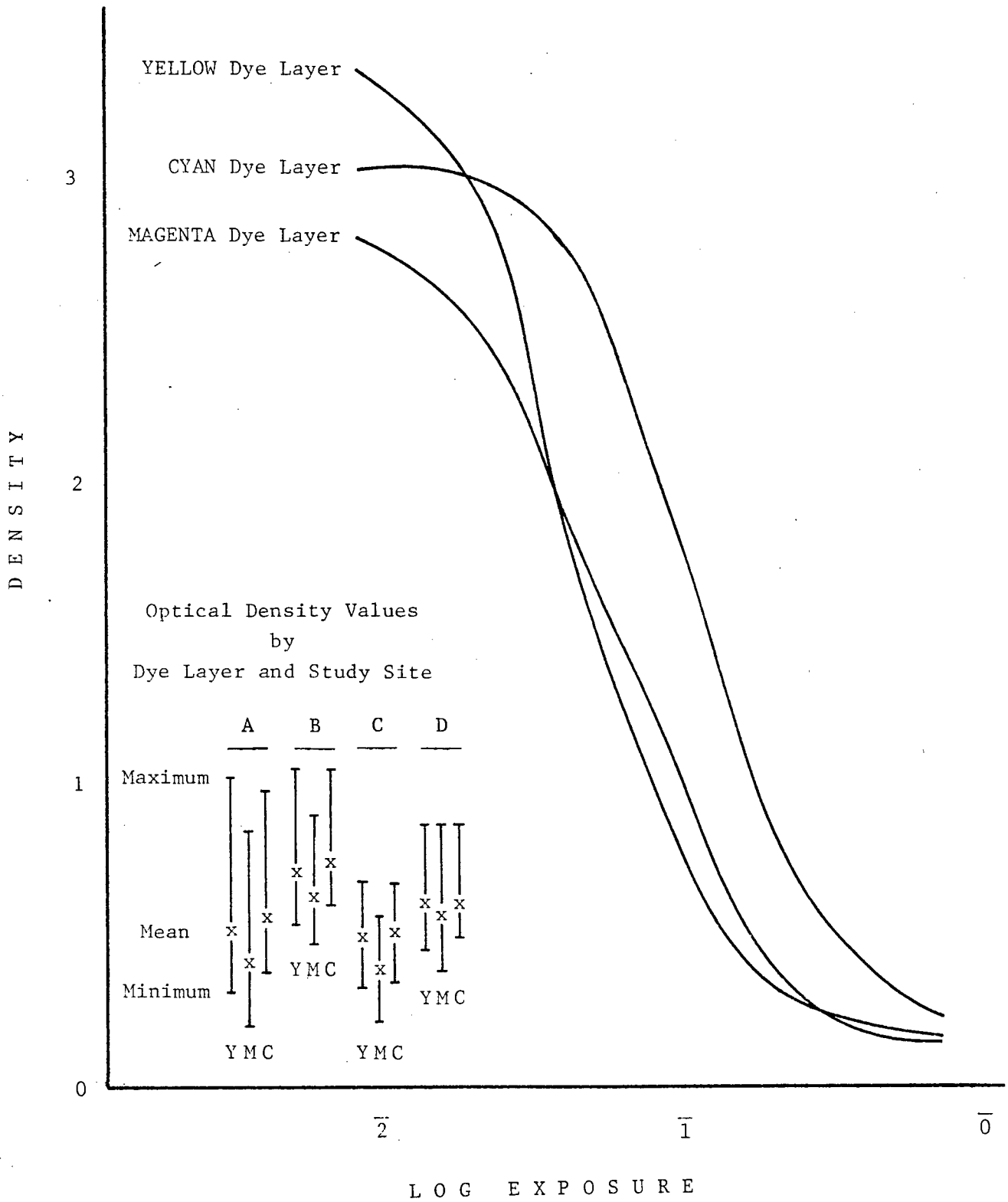
Data Group	N	Soil Physical Variables: Bulk Density R^2	Bulk Density: Signif. Density Values	Soil Moisture R^2	Soil Moisture: Signif. Density Values	Organic Carbon R^2	Organic Carbon: Signif. Density Values
All	149	.247	Y, M, M/Y, C/M, C/Y.	.583	Y, M, C.	.397	M, C, M/Y, C/Y.
On-Trail	50	.367	Y, M, C, M/Y, C/M.	.370	Y, M, M/Y, C/M.	.349	M, C, M/Y, C/M, C/Y.
Trail-Edge	70	.187	C/M.	.588	Y, M, M/Y, C/M.	.345	M/Y, C/Y.
Off-Trail	29	.356	C/Y.	.841	Y, M, C/Y.	.667	Y, M, M/Y, C/Y.
Study Site B	33	.473	M, M/Y.	.718	C, C/Y.	.842	C, M/Y, C/M, C/Y.

Y - yellow dye layer of the colour-infrared film; sensitive to reflected energy in the green spectral region of the electromagnetic spectrum.

M - magenta dye layer of the colour-infrared film; sensitive to reflected energy in the red spectral region of the electromagnetic spectrum.

C - cyan dye layer of the colour-infrared film; sensitive to reflected energy in the near-infrared spectral region of the electromagnetic spectrum.

Figure 8. Exposure Curves of 1:1000 70mm Colour-Infrared Aerial Photograph - July 28, 1979



C, and D are nearest to the toe of the log exposure curve where the reduced optical density of the film prevents relating the film density to the spectral reflectance and hence to the physical ground data variables. Study site B has a range of optical density values farthest from the toe of the exposure curve. It has the greatest potential for relating the film density to the physical ground data variables and also has the largest sample size along a single ORV trail.

Correlations did not consistently improve when the study site B on-trail and trail-edge sample points were analyzed. A possible explanation was identified from the ANOVA for the six optical density values and the three soil parameters (Table 17). The ground survey program for both bulk density and organic carbon had significant changes between on-trail and trail-edge conditions but there were no significant differences between the on-trail and off-trail optical density values, despite the presence of vegetation on the trail-edge.

The analysis for correlations between soil variables and optical density values failed to provide consistent results. Although the correlations for soil moisture and organic carbon did improve with the analysis of only study site B, it is difficult to provide positive concluding statements on the usefulness of the approach. The major drawback of the analysis is the over-exposure of the aerial photographs which limited the useful sample size to one of the four study sites. Another limiting factor to the success of identifying variations in soil conditions following ORV activity is the soil type of the study area. Although the aerial photographs were acquired during the period of grass senescence when the effect of vegetation on soil reflectance was minimized (Siegal and Goetz, 1977), the highly reflective nature of the air-dried silt portion of the rangeland soil effectively masked the within soil variations.

Table 17. ANOVA - Study Site B

Variable	N	Sample Point		ANOVA	
		On-Trail	Trail-Edge	F	Signif.
Bulk Density	33	1.45	1.01	32.74	.01
Soil Moisture	33	4.58	4.67	0.02	--
Organic Carbon	33	3.15	4.00	5.96	.01
Yellow	33	0.733	0.675	1.17	--
Magenta	33	0.632	0.598	0.40	--
Cyan	33	0.748	0.714	0.57	--
$\frac{\text{Magenta}}{\text{Yellow}}$	33	0.865	0.888	0.79	--
$\frac{\text{Cyan}}{\text{Magenta}}$	33	1.189	1.197	0.01	--
$\frac{\text{Cyan}}{\text{Yellow}}$	33	1.029	1.064	0.63	--

The densitometric approach should not be discounted without an additional analysis using properly exposed photography and at a time period when the soil is not completely air-dried. The analysis of study site B indicates a potential for densitometry to identify variations due to soil moisture and organic carbon and the correlations to bulk density, which is the most significant effect of ORVs, may also improve to a more acceptable level.

5.0 RECOMMENDATIONS

5.1 ORV Monitoring Program

5.1.1 Introduction

The procedures and results of this thesis research, and the modifications developed during the field research and from other recent research, can be drawn together to form a method for monitoring ORV impacts to soil and vegetation. The most efficient format utilizes the remote sensing multistage sampling approach to collect data as a continuum from the general to the specific.

5.1.2 Stage I

At stage I, large-scale aerial photographs can provide information on the condition of an entire study area plus allow for mapping and measuring the length of all ORV trails within and out of specific study sites. New areas of ORV activity can be identified in order to allow designation of additional study sites. The selection of an aerial photograph scale for monitoring is a management decision which should be governed by considerations of the optimum scale for maximum information content versus the cost of the aerial photograph acquisition. Decreasing the scale of the aerial photographs to reduce the cost will limit the resolution. This governs the ability of the interpreter to identify new ORV trails which have received only minimum traffic and serve as starting points to major trails. Also affected is the ability to identify new areas of invading undesirable vegetation which are easiest to control at the early stages of competition for dominance.

An entire range of film scales, types and dates were used during this research to compile a history of ORV activity on the Lac du Bois rangelands. Many ORV trails were visible on colour-infrared aerial photographs at the small scale of 1:63,360 because of the spectral contrast between the

exposed soil on the ORVs and the off-trail vegetation.

For the Lac du Bois study area which experiences an annual midsummer dry period and grass senescence, the optimum date for aerial photographic interpretation of ORV trails with colour-infrared film is June. The healthy undisturbed native grasses are approaching maturity and a contrast exists among the unhealthy, damaged or dead native grasses, the invading annual grasses such as Bromus tectorum which has begun its period of summer dormancy, and the areas of exposed soil which have not reached the highly reflective air-dried period of midsummer.

The selection of June as the optimum date differs from the aerial photographs acquired at the end of July for this study. The 1979 choice of dates was an attempt to reduce the effect of vegetation on the soil reflectance properties and to reduce the cost of aerial photograph acquisition with a multiple use approach. Unfortunately the slight overexposure of the film and the lack of contrast between the air-dried silts and the dormant vegetation reduced the usefulness of the aerial photographs. The selection of June is based on the information content of the colour-infrared ground photographs taken during field reconnaissance for this research, on the information content of the existing June aerial photographs for the study area, on the recommendations by Watson (1977) for vegetation species identification, and on the recent research by Leininger and Payne (1980) that selected June as the best time of colour-infrared photography to identify ORV trails which had received only light use during a controlled traffic experiment.

The selection of 1:4000 as an optimum scale for ORV trail monitoring was based on the interpretation experience of mapping the ORV history of Lac du Bois with 1:4000, 1:8000 and 1:12,000 aerial photographs. The resolution of the 1:4000 aerial photographs permitted easier and more accurate identification of the secondary zones of ORV disturbance, plus the scale

is large enough to allow the mapping of most secondary zones of disturbance within the cartographic limits of the aerial photographs. The choice of scale is also supported by research testing the information content of medium to large-scale aerial photographs. For vegetation identification and classification on the Lac du Bois rangelands, Watson (1977) recommended 1:10,000 scale aerial photographs for vegetation mapping but indicated that 1:4000 scale was required for species identification. The recent work on ORV trail identification on Montana rangelands by Leininger and Payne (1980) found that 1:6000 colour-infrared aerial photographs could detect disturbances to vegetation after eight trips along a single trail but the resolution limited the identification of two trip trails. Aird (1980) matched the aerial photograph ground resolution to surface features and correlated this to the aerial photograph scale. The result is the recommendation of aerial photograph acquisition from a 600 metre altitude above ground level (0.16m ground resolution or approximately 1:4000 scale) for monitoring environmental impacts from pipeline construction.

> "For environmental monitoring, a minimum ground resolution of 16cm is essential in order to obtain sufficiently detailed coverage. This degree of ground resolution ensure that vehicle tire tracks, erosion gullies, stones or any larger feature would be recorded and could be interpreted. Any increase in altitude would result in the loss of detail essential to provide the required information." (Aird, 1980, Appendix I).

The utilization of the 1:4000 scale colour-infrared aerial photographs for monitoring changes in ORV trails does not require that all identifiable trails be mapped and measured, due to the potentially enormous nature of the task. Mapping of major trails and providing sequential aerial photographs as a permanent record of changes to the minor trails, through development to major trails, invasion of undesirable vegetation or recovery would be an efficient utilization of the aerial photographs. The use of smaller-scale aerial photographs to map the major trails would restrict the

monitoring of the minor trails.

5.1.3 Stage II

At stage II of the monitoring system, very large-scale aerial photographs can provide more detailed information on the study sites within the study area. Recommendation of 1:600 scale 70mm normal colour or colour-infrared aerial photographs is based on the previous research on rangeland inventory and indirectly supported by the 1979 70mm aerial photographs. Tueller and Booth (1975) evaluated several aerial photograph scales larger than 1:1000 and found that 1:600 scale sequential aerial photographs in stereo pairs could be used to detect and inventory soil movement and evaluate erosion conditions. The 1979 1:1000 scale 70mm colour-infrared aerial photographs of the study sites at Lac du Bois were at the limit of acceptable resolution for erosion evaluation under conditions of good contrast (Tueller and Booth, 1975). Unfortunately the slight overexposure and date of photography resulted in poor contrast on the 1979 aerial photographs and prevented the evaluation of erosion conditions associated with the ORV activity areas on the Lac du Bois rangelands. Acquisition of June aerial photographs at 1:600 scale will allow for erosion evaluation with Tueller and Booth's (1975) method (Appendix A) and the provision of a permanent record of the changing conditions.

The inclusion of this stage of data collection in a method which should attempt to provide information with a minimum of expense is based on the efficiency of data collection using remote sensing. Both Tueller and Booth (1975) and Aird (1980) assessed the costs of data collection from ground survey and from large scale aerial photographs and concluded that remote sensing was considerably less expensive and provided a permanent objective data source. The actual acquisition of the aerial photographs for open lands in British Columbia could be accomplished at a reduced cost by coordination with

the new forest and range inventory program developed by the British Columbia Ministry of Forests (1979). The inventory program proposes to use a remote sensing multistage sampling program which includes as its stage II, collection of very large-scale (1:200 to 1:1000) fixed base 70mm aerial photographs. Photography of selected ORV study sites during the flights to or from the forest sampling sites would be the most cost effective data collection method for any ORV research.

5.1.4 Stage III

The third stage of the monitoring program is ground data collection within each study site. The sample sites should be based on ORV management plans, and the sample sites could represent areas of active ORV use, restricted ORV use and areas closed to ORVs to allow for soil and vegetation recovery. Following the procedures of the ground survey for this thesis, information on soil erosion, soil condition and vegetation cover is collected.

The erosion transects should be permanently located along an ORV trail representative of conditions in the study site. Each transect should represent a section of slope along a single trail and be used to provide quantitative measurements which can be used in conjunction with erosion evaluations and measurements from the stage II large scale aerial photographs.

The soil condition measurements should maintain a monitoring program of bulk density, soil moisture and organic carbon for the surface horizons. The date of measurement should still coincide with the acquisition of the aerial photographs but should also be tested for variations due to sampling date, such as the monthly sampling schedules of Leininger and Payne (1980). This sampling schedule would provide quantitative data on the applicability of the soil compaction principles (Appendix B) to specific study site conditions. Some of the principles relating compaction to moisture con-

tent, organic carbon, texture and initial density should be tested and used by management to control ORV activity at specific times of the year when maximum impact from ORV activity would occur.

The vegetation survey should continue to provide information, regarding vegetation type and surface proportions of vegetation, litter and bare soil for improving the accuracy and reliability of the aerial photograph interpretation for soil and vegetation conditions. Ground photographs, preferably stereo pairs, are an efficient method for vegetation cover surveys of grasses and also provide permanent records of changes along the permanent erosion transects. The existing aerial photographs should be used as a reference to ensure that the transects extend far enough from the trail to reach the undisturbed range areas. Difficulties were experienced during the field research of 1979 in locating the most appropriate undisturbed vegetation site near the ORV trail while standing on the ground. Attention should also be given to locating sample points to record the edge effects of the major ORV trails, since the edges of trails can migrate away from the trail centre with increased ORV activity or towards the trail centre with revegetation encroachment.

5.1.5 Summary of ORV Monitoring Program

As a summary, the recommended procedure for monitoring ORV activity on open lands includes three stages of information collection. Stage I utilizes 1:4000 June, colour-infrared aerial photographs to provide an overview of the study area and permit mapping and measuring ORV trail lengths and zones of secondary disturbance. Stage II utilizes 70mm 1:600 scale June, normal colour or colour-infrared aerial photographs for detailed information of specific study sites and specifically the evaluation of changes in their erosion conditions. Stage III is the ground data collection to

support the interpretation of both stage I and II aerial photographs and to provide quantitative measurements of the volume of soil erosion, changes in the soil variables of bulk density, soil moisture and organic carbon, and changes in the surface vegetation cover proportions.

5.2 ORV Impact Condition Scale

The purpose of developing an impact condition scale is to draw together the information collected by the monitoring program for use at a rangeland management level. The impact condition scale can be used to maintain an inventory of the conditions within each of the three popular ORV management units: open, restricted, and closed.

The scale was developed from the ideas of an impact condition scale for improving the management of wilderness campsites (Merriam et al., 1973; Frissell, 1978). Frissell (1978) identified a pattern of change within a campsite as it deteriorated with increasing use, and provided suggestions of possible management actions at each of five condition classes. The earlier approach by Merriam et al. (1973), which Frissell (1978) had simplified, is more applicable to the quantitative approach developed as the ORV monitoring program. Merriam et al. (1973) measured changes in five campsite conditions. Each of the five conditions were rated on an impact stage value of 1 to 5 and the average stage value score determines the impact stage, I to V.

The ORV impact condition scale (Table 18) was developed for measurement indicators within the monitoring program. Each of the five indicators represent measured changes from an undisturbed off-trail location. The 1:4000 stage I aerial photographs can be used to identify homogeneous units within the study area and the monitoring system procedures used to assess the ORV impact condition within each unit.

Table 18. ORV Impact Condition Scale

	Measurement Indicators				
	Length of ORV Trails per km^2 (b)	Area of Secondary Disturbance % per km^2 (c)	Erosion Condition Class (d)	Percent Increase in Bulk Density (e)	Percent Decrease in Organic Carbon (f)
Impact Stage Value (a)					
1	0.0-4.9	0.0	Stable	0.0	0.0
2	5.0-9.9	0.1-2.9	Slight	0.1-4.9	0.1-4.9
3	10.0-17.9	3.0-9.9	Moderate	5.0-14.9	5.0-19.9
4	18.0-24.9	10.0-24.9	Critical	15.0-29.9	20.0-39.9
5	25.0 +	25.0 +	Severe	30.0 +	40.0 +

(a) Add the stage value scores of all measurement indicators used. The average stage value score determines the Impact Stage.

Impact Stage	Average Impact Stage Value
I	1.0-1.99
II	2.0-2.99
III	3.0-3.99
IV	4.0-4.59
V	4.6-5.00

(b) Measured on Stage I, 1:4000 Colour-Infrared aerial photographs.

(c) Measured on Stage I, 1:4000 Colour-Infrared aerial photographs.

(d) Assessed from Stage II, 1:600 aerial photographs using Tueller and Booth's (1975) methodology (Appendix A); or assessed from soil erosion transects.

(e) Measured during Stage III ground survey as the difference between on-trail and off-trail sample points.

(f) Measured during Stage III ground survey as the difference between on-trail and off-trail sample points.

6.0 SUMMARY

The Lac du Bois rangelands have become a popular area for ORV recreation activities. The resulting environmental impacts to soil and vegetation has forced management agencies to develop policies to attempt to control the activity and reduce its impacts.

Proper policy development and subsequent revisions to meet changing conditions requires a monitoring program which can assess the extent and degree of ORV impacts. An ORV monitoring program for the open lands of British Columbia has been developed from the conditions on the Lac du Bois rangelands. The monitoring program utilizes the remote sensing multistage sampling approach and has three stages of information collection. Stage I uses 1:4000 scale aerial photographs to identify and map ORV trails within a study area. Stage II assesses the erosion conditions within selected study sites and stage III collects ground information to assist the aerial photograph interpretation of stage I and II and to provide quantitative measures of the changes to selected soil and vegetation variables.

Based on the information measured by the monitoring program, an ORV impact condition scale was developed. The simple five point scale provides a summary of the varying impact conditions within a study area. The scale can be used at a management level to assess general changes in the condition of areas designated either open, restricted, or closed to ORV traffic.

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APPENDIX A

Erosion Evaluation From Aerial Photographs

P.T. Tueller and D.T. Booth, 1975

The methodology developed for erosion evaluation defines and explains erosion and erosional terms and ratings with special reference to their detection and interpretation on large scale aerial photographs.

Seven soil surface factors are used to determine the erosion condition class. Each factor is rated according to its characteristics which are identified and/or measured on the aerial photographs. The sum of the seven ratings determines the erosion condition class. The seven factors and their rating scales are shown in the table below.

Erosion Condition Class

	Stable*	Slight	Moderate	Critical	Severe
Bare Ground	5% or less Rating 3	10 15 20 4 5 6	30 40 45 7 8 9	50 60 65 10 11 12	70 75+ 13 14
Vesicular Crust	None 0	Some present but <5% 4-5	5-10% 11-20% 6-7 8-9	21-40% 10-11-12	Above 40% 13-14
Litter	No movement <4	Slight movement 4 5 6	Deposited 7 8 9	Extreme movement 10 11 12	Little remaining 13 14
Wind Erosion		Bare ground 6	Some drifting 7 8 9	Active drifts 10 11 12	Active sand dunes 13 14
Flow Patterns	No erosion <4	Removal and/ or disposition 4 5 6	Moderate soil movement 7 8 9	Movement occurs w/ each event 10 11 12	Becoming channeled or large Barren Fans 13 14 15
Rills	No rills 0	1 interval > 50 ft. 4 5 6	interval 20-50 ft. 7 8 9	interval 5-20 ft. 10 11 12	interval < 5 ft. 13 14
Gullies and S.C.	Stable condition 3	Some erosion 4 5 6	<10% 7 8 9	10 to 50% 10 11 12	>50 Headcutting 13 14 15

*Stable - an erosion condition class of "stable", does not mean the range is in stable condition; it means as far as can be detected from the photography there is no recent erosion.
Erosion Condition Classes: Stable 0-20; Slight 21-40; Moderate 41-60; Critical 61-80; Severe 81-100

APPENDIX B

Soil Compaction Principles By

H.W. Lull, 1959 (p.25)

- The amount of compaction will depend on the degree to which the stress applied to the soil overcomes the resistance the soil offers to deformation.
- The resistance that the soil offers depends on its moisture content, texture, structure, density and organic content.
- As this resistance is overcome, the effect is to pack individual soil particles closer together and to crush soil aggregates, thus reducing pore space.
- Resultant additional solid materials per unit volume increase the resistance of the soil to deformation to a point where resistance and stress are in equilibrium and no further compaction occurs.
- As soil moisture content increases, resistance to stress decreases and compaction can be acheived with progressively reduced loads.
- Maximum density is obtained at a moisture content about midway between field capacity and wilting point.
- Increasing moisture content beyond that point further lowers the resistance to compaction and reduces the maximum density.
- Soils that have the greatest range of particle-size (i.e., medium-textured soils) compact to greatest densities, finer particles filling the voids between coarser particles.
- The less dense the soil, the greater opportunity for compaction.
- The greater the organic content, the smaller the maximum compaction and the greater the moisture content required for maximum compaction.
- Soil freezing tends to compact soil by breaking down water-stable aggregates and tends to loosen compacted soils.
- Duration of compaction depends largely on the stresses the soil undergoes by swelling and shrinking from changes in moisture content and temperatures.
- Compaction increases bulk density, reduces total pore space by the same proportion, reduces noncapillary pore space a greater amount, and has its greatest effect on infiltration and percolation.