

Chapter 2 – Literature Review

Biophysical Remote Sensing Applications in Arctic Environments

2.1 Botany and Vegetation Communities

Arctic tundra vegetation comprises a mosaic of plant communities, usually compact, wind-sculptured, and less than one metre in height (Stonehouse, 1989). Lichens and mosses are prominent growth forms, but tundra communities also include shrubs, sedges, grasses, and forbs (flowering herbs other than grasses). Community composition varies in relation to soil, aspect in relation to sun, drainage, length of snow-cover, and other variables. In other words, the richest soils occur in warm, sheltered spots, providing an environment where tundra can form lush meadows, thickets of tussock grasses, and low shrubs. The poorest soils occur on rocky areas in harsh, unsheltered environments, where only a thin layer of vegetation is able to survive (Stonehouse, 1989).

2.1.1 Sedge meadows

The sedge meadow may be considered the most typical tundra vegetation (Young, 1994). It occurs on almost any flat/rolling terrain in tundra sub-zones 2 – 4 (Appendix 2), and is dominated by a mat of grass-like sedge plants (Young, 1994). This vegetation community becomes increasingly fragmented in more extreme northern areas, but even there it will be the rare greenness amongst exposed rock and gravel. While these communities may be easily distinguished, the “identification of the great majority of grasses, sedges, and rushes, in the Arctic as everywhere else, is not practicable in the field except by people already familiar with them.” (Pielou, 1994, 179) There are over 100 species of sedges recorded in the Northwest Territories (Burt, 1991) and they are often confused with grasses and rushes. The number of grass species, along with the intense technicality required for adequate identification, is deemed overwhelming even by Burt (1991) and is thus minimally

documented in her book. This is a definite consideration when attempting to grasp the diversity of arctic flora, and thus aids in delimiting boundaries of detail in vegetation descriptions. Mainly floral families and genera are identified because of the reality that many of the species within a particular genus maintain such subtle differences that only experienced botanists could endeavour to distinguish species. This is an acceptable constraint as it is considered both impractical and unnecessary for this particular investigation.

2.1.2 *Shrub tundra*

The vegetated tundra shrub cover may range in height from 5cm in the prostrate dwarf-shrub sub-zone to 80cm in the low shrub sub-zone (Walker, 2000) (Appendix 1). Young (1994) characterizes the basic components of this shrub layer as including willow, dwarf birch, and heath, with the relative importance of each varying, but generally dominated by one vegetation type.

Riparian willows are found to follow the smallest tundra rivulets, generally becoming progressively lower in growth as streams become smaller (Young, 1994). When the heads of the streams eventually merge with overall tundra, the low willow shrubs may spread out resulting in hybrid vegetation between riparian willow and tussock tundra. Willows belong to the *Salix* genus (*Salicaceae* family) and display habitat preference variability among plant gender, i.e., females are usually found in moist, fertile, sheltered sites (greatly outnumbering males), whereas males are found in dry, exposed habitats (only slightly outnumbering females) (Pielou, 1994). These plants hybridize frequently, thus making identification difficult and requiring local floral guides for detailed consultation (Burt, 1991).

Heaths belong to the huge, worldwide family of *Ericaceae* (Young, 1994). Although this family is huge and diverse – including such familiar plants as rhododendrons, azaleas,

manzanita, heather, blueberry, cranberry, and mountain laurel – there are many shared characteristics and adaptations that make this group quite well suited to colonize cold acid bogs and tundra areas (Young, 1994). The majority of these species do not extend north of the erect dwarf-shrub sub-zone, but the few that do are usually found in stony uplands far beyond the timberline (Young, 1994; Pielou, 1994). Most heath plants closely associate with *Sphagnum* moss, both tending to invade tussock fields when moisture is abundant and fires have not occurred for long periods of time (Young, 1994). Some of the most commonly found genera and species of the heath family are outlined in Appendix 3.

2.1.3 *Fell field*

Young (1994) describes the term fell field as being applicable to any stony tundra area where vegetation is thin and discontinuous. Originating from the Norse word *fjell* – stony mountain slopes – fell fields usually supplant heath tundra and tussock tundra in the drier areas along a moisture and exposure gradient (Young, 1994). Among the *Dryas* genus there are a variety of species, but they are essentially a dwarf, creeping, slightly woody shrub in the rose (*Rosaceae*) family. These are so typical of fell field areas that they are almost synonymous (Young, 1994). *Dryas* is also a good indicator of calcium as it grows on calcareous soil, forming mats on gravelly, well-drained soil in areas scoured by steady winds (Burt, 1991). Also referred to as mountain avens, this flora grows in tightly interwoven mats that act as soil stabilizers (Burt, 1991), but should not be confused with plants properly referred to as avens, belonging to the *Geum* genus (Pielou, 1994).

2.1.4 *Polar desert*

A polar desert is essentially an extreme form of fell field, usually composed of barren areas of bare rock, shattered bedrock, and sterile gravel (Young, 1994) where only a thin, patchy covering of plant life is found (Pielou, 1994). The vegetation cover has seemingly

been reduced to near zero; however, it is difficult to find a square meter of polar desert that is absolutely devoid of any form of vegetation growth (Young, 1994). The vegetation that is present forms a single thin layer, where cryptograms, including algae, lichens (Appendix 4), mosses (Appendix 5), and hepatics, dominate and are increasingly important with increasing latitude (Pielou, 1994).

2.1.5 Landscape patterns and characteristics affecting vegetation distribution

Various landscape spatial characteristics such as tundra polygons (Appendix 6, Figure 1 & 2), and tundra hummocks (Appendix 6, Figure 3), are often called “patterned ground” (Pielou, 1994). Alternate freezing and thawing cause these particular formations, and they develop best in ground where vegetation is sparse or absent (Pielou, 1994). Arctic environments, especially polar desert where colourful flowers are scarce, must not be confused with environments that are devoid of any activity. Some of the most common patterned ground designs are outlined in Appendix 7. It is also important to note the potential effects that permafrost, tundra polygon formation, tundra hummocks, and microtopography may play on the distribution, formation, and composition of vegetation communities (Appendix 6) – all of which influence the available moisture regimes upon which community development are so dependent (Appendix 8).

These general botanical and vegetation community characteristics are important to keep in mind while examining the following sections relating to remote sensing and vegetation spectral response trends. The unique tundra landscape, low stature vegetation, and adherence to microtopographic regimes all impact the manner in which satellite imagery, surface spectra, and vegetation indices may be interpreted.

2.2 Background on Environmental Remote Sensing in Polar Regions

Arctic tundra landscapes are characterized by multiple scales of spatial heterogeneity (McFadden *et al.*, 1998). These characteristics make them particularly challenging for remote sensing studies as well as for the design of appropriate sampling methods necessary to capture the small scale variability inherent in tundra vegetation studies. Arctic regions such as coastal plains, polar deserts, or arctic foothills are defined by climatic and hydrological influences, and may extend over hundreds of kilometers (McFadden *et al.*, 1998). Each region may be deemed a mosaic where vegetation types are found at scales ranging from 100m to 1km; while microsite variations may occur within centimeters to meters (e.g., changes in relief due to hummocks and frost action in tussock tundra) (McFadden *et al.*, 1998). Hence, spatial variability must be considered when designing sampling methods for relating field data to remote sensing images (e.g., Landsat TM with 30m spatial resolution).

Further considerations, translating into demands for efficient sampling methods, are: the expense of logistical support, the short Arctic growing season, and the inaccessibility of many northern locations (Lévesque, 1996). All things considered, large-scale vegetation diversity and abundance assessments are difficult endeavours due to short visitation time and costly field excursions, emphasizing the critical importance of accurate, efficient, and affordable sampling protocols (Lévesque, 1996) when planning *in situ* data collection for remote sensing data analysis. These same constraints form support for the utility of remotely sensed data acquisition. Remote sensing data, available at a range of spatial and spectral resolutions, offer significant potential for observing, investigating, and analyzing biophysical properties of vegetation at various landscape scales (Tieszen *et al.*, 1997). Remote sensing data may provide continuous spatial coverage of vegetation and terrain

patterns (Stow *et. al.*, 2000). In polar regions, remotely sensed data have shown potential, depending on sensor capability, to: i) provide baseline information necessary to delineate vegetation communities (Hope *et. al.*, 1995; Spjelkavik, 1995; Rees *et. al.*, 1998); ii) outline vegetation spatial distribution (Walker *et. al.*, 1982; Stow *et. al.*, 1989; Mosbech and Hansen, 1994; Rees *et. al.*, 1998; Muller *et. al.*, 1999); iii) provide a means of estimating above-ground biomass (Hope *et. al.*, 1993; Shippert *et. al.*, 1995; Spjelkavik, 1995; Walker *et. al.*, 1995); and iv) provide input into ecological models (Stow *et. al.*, 1993b; Ostendorf and Reynolds, 1998; McMichael *et. al.*, 1999).

2.3 Satellite Sensors

Optical satellite sensors are often employed for studying various vegetation parameters, regardless of latitude. Rees *et. al.* (1998) highlight several recent investigations showing the usefulness of satellite optical data (e.g. Landsat MSS, TM, and SPOT HRV/XS data) for discriminating different vegetation units in arctic regions. There has been much effort expended in attempting to relate biophysical variables (e.g., leaf area index (LAI) or biomass) to reflectance characteristics recorded in remote sensing images but there remains limited information available on such properties for arctic vegetation communities (Hope *et. al.*, 1993).

A key concern with regards to selecting a sensor type is the spatial resolution – analogous to the scale of observations (Woodcock and Strahler, 1987). Ranging from field spectrometers to space orbiting satellites, the instantaneous field of view (IFOV) is a determining factor in the scale of observation and thus the degree of spectral aggregation occurring in each pixel (Davidson and Csillag, 2001). These discrepancies, along with other constraints (Table 2.1) must be considered when incorporating remotely sensed imagery into biophysical analyses because ecological relationships between pattern and process often vary

with scale; therefore, the selected scale of observation may not necessarily be the most appropriate for the relationship in question (Davidson and Csillag, 2001).

The most extensive tundra investigations employing satellite imagery are localized within a permanent study site initiated in 1984 by the United States Department of Energy (i.e., the *Response, Resistance, Resilience to, and Recovery from, Disturbance in Arctic Ecosystem – R⁴D* project) in the Arctic Foothills of Alaska. The R⁴D project aims to develop models of tundra ecosystem functioning using remotely-sensed data to provide information regarding vegetation productivity, biomass, and species composition (Hope *et. al.*, 1993). Other studies have been performed in different locations across Canada, Alaska, Europe, and Russia, but with less frequency and permanence than those established on the North Slope of Alaska (Table 2.2).

While these studies have yielded interesting and promising results, there are a few drawbacks to employing satellite imagery with a spatial resolution greater than 10m. Stow *et. al.* (1989; 1993b) found that approximately 30% of mapped vegetation units were less than the 20m nominal

Table 2.1 - Constraints for satellite-based vegetation mapping

Constraint	Description
Separating vegetation classes	It is impossible to separate vegetation classes using vegetation cover characteristics if the classes are minimally vegetated – where the spectral signature is dominated by bare ground
Mixed pixels	It is impossible to map vegetation classes that occur in units of subpixel size
Spectral separability	It is impossible to distinguish vegetation classes if there is no significant difference in spectral signature
Transition zones	Satellite-based mapping does not produce sharp borders between vegetation units that maintain broad transition zones in nature

Adapted from Mosbech and Hansen, 1994

spatial resolution of SPOT (usually characterized by spatial scales of less than 45m in at least one dimension). For example, water track vegetation is the most difficult community type to resolve spatially because of its narrow width in the across-track dimension (Stow *et al.*, 1989; Stow *et. al.*, 1993b). This is an important consideration as it implies that SPOT (in

Table 2.2 – Summary of satellite sensor applications in arctic environments

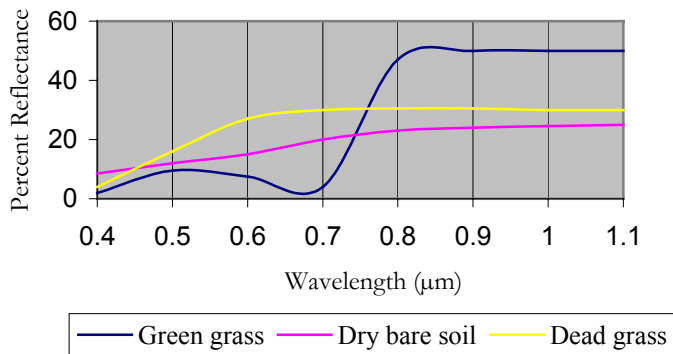
APPLICATION	SENSOR	SOURCE
spectral, spatial and temporal reflectance characteristics of arctic tundra vegetation	SPOT HRV/XS (20m pixels)	Stow <i>et. al.</i> , 1993b
vegetation mapping	SPOT HRV/XS (20m pixels)	Stow <i>et. al.</i> , 1989; Stow <i>et. al.</i> , 1993b; Mosbech and Hansen, 1994
trends in NDVI causes and variations	SPOT HRV/XS (20m pixels)	Walker <i>et. al.</i> , 1995; Hope <i>et. al.</i> , 1995; Jacobsen and Hansen, 1999
estimating biophysical variables	SPOT HRV/XS (20m pixels)	Shippert <i>et. al.</i> , 1995; Walker <i>et. al.</i> , 1995
vegetation mapping	Landsat MSS (80m pixels)	Walker <i>et. al.</i> , 1982; Muller <i>et. al.</i> , 1999
vegetation damage assessment	Landsat MSS (80m pixels)	Rees <i>et. al.</i> , 1998
land cover classification	Landsat TM (30m pixels)	Mosbech and Hansen, 1994
correlating field and satellite data	Landsat TM (30m pixels)	Spjelkavik, 1995
biomass estimation	Landsat TM (30m pixels)	Spjelkavik, 1995
comparing vegetation mapping methods	AVHRR (1.1km pixels)	Muller <i>et. al.</i> , 1999
spectral-radiometric and spectral-temporal feature extraction	AVHRR (1.1km pixels)	Stow <i>et. al.</i> , 2000

multispectral mode) – and by association other coarser resolution sensors – cannot resolve some of the important components of tundra landscapes. Stow *et. al.* (1989; 1993b) then conclude that a spatial resolution of at least 10m would be necessary in order to distinguish between various tundra vegetation communities of interest. This is where advancing technology and higher resolution satellites will become increasingly important in future studies.

2.4 Tundra Spectral Characteristics

Optical remote sensing is a way of passively capturing information about surface reflectance features. Vegetation possesses unique spectral characteristics (Figure 2.1) that aid in vegetation studies and analyses. Chlorophyll molecules preferentially absorb light in the blue (0.45-0.52 μ m) and red (0.63-0.69 μ m) regions of the electromagnetic spectrum (i.e., up to 90% of incident light in these regions) (Campbell, 1996; Jensen, 2000). Also, for a typical healthy leaf, the spongy mesophyll cells may cause as much as 76% of incident near infrared (nir) energy (i.e., 0.9 μ m) to be reflected (Jensen, 2000). These differences in chlorophyll

Figure 2.1 - Typical reflectance characteristics of green grass, dry bare soil, and dead grass



Adapted from Jensen, 1996

absorption of visible wavelengths, and near infrared reflectance aid in plant type discrimination, plant stress analysis, and plant growth cycle monitoring, while providing useful input parameters into a host of vegetation indices (VIs). Because this characteristic plant spectral

signature is related directly to plant physiology, many VIs have been developed as a means of quantitatively measuring certain biophysical parameters of interest (Laidler and Treitz, 2001).

Reflectance measurements from both hand-held radiometers and satellite sensors have been employed in attempts to characterize spectral signatures of particular tundra cover types. Asrar *et. al.* (1989) highlight the value of data acquired from hand-held radiometers to infer plant canopy attributes without destructive sampling. Determining the relationship between vegetation quantities and spectral reflectance can be community specific, which has important implications for dealing with remotely sensed data that may include mixed pixels (Stow *et. al.*, 1993b). Often, the most accurate and informative means of gathering spectral information about a particular tundra vegetation community of interest is to perform *in situ* radiometric measurements and data collection, and even to calculate certain vegetation indices with these data. Hope *et. al.* (1993) describe three main uses of non-imaging hand-held spectral radiometers, reminding readers that this is often the first step in multi-level remote sensing studies (Table 2.3). Tundra vegetation spectral reflectance characteristics recorded using satellite sensors are often similar in trends, but different in intensity, compared to spectra collected by hand-held radiometers in the field. Spectral characteristics

Table 2.3 – Uses of non-imaging hand-held spectral radiometers

1. relationships between biophysical quantities and spectral reflectances can be established without the confounding effects of the atmosphere
2. surface targets can be accurately isolated
3. the area sampled by radiometer is small enough to be able to realistically collect an adequate sample of ground reference data, while still providing the analyst with the flexibility to exploit periods of little or no cloud cover

Source: Hope *et al.*, 1993

derived from ground-level radiometric data provide a preliminary understanding of spectral signatures that may then be expanded to interpretation at satellite imagery scales. The easiest method of

comparing surface and satellite spectral reflectance characteristics is to employ ratio-based vegetation indices (VIs). However, the following must be considered when attempting to relate field and satellite reflectance data:

1. time of year and maturity in growing season has a drastic effect on NDVI values for both physiological and illumination reasons (Stow *et al.*, 1993a; Stow *et al.*, 1993b; Vierling *et al.*, 1997)
2. spectral reflectance characteristics of certain vegetation types detailed in one geographic location may vary at another location, due to various local and microtopographical/microclimatological characteristics (Stow *et al.*, 1989; Spjelkavik, 1995; Stow *et al.*, 2000)
3. sampling schemes, radiometer height above ground, IFOV, bandwidth and sensitivity, frequency of measurements, averaging of values, calibration techniques, standard deviation of values, etc., must all be factored into analysis of the results – these elements are rarely held constant across studies, and thus must be considered when attempting to compare results (Stow *et al.*, 1993b; Rees *et al.*, 1998)
4. vegetation and site familiarity are generally used in spectral analysis, providing invaluable *in situ* experience crucial to producing more accurate, informative, and statistically representative results (e.g., Edwards *et al.*, 2000)
5. it is important to consider outside factors affecting spectral signature, such as plant structure, soil acidity, geologic formations underlying the soil, site moisture, and preferential plant habitat (Shippert *et al.*, 1995; Walker *et al.*, 1995; Vierling *et al.*, 1997)

2.5 Spectral Vegetation Indices

It has been demonstrated in a range of vegetated ecosystems, that simple transformations of band reflectances are more closely correlated with plant biophysical qualities, and are generally less sensitive to external variables such as solar zenith angle, than individual image bands (Laidler and Treitz, 2001). If biophysical parameters are strongly correlated with remotely sensed reflectance data, then these data maintain the potential to

predict biophysical characteristics for variable scene and sensor characteristics over large areas (for a detailed review see Treitz and Howarth, 1999). Vegetation indices are typically formed from combinations of several spectral values that are mathematically manipulated in a manner designed to provide a single value indicating the amount or vigour of vegetation within a pixel (Campbell, 1996). The most widely used of these transformations is the normalized difference vegetation index (NDVI) (Rouse *et. al.*, 1974) (Appendix 9). NDVI is useful mainly because it normalizes the difference between maximum absorption within the red wavelengths and peak reflectance in the nir. This relationship between the red and near-infrared wavelengths provides the most information regarding vegetative properties (e.g., health, stress level, green biomass, and chlorophyll content). Hence, the most common VIs utilize the information content of the red and near-infrared spectral channels (Appendix 9). The advantage of using ratios of sensitive (nir) and insensitive bands (red) is that the latter functions as a baseline that factors out variability due to causes other than variations in leaf chlorophyll content (Treitz and Howarth, 1999). Vegetation indices have been used to estimate the intercepted, photosynthetically-active radiation (IPAR) of plant canopies (Baret and Guyot, 1991; Sellers *et. al.*, 1992), above ground biomass (Boutton and Tieszen, 1983; vegetation cover (Richardson and Wiegand, 1977; Purevdorj *et. al.*, 1998), chlorophyll content (Tucker, 1977), productivity (Box *et. al.*, 1989), net above-ground primary production (NPP) (Walker *et. al.*, 1995), and leaf area index (LAI) (Baret and Guyot, 1991).

In tundra environments, NDVI is the most commonly employed VI (e.g., Hope *et. al.*, 1993; Stow, *et. al.*, 1993b; Mosbech and Hansen, 1994; Shippert *et. al.*, 1995; Walker *et. al.*, 1995; Rees *et. al.*, 1998). For an extensive review of the results of these studies – both *in situ* (Appendix 10) and remote (Appendix 11) – refer to Laidler and Treitz (2001). More

importantly, VI relations to biophysical parameter estimation such as biomass or percent vegetation cover will be discussed as essential background for later analyses.

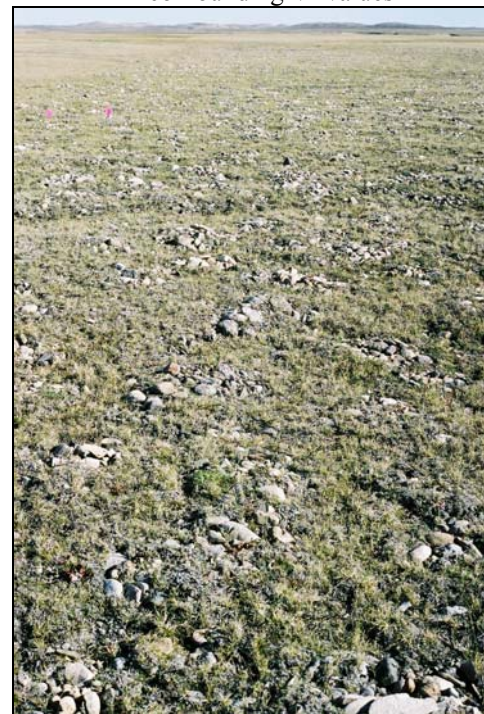
2.6 Biophysical Parameter Estimation

Through studies of the relationship between percent vegetation cover, vegetation distribution, biomass, and spectral reflectance (via VIs) several key conclusions have been noted as informing the direction of this thesis, as well as placing results within a broader context.

Rees *et. al.* (1998) suggest that the VI concept, at least at the scale of Landsat MSS (i.e., 80m pixels), is generally of very limited use in arctic environments, and that NDVI alone may be misleading without the availability of a preliminary classification of vegetation groups so that stone, lichen, and dwarf shrub tundra groups can be adequately distinguished.

Mosbech and Hansen (1994) analyzed both SPOT and Landsat TM with regards to vegetation spectral characteristics. They found that the delimitation of primary vegetation types (e.g., fen, grassland, scrub heath, copse, and snowbed) was more accurate than subdivided types. Generalized vegetation types at these scales are a function of the “mixed pixel problem”, whereby factors other than the presence and amount of green vegetation (i.e., senescent vegetation, soil, gravel, shadow) combine to form composite spectra (Figure 2.2) (Asner, 1998; Davidson and Csillag, 2001). The

Figure 2.2 – Example of background materials confounding VI values



Boothia Peninsula, Nunavut; July, 2001
Exposed soil or rock surfaces tend to alter the spectral reflectance signature of vegetation that is low to the ground or sparsely distributed.

effects of composite spectra on the accurate estimation of biophysical properties over large areas, may be reduced by employing higher spatial resolution data to better depict the spatial variability within vegetation communities.

Stow *et. al.* (1993b) found that SPOT NDVI values were consistently lower than field-derived NDVI, with a slightly compressed range likely caused by atmospheric scattering of red wavelengths. Stow *et. al.* (1993b) view SPOT NDVI values as potentially very useful, so long as the errors and nature of the variability are understood. Although they suggest higher spatial resolution (i.e., 9m) data would improve NDVI correlations to biophysical parameters, SPOT data provide the necessary preliminary information to: i) identify initial conditions for patch scale models by inventorying landscape conditions and their relative proportions; ii) stratify landscapes into relatively homogeneous response units for spatially-distributed modeling of material and energy transport; iii) extrapolate results of model simulations by mapping areas that are potentially sensitive to particular disturbances; and iv) assess results of landscape and regional-scale model simulations by comparative spatial pattern analysis.

Walker *et. al.* (1995) investigated the effects of soil acidity and landscape age in a comparative analysis between NDVI derived from field radiometric data and SPOT data. The mean satellite-derived NDVI of mapped acidic dry, moist, and wet vegetation units was consistently higher than those of corresponding non-acidic units; however, satellite-derived NDVI values were about 40% of field-derived NDVI values (likely due to factors associated with sun-target-sensor viewing geometry). They conclude that factors contributing to different NDVI values on different glacial surfaces include: i) a greater abundance of dry, well-drained sites on younger surfaces; ii) more non-sorted circles and stripes on younger hillslopes; and iii) more shrub-rich water tracks on older landscapes.

Many studies have investigated the relationship between VIs and biomass, going on the assumption that a VI is strongly correlated with the "amount" (biomass or LAI) of vegetation present in a given area (Hope *et. al.*, 1993; Stow *et. al.*, 1993b; Mosbech and Hansen, 1994; Shippert *et. al.*, 1995; Walker *et. al.*, 1995; Spjelkavik, 1995; Rees *et. al.*, 1998; McMichael *et. al.*, 1999). Within biophysical remote sensing literature, biomass is often referred to as the total amount of photosynthesizing vegetation present in any one area (Dancy *et. al.*, 1986; Baret and Guyot, 1991; Hope *et. al.*, 1993; Walker *et. al.*, 1995; Davidson and Csillag, 2001). Shippert *et. al.* (1995, 147) define it more formally as "a measure of the amount of carbon stored in the canopy". Vegetation indices have the potential to provide an efficient means of estimating biomass, thereby contributing to various areas of research (e.g., land cover change, vegetation mapping and monitoring, climate change).

Hope *et. al.* (1993) discuss varying degrees of success in relating NDVI values to field biomass measurements. They found that the change in NDVI was very similar to the general pattern of biomass amount, but that biomass was not a significant variable in any of the regression equations. The relationship between biophysical properties and spectral reflectance must be approached with caution because it may be unstable across a growing season due to changes in vegetation phenology, illumination and/or background conditions (Hope *et. al.*, 1993).

As part of an effort to develop multi-scale models of arctic tundra ecosystems to predict disturbance effects related to energy development in Alaska, Stow *et. al.* (1993b) indicate that there is a significant linear relationship between percent shrub cover and NDVI. In addition, they found that NDVI spatial trends along a toposequence corresponded to variations in abundance of green vegetation matter as well as vegetation composition caused by site moisture conditions (Stow *et al.*, 1993b). A related trend

regarding growing season was explored by Mosbech and Hansen (1994). They highlight that great differences in NDVI are seen during the growing season for different vegetation types due to differences in snow cover, water supply, and soil water storage. Based on the fact that peak green biomass occurs in early August, NDVI was found to have a high correlation with soil coverage by green biomass, where increasing NDVI values indicated increasing vegetation coverage along with increasing biomass.

Shippert *et. al.* (1995) describe the relationship between NDVI and biomass for community types as one that is asymptotic. It is thought that as vegetation density increases, absorption of red wavelengths approaches a maximum, beyond which any additional vegetation density would not contribute to an overall change in the reflectance signature (Laidler and Treitz, 2001). This also supports Hansen's (1991) results, which demonstrated an asymptotic relationship between NDVI and biomass for data from many Arctic and sub-arctic vegetation types. One important conclusion is that total above-ground biomass is better correlated to NDVI than green biomass alone. It is often difficult to isolate green biomass as a distinct entity, thus investigations into the utility of separating above-ground biomass into plant functional types such as shrubs (low, erect, prostrate and hemi-prostrate woody vegetation), graminoids (grasses, sedges, and rushes), forbs (various flowering tundra plants), and non-vascular plants (bryophytes and lichens) (after Walker, 2000) (Appendix 12) may provide greater insight into biomass correlations with NDVI (Laidler and Treitz, 2001). Similar to Walker *et. al.* (1995), Shippert *et. al.* (1995) discovered that LAI and biomass images created from SPOT-NDVI, using regression equations, showed trends in LAI and biomass across the North Slope of Alaska landscape that are expected on the basis of local geobotanical maps.

Besides the demonstrated linear asymptotic relationship between NDVI, LAI, and biomass, a new dimension is added by considering that the strength of the relationship is reduced with increasing detail. Shippert *et. al.* (1995) suggest that lowering the resolution of models may increase predictability by averaging out chaotic behaviour, but it will be at the expense of losing detail about the phenomenon of interest. There may not be a strong relation between NDVI and biomass within one vegetation type; however, this same relationship can be quite strong among many vegetation types. Based on this observation, NDVI may not be an appropriate means for estimating biomass if one is interested in detailed variations within a single vegetation type (Shippert *et. al.*, 1995). On the other hand, investigations into particular vegetation combinations may prove fruitful in identifying ecologically significant communities and estimating their contributions to above-ground biomass in tundra environments. If interest lies in broad changes in biomass among differing vegetation types, then NDVI may be an appropriate biomass estimator. SPOT NDVI-derived LAI and biomass images were useful in providing realistic representations of spatial variation and magnitudes of LAI and biomass on the North Slope of Alaska (Shippert *et. al.*, 1995).

2.7 Conclusions

Biophysical remote sensing in arctic environments seems to be in the exploratory stages with many attempts being made to establish methodological protocols and baseline vegetation inventories. Increasing remote sensing investigations, and research into correlation methods with surface variables of interest, are also crucial due to the logistical complexities of conducting arctic field excursions. Contemporary remote sensing research in arctic environments has provided background information on a number of issues related to the research carried out for this thesis.

First, the methodological descriptions of field data collection (e.g., percent cover analysis, biomass harvesting, spectral measurements, etc.) and image analysis (e.g., VI calculation, regression analysis, digital number manipulation, etc.) techniques supported the design of the site-specific data acquisition methods for this research.

Second, despite the fact that authors such as Stow *et. al.* (1993a), Hope *et. al.* (1993), Shippert *et. al.* (1995), and Jacobsen and Hansen (1999) have highlighted the usefulness of the large spatial extent provided by satellite sensors, it is believed that improvements in estimating biophysical aspects of arctic environments would likely result from increased spatial resolving power. Employing IKONOS satellite data (i.e., 4m pixels) represents an attempt to minimize spectral confusion caused by mixed pixels resulting from small-scale tundra vegetation variability.

Third, the narrow realm of investigation into the usefulness of VIs in arctic environments (i.e., simple ratio and NDVI) was unexpected. Thus, the use of other VIs such as the soil-adjusted vegetation index (SAVI) (Huete, 1988) – using different soil correction parameters – as well as the modified soil-adjusted vegetation index (MSAVI) (Qi *et. al.*, 1994) is proposed as an important experiment to determine the effects of exposed soil or rock cover on tundra reflectance characteristics. This may be crucial in allowing for progression towards more representative results in sparsely vegetated areas where bare soil or exposed gravel tills are highly influential on vegetation community spectral response.

Finally, as these key concepts assisted in the formulation of this research, they were also an essential source for raising questions about the results, as well as conventionally accepted findings. The literature review provides a basis for comparison, but keeping in mind the difference in geographical location – and thus vegetation community composition – it does not necessarily provide studies for validation. This is both an exciting and

frustrating aspect of the research, and must not be lost in the evaluation of the following thesis components.