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用V-I-S模式描述都市土地覆蓋：以猶他州鹽湖城為例

Describing Urban Land Covers Using the V-I-S (Vegetation-Impervious Surface-Soil) Model: Modeling Salt Lake City, Utah Metropolitan Area

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摘 要

都市地區的土地覆蓋物是多樣的，這使得都市地區在空間上及光譜上非常的異質化，也使得都市地區的環境模式化非常困難·借助於既有的 V-I-S（Vegetation 植生, Impervious surface 不透水表面，Soil 土壤）模式及軟分類法，都市地區能夠被簡化成三種基本物質的組成，而這種簡化使得都市地區能夠被數值化描述及分析·在這篇文章裡，多種具有代表性的都市特徵將逐一被檢視，這些都市特徵的 V-I-S 組成會被數值化性得展示在不同的表格及圖形，這種數值化資料提供了不同土地覆蓋或土地利用比較的基礎·此外，多條空間剖面從市中心向外延伸到都市週遭地區也顯示了 V-I-S 組成因地而異，但也都遵循著一個共同趨勢：從市中心到郊區，不透水表面會遞減，而植生會遞增·

關鍵字：土地覆蓋組成、軟分類、都市遙感探測、V-I-S **模式、鹽湖城**

Abstract

A great diversity of land cover types is present in urban areas. This diversity makes urban areas spatially and spectrally heterogeneous, and in turn makes urban environmental modeling challenging. With an urban land cover based model, the V-I-S (Vegetation-Impervious surface-Soil) model, and a previously developed soft classifier, urban environments could be simplified and therefore represented as combinations of three basic urban components. With this simplification, urban environments could be described and analyzed quantitatively. Typical urban features were selected. The V-I-S compositions of these selected urban features are shown in a quantitative manner by various forms, such as tables, plots, feature space plots, and the V-I-S diagrams. This quantitative data provide bases for comparisons

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between different land cover/use types. In addition, spatial profiles are also drawn from the downtown area towards city boundaries to show the general trends of change in land cover composition across an urban landscape. As expected, impervious surface general decreases as one moving towards city boundaries, while vegetation or soil increases.

Keywords: land cover composition, soft classification, urban remote sensing, the V-I-S model, Salt Lake City

Introduction

Urban environments are an extremely heterogeneous area, both spatially and spectrally, and often pose great challenges to researchers in urban studies, even in tasks such as characterizing urban environments. Spatial and spectral heterogeneity often leads to mixed pixels, a common problem in satellite images on urban environments (Forster 1985, Foody 1992, Ridd 1995, Jensen 2005). A mixed pixel is a pixel with more than one category of land cover/use types inside its corresponding ground area. Traditional per-pixel classification approach uses one dominant land cover/use type to represent the entire pixel, and ignores other land cover/use types. For in-depth urban studies, especially urban environmental modeling, it is necessary to conserve all of the land cover/use information.

In geographic information science (GIScience) literature, land cover classes and land use classes are often used simultaneously, and sometimes interchangeably. However, a distinction between them must be made. Remote sensing equipments only sense the materials on the land, not how the land is used (Ridd 1995, Jensen 2005). In other words, remote sensing equipments only sense land cover materials, not land use types. Land cover materials are the materials on top of the land (grass, concrete, asphalt, soil, etc.), and land use types are what the lands are used for (commercial areas, residential areas, recreational areas, etc.). Land use types are referred to by human perception. A single land use type may include multiple land cover materials. On the other hand, the same land cover material may appear in different land use types. Even more, different land use types may contain same land cover types, but with different proportions. There is a many-to-many relationship between them.

As shown in figure 1(a), green vegetation (a land cover material) may appear in a golf course (commercial or recreational area, a land use type) or a crop field (agricultural area, a land use type). On the other hand, residential areas (a land use type) may consist of vegetation (a land cover material) and impervious surfaces (a land cover material). With different compositions of vegetation and impervious surface, the resulting residential areas may be different in nature. In low density residential areas vegetation may appear more than impervious surfaces. On the other hand, in high density residential areas, impervious surface may appear more than vegetation. Figure 1 (b) summarizes and demonstrates the many-to-many relationship between typical land cover materials and typical land use types.

In order to take full advantage of remote sensing and associated digital image processing

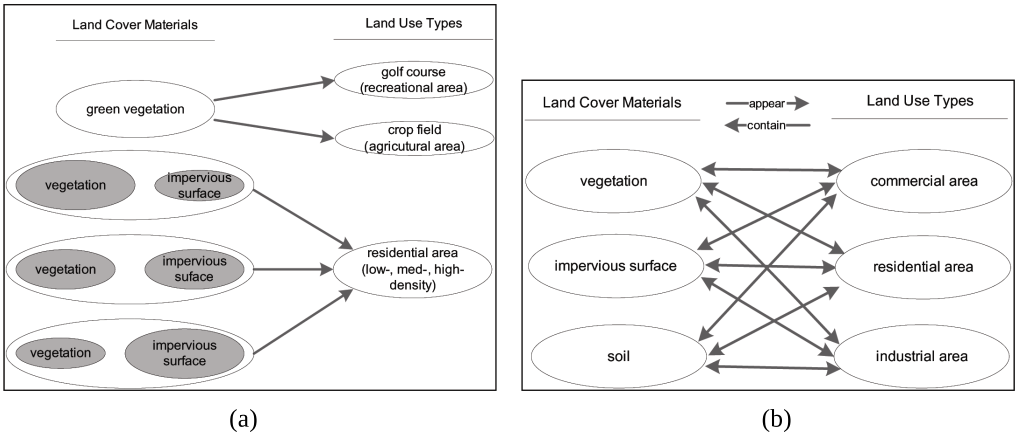


Figure 1. Many-to-many relationship between land cover materials and land use types.

techniques, there are needs on simplifying heterogeneous urban environments into models, especially land cover based models. Ridd (1995) proposed the V-I-S (Vegetation-Impervious Surface-Soil) Model to simplify and study the urban morphology. This study applied the V-I-S Model and a previously developed soft classifier onto the Salt Lake City, Utah metropolitan area, and performed a quantitative environmental modeling to describe (from a descriptive model perspective) the area in a simplified and quantitative manner. The following two sections explain spatial models, the process of modeling, and the V-I-S Model, followed by a section explaining the process of estimating land cover components and its accuracy, followed by a section describing the quantitative modeling of the study area.

Spatial Modeling and Spatial Models

Spatial modeling is a process of simplifying the real world or the area under study to some modeled world or area for human and technological comprehension. A spatial model is the results of the modeling process, and it is a simplified representation of the real world or the area under study (Peuquet 1984, Batty and Xie 1994, Yuan 2002, Longley et. al. 2005). Based on the purposes of spatial models, there are descriptive models, predictive models, and prescriptive models. A descriptive model is a model that describes the area or object under study. A predictive model is a model that predicts unknown or missing data from existing situations. A prescriptive model is a model that estimates possible results or solutions from a given hypothetical situation (DeMers 2002, Lo and Yeung 2002, Chang 2006).

A descriptive model may be the simplest form of a model. However, it may provide the foundation for many further studies or analyses. In reality, there might be infinite factors affecting a phenomenon. Unfortunately, most modern technologies, including spatial technologies, can only process finite factors. It is necessary to have a modeled world or area under study if spatial technologies are to be used.

Most geographic information system (GIS) data consist of two parts: location and attribute. The location part concerns ‘where is it?’ while the attribute part concerns ‘what is it?’ (Heywood et. al. 2002, Longley et. al. 2005). Depending on the representation or viewpoint, different data models may be used. Generally speaking, the object representation views the world as filled with discrete objects and uses the vector data model. The field representation views the world as a continuous field and uses the raster data model (Wegener 2000, Cova and Goodchild 2002, Longley et. al. 2005). With the object representation the study area is represented by boundaries and attributes. The boundaries between attributes are clear. On the other hand with the field representation, there is no pre-defined attributes. Instead, this representation records directly from observations. It is a direct recording of the same variable in the whole study area. For a digital elevation model (DEM), it is the elevation that is recorded. For remote sensing, it is the spectral reflectance that is recorded (Burrough and McDonnell 1998, Lo and Yeung 2002, Longley et. al. 2005).

It is natural to use the field representation and the raster data model in a study if the exact attributes under study are unknown or undecided, such as remote sensing data being a snapshot of the environments and to be processed for information extraction (Jensen 2000, Lo and Yeung 2002). It is also natural to use the field representation and the raster data model in a study if the variation inside the variable is large, such as elevation in DEM (Burrough and McDonnell 1998, Longley et. al. 2005). Urban areas with extreme heterogeneity pose a great challenge for modeling. To fully understand the urban physical environments it is necessary to have a descriptive model to simplify urban environments based on urban physical characteristics, more specifically land cover materials (Ridd 1995). With such a model further studies may uncover some information about urban areas that was not available in the past.

This study presents the study area with a descriptive model. For the descriptive model to be reliable the process of simplification and these chosen components must be closely examined as well as the accuracy of its representation. The results will be presented after an accuracy assessment. Different from most remote sensing projects, this study does not indicate any single land use/cover type for pixels. Instead this study describes urban environments as compositions of basic urban land cover materials.

The V-I-S Model

Ridd (1995) and his fellow colleagues studied the land cover materials in the Salt Lake Valley, UT area. He concluded three basic types of land cover materials in urban areas (vegetation, impervious surface, and soil) and proposed the V-I-S model. By using these three basic material types, general urban features could be represented by combinations of them (water pixels are treated separately). The concept of this model is best explained by a V-I-S diagram as shown in figure 2.

In figure 2, there are three axes and three corners. The vegetation axis (the bottom one) indicates the percent vegetation, which increases from the S corner to the V corner (100 percent vegetation). The impervious surface axis (the left hand side one) indicates the percent impervious surface, which

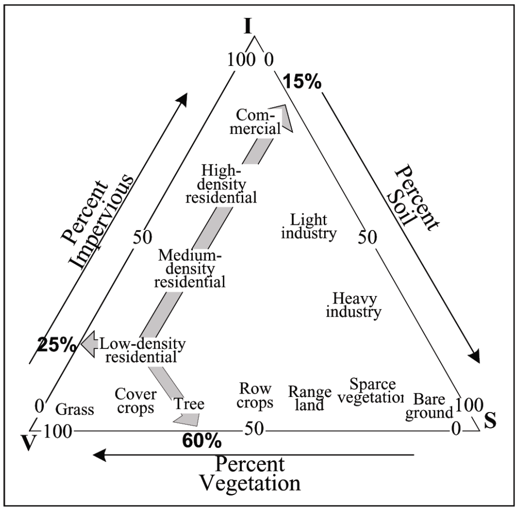


Figure 2. A V-I-S diagram showing typical urban/suburb features.

increases from the V corner to the I corner (100 percent impervious surface). The soil axis (the right hand side one) indicates the percent soil, which increases from the I corner to the S corner (100 percent soil). Inside this triangle, any plot has its own V-I-S composition. Taking the low-density residential area as an example, project it to the vegetation axis, it may read 60, the impervious surface axis 25, and the soil axis 15. So the low-density residential area would be a combination of 60 percent vegetation, 25 percent impervious surface, and 15 percent soil. However, this figure does not imply a single plot inside the V-I-S diagram and therefore a single V-I-S composition for urban features. Instead, urban features may be represented by a small area in the V-I-S diagram and therefore ranges in its V-I-S composition.

This model was tested on different nations on different continents, including the Salt Lake City area, USA (Chung 1989, Card 1993, Ridd 1995), the southeast region of Queensland, Australia (Ward et. al. 2000), and the Bangkok Metropolitan area, Thailand (Madhavan et. al. 2001). The satisfactory results confirmed the practical values of the V-I-S concept as a model that may enrich quantitative urban investigations through remote sensing technology. A previously developed soft classifier based on the V-I-S model (Hung and Ridd 2002) was adapted to estimate urban land cover composition.

Urban Land Cover Composition

(1) Study Area and Data

An urban area that presents a high degree of heterogeneity is an ideal candidate for this research. It is desirable for this urban area to have an intense urban landscape with great diversity in land cover/use types. Salt Lake City is the county seat of Salt Lake County and the capital of the State of Utah. There are many different activities here. There are man-made features, such as commercial areas, heavy and light industrial areas, high and low density residential areas, transportation networks, airports, university campuses, agricultural areas, and an open-pit copper mine, as well as natural features, such as a salt desert, wetlands, lakes, forests, and mountain woodlands. Because of the great diversity in land cover/use types and rapid growth, Salt Lake City and vicinity area (Salt Lake Valley) has been selected as the study area, as illustrated in figure 3.

A Enhanced Thematic Mapper Plus (ETM+) satellite image covering the study area (World Reference System 2, Path 038 Row 032) taken on 14 August 1999 was purchased. In addition, a set of gray level aerial photo taken on 4 May 2000 was purchased for the purpose of accuracy assessment. The scale of these aerial photos is approximately 1:20,000.

(2) Land Cover Composition Estimation

A previously developed soft classifier was adapted (Hung and Ridd 2002). Unfortunately, their study area was only a small portion of the Salt Lake City metropolitan area. To performing the quantitative environmental modeling, it is necessary to examine the whole metropolitan area. Many technical details were explained by Hung and Ridd (2002), only an overview of their methodology will be provided here.

Figure 4 outlines the steps in the land cover composition estimation task. It is similar to the supervised classification approach. The ETM+ image was first pre-processed to filter out water bodies,

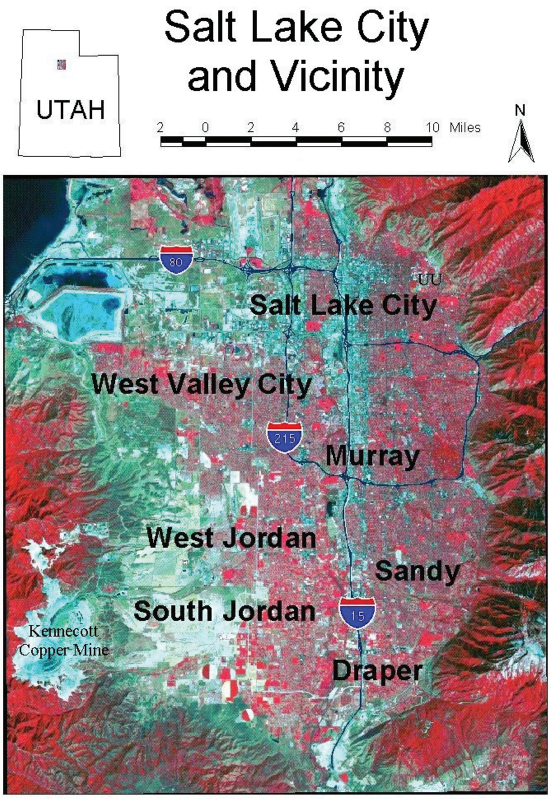


Figure 3. The study area: Salt Lake City and vicinity area, Utah.

such as lakes, ponds, rivers, streams, etc. by using a GIS layer as a mask. Then training sites defining basic land cover materials in the study area were selected. The Baye's Algorithm often used in Maximum Likelihood Classification was then applied to calculate likelihood between the current pixel and training sites. Likelihood was then converted to percentages, and then verified against the pixel brightness values. If these percentages were verified valid, then move on to the next pixel. If these percentages were verified invalid, expert system rules were used to adjust these percentage till them were valid. As most remote sensing projects, estimations were assessed against ground truth to report accuracy.

Though Ridd proposed three basic components, it is practically difficult to obtain high classification accuracy with only three classes because of great diversity within each class, and therefore confusion between classes. Through a series of trial-and-errors of supervised classifications with different training sites and classification schemes, it is concluded that six, instead of three, land cover components would be ideal in the digital image processing stages, such as soft classification and accuracy assessment. However, during the analysis and modeling stage, six components are aggregated back to three, to be consistent with the V-I-S model. Among these six land cover components, two of them are for vegetation, three for impervious surface, and one for soil. These six land cover components are Vgg: green grass vegetation, Vts: tree/shrub vegetation, Ibr: bright impervious surface, Imd: medium impervious surface, Idk: dark impervious surface, and Sdv: soil/dry vegetation. In addition, water bodies are treated separately.

The Vgg component includes healthy green grass vegetation, usually found in golf courses, baseball fields, cemeteries, or parks. The Vts component includes trees and/or shrub vegetation, usually found in mountain foothills, residential areas, or parks. The Ibr component includes materials with high reflectance, such as rooftops, metal, tile, and some high reflectance artificial materials usually found in commercial areas or building complexes. The Imd component includes materials with medium reflectance, such as concrete, rooftops, and weathered asphalt usually found in commercial areas, industrial areas, or residential areas. The Idk component includes materials with low reflectance, such as asphalt and concrete, usually found in transportation networks or parking lots. The Sdv component includes soil and/or dry vegetation, usually found in mountain foothills, abandoned fields, or unused lands. Soil and dry vegetation are put together as one component because they are quite similar in their spectral reflectance characteristics, as well as the brightness values from satellite images (Hoffer 1978).

Training sites of these six land cover components were selected from the satellite image, with reference to aerial photos. Training statistics were calculated. A previously developed soft classifier (As explained earlier) was adapted and applied. The resulting land cover composition is presented in the forms of images (referred to as ground component percentage images), as shown in figure 5. Figure 5 (a) shows the Vgg percentage image, (b) for Vts, (c) for Ibr, (d) for Imd, (e) for Idk, and (f) for Sdv. In addition, figure 5 (g) shows the V-I-S percentage image with false color display (red for soil from Sdv, green for vegetation from combination of Vgg and Vts, and blue for impervious surface from combination of Ibr, Imd, and Idk). Figure 5 (h) shows the ETM+ satellite image in false color display (R,G,B/4,3,2).

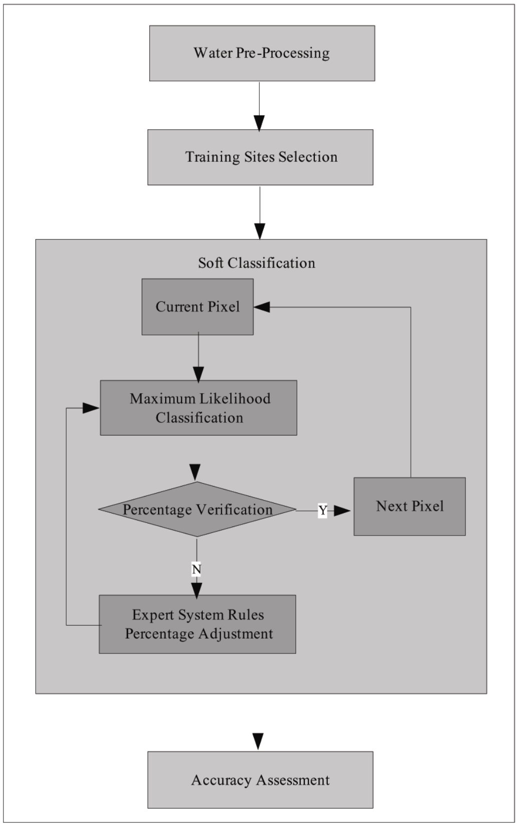
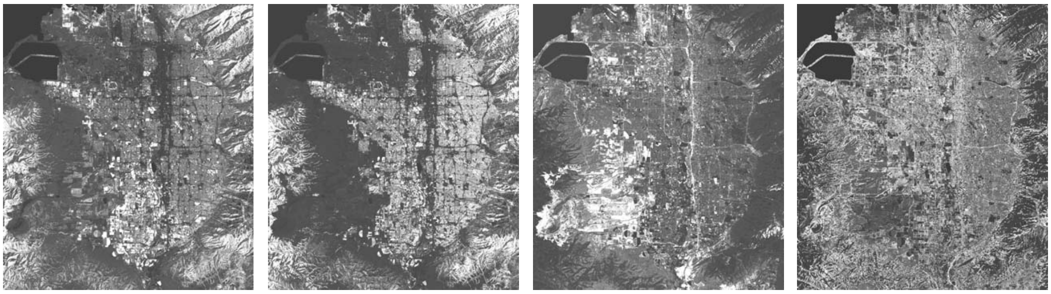


Figure 4. Soft classification overview.

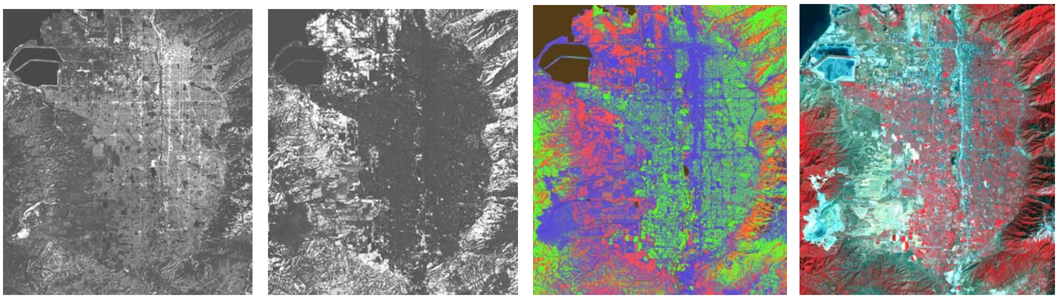
By visual inspection of these images one can observe that areas with high component percentages appear brighter as expected. For example, high Vgg percentage areas in (a) are golf courses, grass covered mountainous areas, parks, school yards, crop fields, and cemeteries. For high Vts percentage areas in (b), they are foothills, residential areas, parks, and cemeteries. For high Ibr percentage areas in (c), they are buildings, new paved concrete, and metals in commercial and industrial areas. For high Imd percentage areas in (d), they are weathered asphalt, concrete, and rooftops in commercial and industrial areas. For high Idk percentage areas in (e), they are asphalt, mainly transportation network and parking lots. For high Sdv percentage areas in (f), they are foothills, abandoned fields, and fallow crop fields.

(3) Estimation Accuracy

Though the performance of the soft classifier has been evaluated previously by Hung and Ridd (2002), it is necessary to perform the accuracy assessment again because of different study areas and datasets. Accuracy is assessed by regression analysis (Fisher and Pathirana 1990, Foody 1992, Hung and Ridd 2002). Correlation coefficients are reported as indices of closeness between the estimated and



(a) Vgg percentage image (b) Vts percentage image (c) Ibr percentage image (d) Imd percentage image



(e) Idk percentage image (f) Sdv percentage image (g) V-I-S percentage image (h) ETM+ satellite image

Figure 5. Ground component percentage images.

surveyed ground component percentages. Two areas are selected as accuracy assessment sample areas, as illustrated in figure 6. Area 1 is within Salt Lake City, which can be considered as stable in terms of urban growth. Table 1 (a) lists the correlation coefficients for area 1. Area 2 is within West Jordan and South Jordan, which can be considered as a rapid growth area. Table 1 (b) lists the correlation coefficients for area 2. The last row lists the sample points for each ground component.

Relationships significant at 0.01 confidence level are indicated by ** mark, at 0.05 level by * mark. Each ground component is assessed and reported by coefficients along the diagonal. Moreover, a coefficient is also reported as an overall assessment and is listed on the upper left corner of each table. In table 1 (a), which is for area 1, within Salt Lake City, the overall coefficient is 0.755 and it is significant at 0.01 confidence level. For individual ground component, a coefficient of 0.920 is found for Vgg, 0.667 for Vts, 0.588 for Ibr, 0.754 for Imd, 0.788 for Idk, and 0.683 for Sdv. They are all significant at 0.01 confidence level. In table 1 (b), which is for area 2, West Jordan and South Jordan area, the overall coefficient is 0.833 and it is significant at 0.01 confidence level. For individual ground component, a coefficient of 0.921 is found for Vgg, 0.790 for Vts, 0.768 for Ibr, 0.897 for Imd, 0.919 for Idk, and 0.801 for Sdv. They are all significant at 0.01 confidence level.

Quantitative Urban Environmental Modeling

Urban environments are represented by V-I-S components in a quantitative manner. This is an

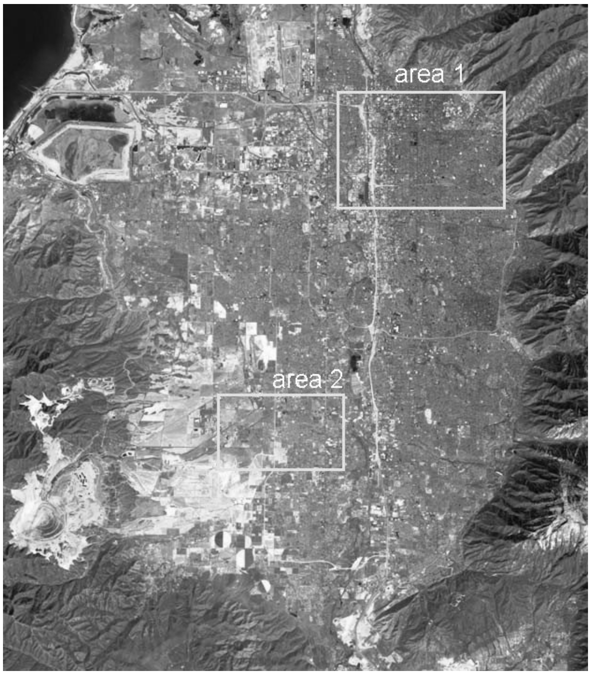


Figure 6. Accuracy assessment sample areas. Areas 1 is Salt Lake City area. Area 2 is West Jordan and South Jordan area.

approach for urban environmental modeling. General urban features and spatial profiles across urban landscape are selected and their V-I-S composition, along with their red visible light (Red) and near infrared (NIR) reflectance, are summarized in charts, plots, and V-I-S diagrams to demonstrate the advantage of using V-I-S composition for urban environmental modeling. It should be noted that though percents for a given urban feature were averaged to derive a single set of V-I-S reading and plotted on charts, plots, and diagrams, it does not imply that urban features could have only one set of V-I-S readings. As explained earlier, a given land use type could consist of various land cover materials. Additionally, composition of land cover materials varies from location to location.

(1) General Urban Features

Several locations were selected from the satellite image and associated ground component percentage images to demonstrate the V-I-S composition for general urban features. They are downtown Salt Lake City (DT), light industrial area (Il), heavy industrial area (Ih), city park (P), golf course (G), low density residential area (Rl), medium density residential area (Rm), high density residential area (Rh), the University of Utah campus (UU), foothill (F) with exposed soil and rocks, ranch (R), crop field with green vegetation (Cv), crop field with mixed vegetation and soil (Cm), and crop field with soil (Cs). Locations for these features are illustrated in figure 7. Their V-I-S composition is summarized in table 2, a bar graph chart in figure 8 (a), a Red/NIR feature space plot in figure 8 (b), and a V-I-S diagram in figure 8 (c).

Table 1. Correlation coefficients for accuracy assessment report. ** significant at 0.01 confidence level, * significant at 0.05 confidence level.

(a) Correlation coefficients for area 1.

overall: **0.755****		surveyed component percentage					
		Vgg	Vts	Ibr	Imd	Idk	Sdv
estimated component percentage	Vgg	**0.920****	0.073	-0.398**	-0.478**	-0.419**	-0.152*
	Vts	0.335**	**0.667****	-0.292**	-0.262**	-0.268**	-0.323**
	Ibr	-0.398**	-0.301**	**0.588****	0.434**	0.054	0.017
	Imd	-0.496**	-0.277**	0.538**	**0.754****	0.157*	-0.170*
	Idk	-0.383**	-0.175*	0.033	0.060	**0.788****	-0.154*
	Sdv	-0.242**	-0.073	-0.213**	-0.208**	-0.183**	**0.683****
sample points		30	54	30	30	30	30

(b) Correlation coefficients for area 2.

overall: **0.833****		surveyed component percentage					
		Vgg	Vts	Ibr	Imd	Idk	Sdv
estimated component percentage	Vgg	**0.921****	0.378**	-0.381**	-0.366**	-0.339**	-0.297**
	Vts	0.401**	**0.790****	-0.359**	-0.118	-0.204**	-0.445**
	Ibr	-0.400**	-0.412**	**0.768****	-0.077	-0.185**	0.353**
	Imd	-0.381**	-0.241**	0.127	**0.897****	0.102	-0.287**
	Idk	-0.276**	-0.310**	-0.072	0.066	**0.919****	-0.281**
	Sdv	-0.184**	-0.106	-0.140*	-0.357**	-0.269**	**0.801****
sample points		30	30	30	54	30	30

From table 2 and figure 8, one may observe the ground component composition for general urban features in a quantitative manner. For example, downtown (DT) has 7 percent vegetation, 3 percent soil, but 90 percent impervious surface as expected. These values are graphically displayed in figure 8 (a) and (c), where DT is near the I corner with high percent impervious surface. Moreover, DT has a high Red (106) consistent with high albedo, and low NIR (86) due to small amount of vegetation. These values are graphically displayed in figure 8 (b).

Also interesting is the relationship between low-to-high density residential areas (Rl-Rm-Rh). In table 2, vegetation decreases in order (68-50-29 percent) whereas impervious surface increases (26-43-66 percent). The soil component remains uniformly low at 6 or 7 percent. The interchange between V and I is represented graphically in figure 8 (a). Red/NIR feature space plot illustrates the interchange as ‘brightness’ increases in Red (67-71-76), while ‘greenness’ decreases in NIR (126-117-105). Figure 8 (b) shows this trend. It is interesting to see the same relationship in the V-I-S diagram as in figure 8 (c), where soil remains low, while impervious surface gives space to vegetation.

An impressive point from figure 8 (c) is that residential areas with different densities could be easily identified and distinguished from each other. High-density residential areas refer to areas with large residential buildings and small amounts of vegetation, such as apartment complexes. They are usually found around downtown in older residential areas. Medium-density residential areas refer to areas with single housing units and moderate amount of vegetation. Most of the residential areas are

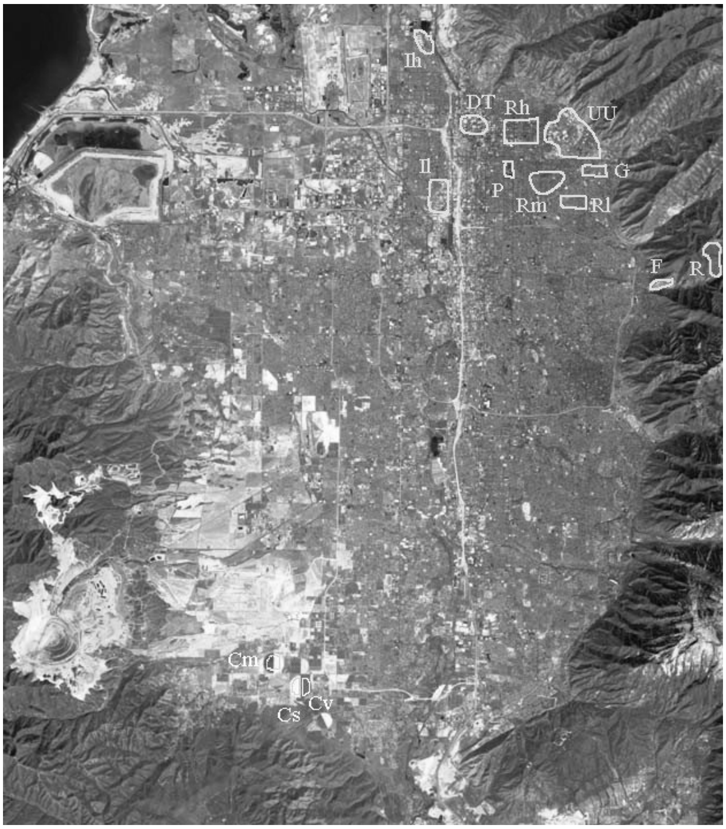


Figure 7. Locations of general urban features: downtown (DT), light industry (Il), heavy industry (Ih), city park (P), golf course (G), low density residential area (Rl), medium density residential area (Rm), high density residential area (Rh), UU campus (UU), foothill (F), ranch (R), crop field with green vegetation (Cv), crop field with mixed vegetation and soil (Cm), crop field with soil (Cs).

medium-density residential areas. Low-density residential areas refer to areas with individual housing structures and large amount of vegetation coming from big backyards or front yards. In this study, it has been demonstrated that they all have their own unique V-I-S composition.

Figure 8 (c) is another example to explain the differences between the literal definitions of land use and land cover types. As mentioned earlier and illustrated in figure 1, there is a many-to-many relationship between land cover materials and land use types. Backing to figure 8 (c) and taking G (golf course) and Cv (crop field with green vegetation) for example, they both are filled with healthy green vegetation, in terms of land cover materials. However, in terms of land use types, they would be classified as recreational (or commercial) and agricultural areas, two different types. Another example would be residential areas with different densities, such as low-density (Rl), medium-density (Rm), and high-density (Rh) residential area. They all are classified as residential areas, in terms of land use types. However, each one of them has its own land cover materials and composition.

Table 2. V-I-S composition for general urban features: downtown (DT), light industry (Il), heavy industry (Ih), city park (P), golf course (G), low density residential area (Rl), medium density residential area (Rm), high density residential area (Rh), UU campus (UU), foothill (F), ranch (R), crop field with vegetation (Cv), crop field with mixed vegetation and soil (Cm), crop field with soil (Cs), TM band 3 (Red), TM band 4 (near infrared, NIR).

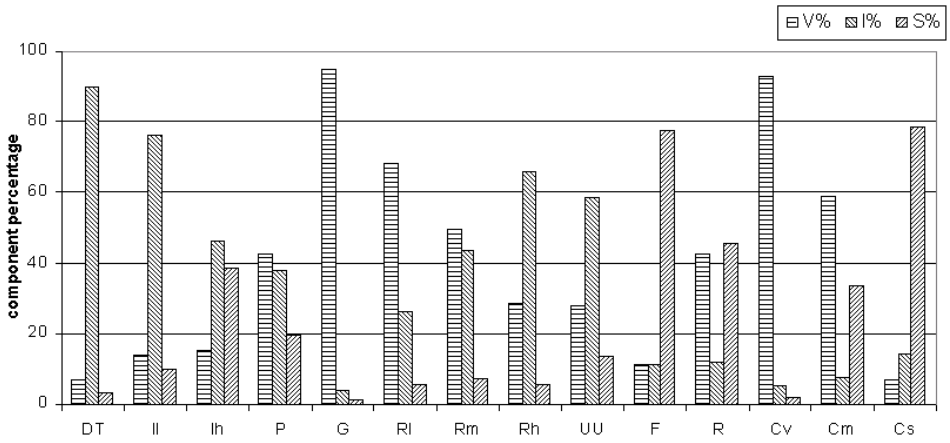
	V%	I%	S%	Red	NIR
DT	7	90	3	106	86
Il	14	76	10	104	110
Ih	15	46	39	104	109
P	43	38	20	53	116
G	95	4	1	48	213
Rl	68	26	6	67	126
Rm	50	43	7	71	117
Rh	29	66	6	76	105
UU	28	59	13	89	124
F	11	11	78	32	110
R	43	12	45	35	119
Cv	93	5	2	44	184
Cm	59	7	33	46	141
Cs	7	14	79	178	167

Figure 8. Mapping general urban features: downtown (DT), light industry (Il), heavy industry (Ih), city park (P), golf course (G), low density residential area (Rl), medium density residential area (Rm), high density residential area (Rh), UU campus (UU), foothill (F), ranch (R), crop field with green vegetation (Cv), crop field with mixed vegetation and soil (Cm), crop field with soil (Cs).

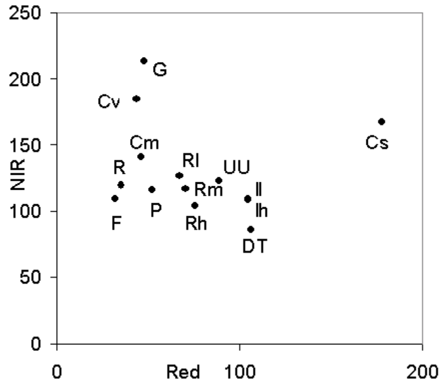
Knowing the differences between land cover materials and land use types, it would be easy to explain some similarities in figure 8 (c), such as these between the university campus (UU) and a high-density residential area (Rh), between a ranch (R) and a crop field with mixed vegetation and soil (Cm), and between a foothill (F) and a crop field with soil (Cs).

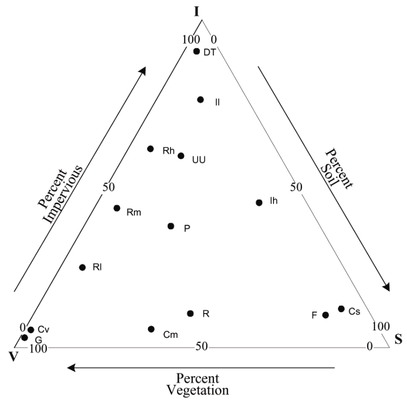
(2) Spatial Profiles

In addition to V-I-S composition for general urban features, five spatial profiles, as illustrated in figure 9, were drawn on the ETM+ satellite image and associated ground component percentage images to show V-I-S composition change across urban landscapes. These profiles show only the general, not detailed, trend of ground composition change. They have been divided into sections according to land use types. The following figures illustrate these profiles in plot format, but the land use types along the X axis are not to scale. In addition, ground component percentages for each section along the profiles are created by averaging all pixels within that section.



(a) In a chart





(b) In a feature space plot

(c) In a V-I-S diagram

The first profile goes from Salt Lake City's downtown commercial area (CM) eastward across a high density residential area (Rh), a medium density residential area (Rm), a low density residential area (Rl), a building complex (B), and reaches the foothill (F) of vegetation, exposed soil, rocks, and topographic shadows, a distance of approximately 6000 meters. The changing composition is quantified in table 3 showing an increase in V percentage (12-67 percent) and a decrease in I percentage (84-26 percent) from CM to Rl until B and F alter the trend. S percentage remains low (4-7 percent) until B and F are reached. The Red and NIR are consistent with these values. Figure 10 further illustrates these relationships in three graphic forms. Figure 10 (a) illustrates the interchange between V percentage (stably increasing) and I percentage (stably decreasing), while S percentage remains consistently low (7 percent or less) until B and F are reached. Undoubtedly the building complex (B) has high I percentage value, which will alter the trends of I percentage from decreasing to increasing. In the meantime, it will also alter the trends of V percentage from increasing to decreasing. It is right next to some exposed soil and rocks. Therefore, S percentage increases a little. Finally, this profile ends at foothill. This part of the

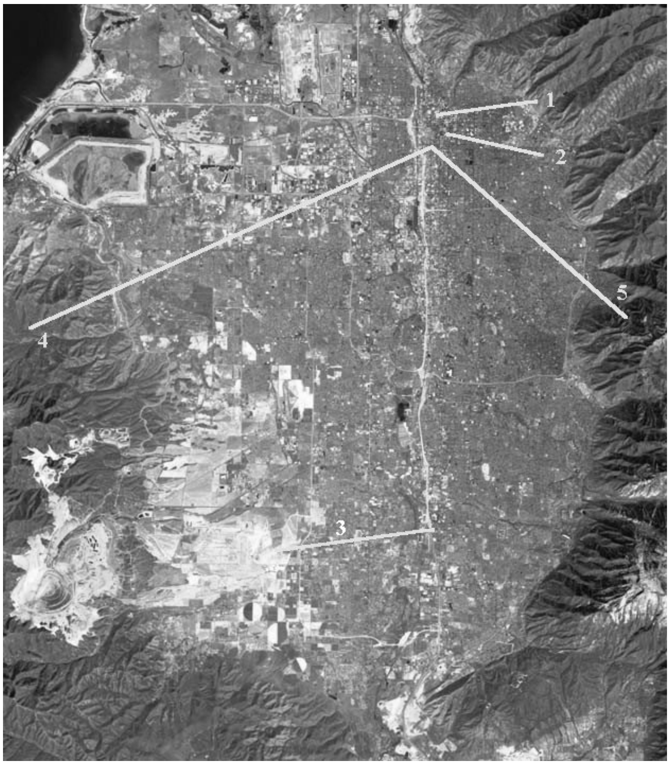


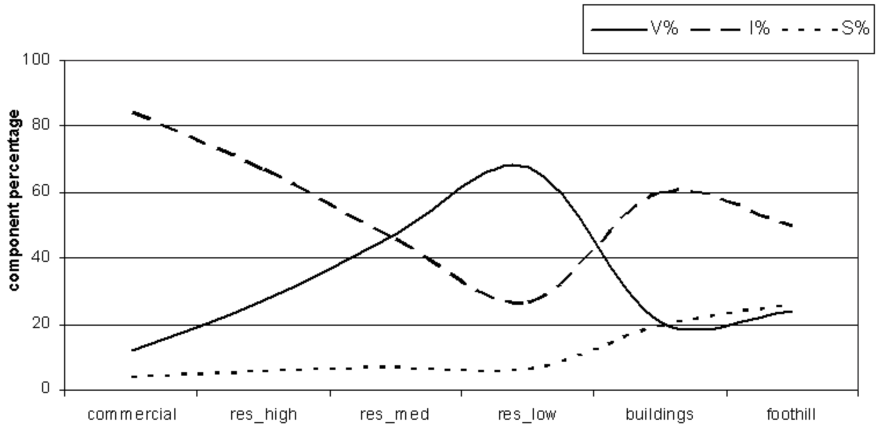
Figure 9. Five spatial profiles across urban landscape.

foothill consists of vegetation, exposed soil, rocks, and occasionally topographic shadows caused by high and sudden shifts of elevation in the terrain. Because of rocks and shadows, the I percentage is higher than expected, but it practically is a mixture of V, I, and S. Figure 10 (b) shows the changes in Red and NIR in feature space plot. NIR increases while Red decreases as the profile starts from CM moving to Rl. From Rl to F, The trends changes as Red increases but NIR does not change much. Figure 10 (c) shows the migration through the V-I-S diagram. It starts near the I corner indicating high I percentage. It then moves along the I axis toward the V corner indicating the interchange between I and V percentage. Suddenly it turns toward the S axis indicating increases in I percentage and S percentage. It then ends near the center of the diagram indicating a mixture of V, I, and S.

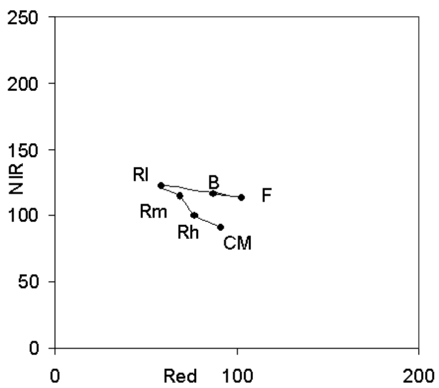
The second profile goes from Salt Lake City's downtown commercial area (CM) toward the southeast across a high density residential area (Rh), a medium density residential area (Rm), a low density residential area (Rl), and reaches a golf course (G), at an approximate distance of 6000 meters. In this case with the profile ending in a golf course, V percentage continues to increase as expected at the expense of I percentage, as shown in table 4 and figure 11. This is an ideal profile to quantitatively illustrate the interchange between V, I, and S components across an urban landscape. As noticed from figure 11 (a), S percentage remains consistently low, while I percentage stably decreases from urban centers toward city boundaries and V percentage stably increases at the same time. The V-I-S diagram in

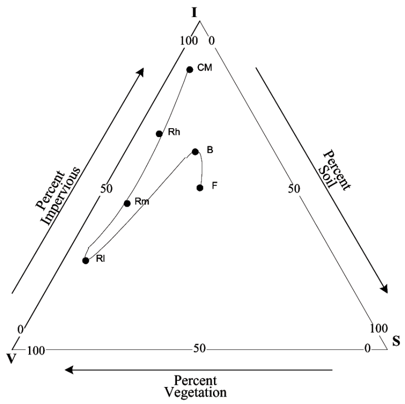
Table 3. The first spatial profile: Salt Lake City downtown commercial area (CM), high density residential area (Rh), medium density residential area (Rm), low density residential area (Rl), building complex (B), foothill (F).

	V%	I%	S%	Red	NIR
CM	12	84	4	91	91
Rh	27	67	6	77	100
Rm	47	46	7	69	115
Rl	67	26	6	59	123
B	21	60	19	103	114
F	24	50	26	87	116



(a) In a chart





(b) In a feature space plot

(c) In a V-I-S diagram

Figure 10. The first spatial profile: Salt Lake City downtown commercial area (CM), high density residential area (Rh), medium density residential area (Rm), low density residential area (Rl), building complex (B), foothill (F).

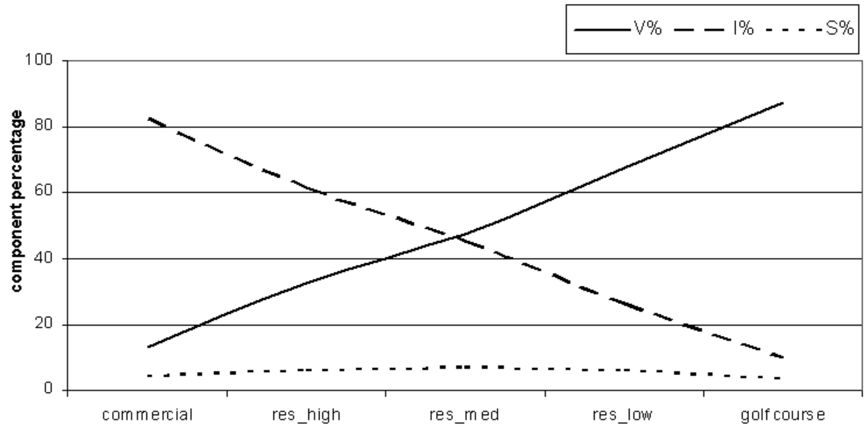
figure 11 (c) shows a constant trend from the I corner with high percent impervious surfaces to the V corner with high percent vegetation. The feature space plot in figure 11 (b) verifies this trend, a stable increase in NIR with a stable decrease in Red. This profile presents a typical trend moving from the inner city towards city boundaries: decreases in impervious surface, increases in vegetation, and fluctuations in soil.

The third profile goes from a commercial area (CM) across a mixture of residential and commercial areas (MX), and reaches harvested farmlands (FM), at an approximate distance of 8000 meters. It is summarized in table 5 and figure 12. This profile presents another typical trend moving from the inner city towards city boundaries: an overall decrease in impervious surface, an overall increase in soil, and fluctuations in vegetation. As observed in figure 12 (a) between CM to MX, I decreases and V increases while S remain relatively stable. From MX to FM, I continues to decrease, V turns the trend to decrease, while S begins to increase. In figure 12 (c), it starts from near the I corner with high I percentage, moving along the I axis to near the middle of the I axis indicating an interchange between I and V. And then it turns toward the S axis indicating a sudden drop in V percentage. It ends somewhere near the S corner but close to the S axis indicating S as the dominating component in the landscape. As seen in figure 12 (b), Red starts decreasing but ends increasing, while NIR slowly increases.

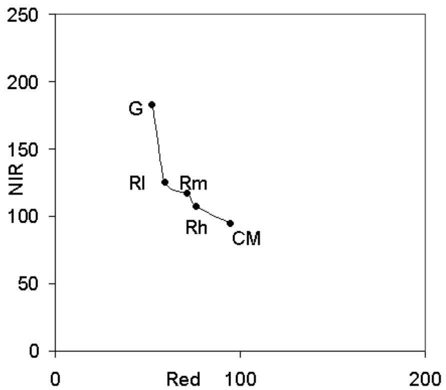
The fourth profile goes from a commercial area (CM) toward the southwest across a mixture of residential and commercial areas (MX), farmlands (FM), and reaches the Oquirrh Mountains (MT), at an approximate distance of 26,000 meters. It is summarized in table 6 and figure 13. Overall, the section from CM to FM of this profile is similar to the third profile only at a smaller magnitude: an overall decrease in impervious surface, an overall increase in soil, and fluctuations in vegetation. However, near the end, V dramatically increases at the expense of I and S as it ends at a mountainous area. This dramatic change in I near the end could be observed in figure 13 (a) and (c). In figure 13 (b), the majority of this profile remains relatively consistent from CM to FM. As it goes to MT, Red decreases and NIR increases.

Table 4. The second spatial profile: Salt Lake City downtown commercial area (CM), high density residential area (Rh), medium density residential area (Rm), low density residential area (Rl), golf course (G).

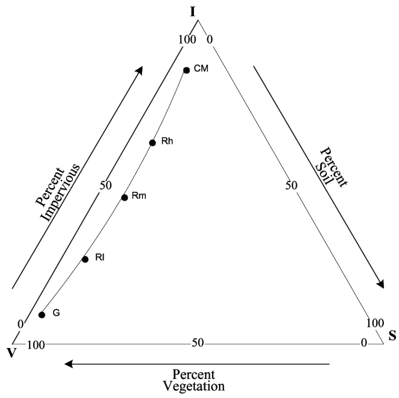
	V%	I%	S%	Red	NIR
CM	13	83	4	95	95
Rh	33	61	6	77	107
Rm	48	45	7	71	117
Rl	68	26	6	60	125
G	87	10	3	53	183



(a) In a chart



(b) In a feature space plot

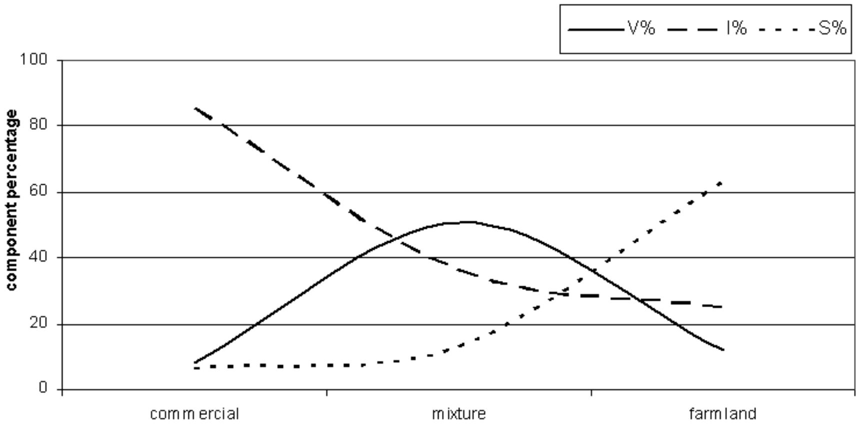


(c) In a V-I-S diagram

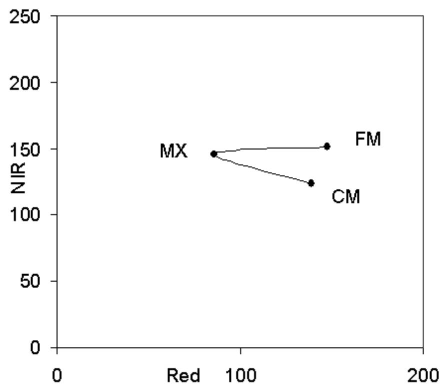
Figure 11. The second spatial profile: Salt Lake City downtown commercial area (CM), high density residential area (Rh), medium density residential area (Rm), low density residential area (Rl), golf course (G).

Table 5. The third spatial profile: commercial area (CM), mixture of residential, commercial, and agricultural areas (MX), farmlands (FM).

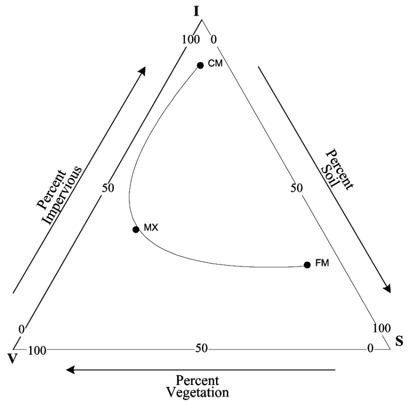
	V%	I%	S%	Red	NIR
CM	8	86	6	139	124
MX	51	36	13	86	146
FM	12	25	63	148	151



(a) In a chart



(b) In a feature space plot

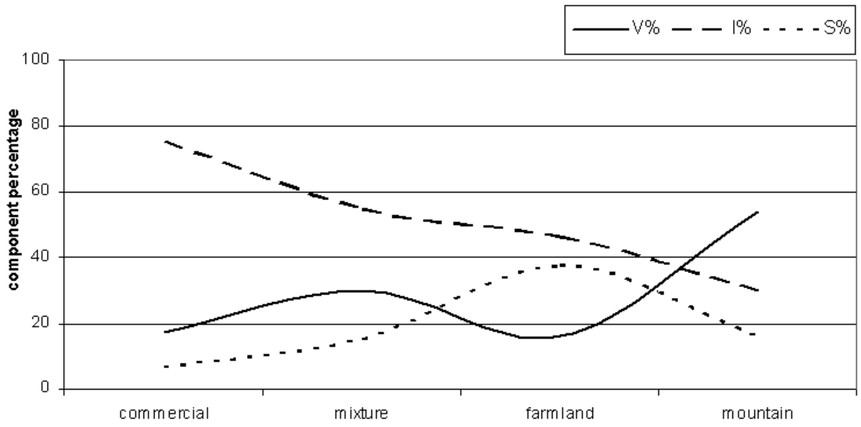


(c) In a V-I-S diagram

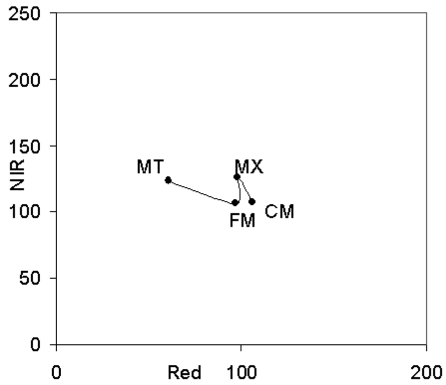
Figure 12. The third spatial profile：commercial area (CM), mixture of residential, commercial, and agricultural areas (MX), farmlands (FM).

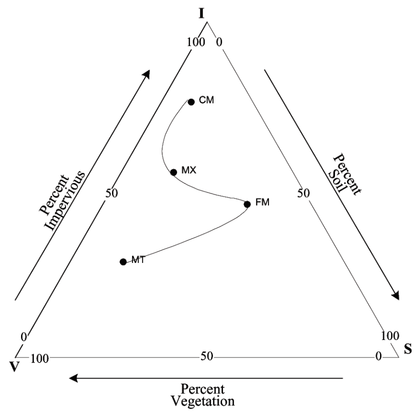
Table 6. The fourth spatial profile: Salt Lake City downtown commercial area (CM), mixture of residential, commercial, and agricultural areas (MX), farmland (FM), Oquirrah Mountain (MT).

	V%	I%	S%	Red	NIR
CM	17	76	7	106	107
MX	30	55	15	98	126
FM	16	46	38	97	107
MT	54	30	16	60	124



(a) In a chart





(b) In a feature space plot

(c) In a V-I-S diagram

Figure 13. The fourth spatial profile: Salt Lake City downtown commercial area (CM), mixture of residential, commercial, and agricultural areas (MX), farmland (FM), Oquirrah Mountain (MT).

The fifth profile goes from a city commercial area (CM) toward the southeast across a mixture of residential and commercial areas (MX), and reaches the Wasatch Front (MT), at an approximate distance of 15,000 meters. This transition is similar to the second profile in terms of V-I-S composition only at a smaller magnitude, and is exhibited in table 7 and figure 14. As expected in figure 14 (a), S percentage remain consistent while V stably increases and I stably decreases. Figure 14 (c) shows a trend of moving from the I corner to the V corner indicating an interchange between V and I, while S remain relatively unchanged. Seen in figure 14 (b) is a decrease in Red with a fluctuations in NIR.

The setting for cities in general is a commercial core moving outward through high density, medium density, and low density residential areas, to agricultural areas or natural environments. Responding to this setting in terms of V-I-S composition is a trend of decreasing impervious surfaces and increasing vegetation and/or soil. This trend holds for Salt Lake City. A graphic display of this trend can be found in all of these five profiles. A common theme among them is the significant decrease in impervious surfaces. Depending on where the profile ends, some profiles may have significant increases in vegetation, such as the second and fifth profiles, others may have significant increases in soil, such as the third profile. However, there are many variations as seen in these profiles. The main reason for these variations is that areas peripheral to the metropolis vary from foothills to irrigated farms, dry farms, desert ranges, and saline areas near the Great Salt Lake. In addition, like most large cities, there are satellite shopping centers and small towns with their own concentric rings of configuration.

The V, I, and S percentage are obvious both in line charts as in figures 10 to 14 (a) and in V-I-S diagrams as in figures 10 to 14 (c). On the other hand, feature space plot as in figures 10 to 14 (b) show the changes in two bands of the satellite image pixel brightness values: red visible (Red) and near infrared (NIR). Though the Red/NIR feature space plot is not directly linked to V, I, and S percentage, it indirectly shows the changes in impervious surfaces and vegetation. Strength of visible light (Red in this study) is strongly related to impervious surface. Bright impervious surface (Ibr) has high Red values, medium impervious surface (Imd) has medium Red values, and dark impervious surface (Idk) has low Red values. Strength of near infrared (NIR in this study) is strongly related to vegetation. Green grass vegetation (Vgg) has high NIR values, and Tree/shrub vegetation (Vts) has medium NIR values.

Discussion and Summary

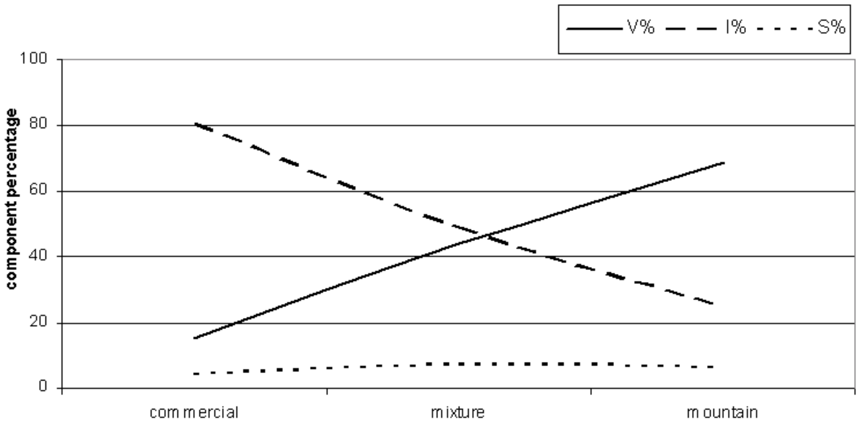
This study proposes a direction for urban environmental modeling. This direction involves the V-I-S model to study and analyze urban areas in terms of land cover materials, not land use types. It cannot be over-emphasized that it is land cover materials that can be sensed remotely, not land use types, which can only be inferred by human interpretation.

Unlike other remote sensing projects, this study did not assign any single land use/cover type to pixels. Instead, urban areas are represented by three numbers indicating the percentages of three basic land cover materials found in urban areas. By this representation, urban areas are simplified and described by land cover composition. An assumption was made: urban areas are made of only these three basic land cover components. Therefore, a closed number system is utilized to ensure the total equals 100 percent. Though a closed number system is a natural choice for representation of composition, it enforces an inverse relationship between components so that one increases others must decrease. In a modeled or the real world urban environment, this is naturally expected because there is only one material could be seen on the “top” of the land. Therefore, one land cover material appears more, others must appear less. However, further studies should be conducted to explore the impact brought by using a closed number system.

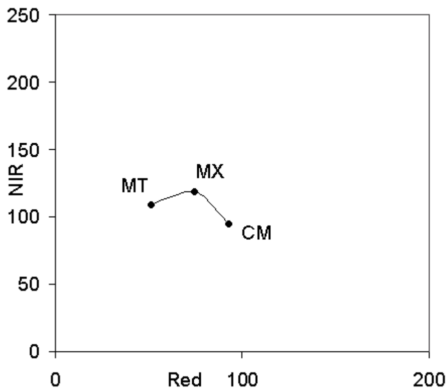
Overall, the relationship between the estimated ground component percentage and surveyed ground component percentage is significant. It suggests that the ground component percentage estimation is accurate for use in further analyses. However, it is still believed that more studies should be conducted

Table 7. The fifth spatial profile: Salt Lake City downtown commercial area (CM), mixture of residential and commercial areas (MX), Wasatch Front (MT).

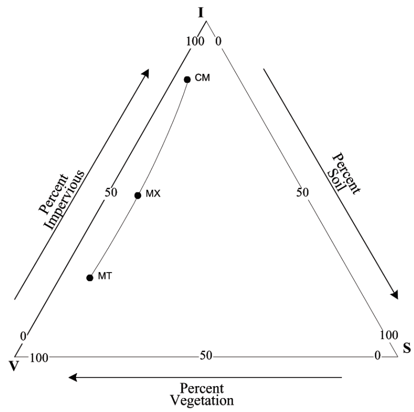
	V%	I%	S%	Red	NIR
CM	15	81	4	93	94
MX	44	49	7	75	119
MT	69	25	6	52	109



(a) In a chart



(b) In a feature space plot



(c) In a V-I-S diagram

Figure 14. The fifth spatial profile: Salt Lake City downtown commercial area (CM), mixture of residential and commercial areas (MX), Wasatch Front (MT).

in order to have a better understanding of the accuracy of this process and to find ways to improve it.

Scale is a consideration when performing quantitative urban environmental modeling. The quantitative data of general urban features is greatly affected by the size of the selected feature. As one may notice, the quantitative data of features is derived from small areas. This is so to preserve uniqueness in V-I-S composition in each feature. A large area may contain a great variety in land cover materials and, therefore, generalize the uniqueness in V-I-S composition. There is much room for studying the effects of scale on an urban environmental modeling.

Spatial profiles are also affected by scale. The profiles in this study show a general trend of changes in V-I-S composition. Each profile is divided into sections according to land use types it crosses. Each section may consist of hundred of pixels, but is only represented by one V-I-S composition. Such division and generalization is necessary to show the general, not detailed, trend of changes in V-I-S composition. Without it, spatial profiles will show changes in V-I-S composition from pixel to pixel, which may fluctuate immensely and hide the general trends.

It should be noted that though in this study the urban features and spatial profiles show only one set of V-I-S percents, it does not imply that they appear with only this combination. These V-I-S percents were derived from averaging over selected areas (for urban features) or lines (for spatial profiles). There are variations on the V-I-S percents within each feature or profile. If all of these variations were to be shown, some figures would look differently. For example, each dot in figure 8 (c) would be replaced by a cloud of dots and centered at the averaged dot. Also, the smooth line in figure 9 (a) would be redrawn as a spiky line following the same direction as the averaged line goes. With such representation, though details are shown, general trends are lost. There is much room to explore the variations on the V-I-S percent within each feature or profile. However, it is necessary to do the average and show only the general trend for the purpose of a descriptive model which is to simplify the study area into a modeled area for easy comprehension and further studies.

An urban environmental modeling is made possible in this study through the V-I-S Model. Ground component percentage images provide quantitative data on urban areas. Land cover composition on general urban features and spatial profiles across urban landscape were extracted and shown in a quantitative manner with tables, charts, plots, and diagrams. The amount of land cover materials and spatial distribution of them may provide valuable information to other urban studies. To name a few, urban heat island is greatly affected by presentence of impervious surfaces. Knowing the temperatures and the amount and spatial distribution of impervious surfaces, one may study the contributions from different types of impervious surfaces to urban heat island. Urban runoff is also greatly affected by impervious surfaces and vegetation. One may study the impacts brought by different configurations of vegetation and impervious surface. Urban planning concerns the existence of green space. One may utilize the land cover composition data to monitor, maintain, or design urban green space, such as the needs of green spaces in communities. Even more, combined with demographic or socio-economic data, this quantitative data could assist in population projection and inner-city population migration studies.

The classification methodology was originally developed by Hung and Ridd (2002). Their approach could be easily modified and applied to other study areas or other satellite images. The requirement for spectral resolution is minimal. In addition to Landsat images, many popular satellite images, such as SPOT or Formosat-2 image, could be used with only few adjustments.

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