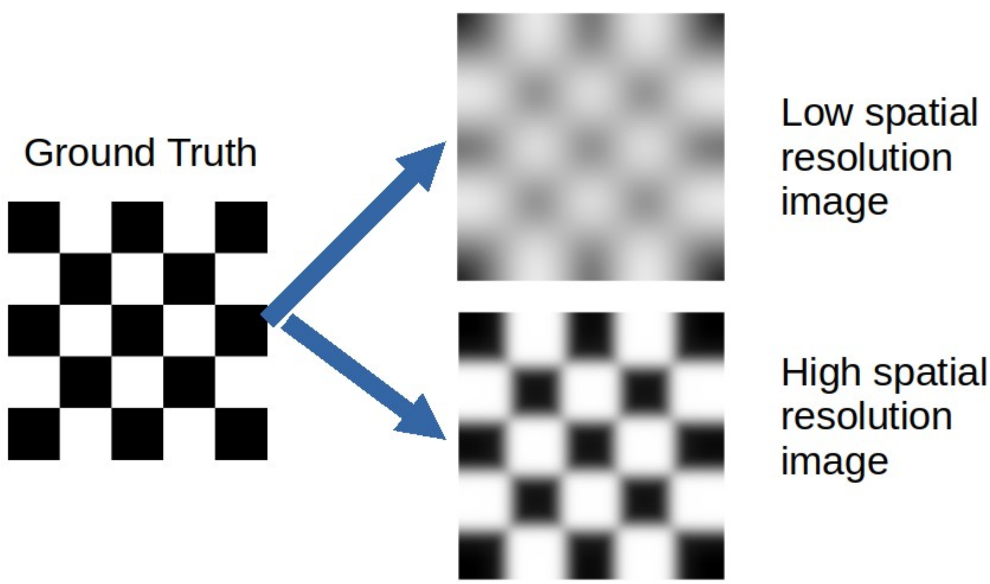
Remote Sensing Comprehensive (25 points each)
Read all questions first. Answer each statement or question thoroughly and in complete sentences. Figures need to be used where noted, and the text response should connect to each figure. Figures need to be well described. Some questions will require more information than others. See rubric for the grading of each question. A total of at least 160 points are needed to pass.

1. **Describe the four types of resolution that are important for remote sensing and the tradeoffs between them. Think about the application of each of the different resolutions and discuss what applications are better suited for certain resolutions. Use figures to help explain.**
The four basic types of resolution are spatial, spectral, radiometric, and temporal.

Spatial: In digital imagery, this refers to the minimum geographic area whose irradiance can be primarily attributed to the response of a particular pixel on the detector and is commonly measured in meters-per-pixel (for square pixels). What constitutes “primarily attributed” varies depending on definition, but often relies on the modular transfer function (MTF), which identifies what spacing of black-and-white sinusoidal patterns can be distinguished, a rudimentary version of which can be seen in the below figure. As resolution decreases, fine spatial features (in these cases the edges of the squares) can no longer be distinguished and pixels tend to represent radiance averages of larger and larger areas. In film/analog imagery, the MTF as evaluated by a human interpreter can be used to estimate spatial resolution, though the more common measure is magnification ratio, as calculated from the distance-to-target and the effective focal length of the sensor.



Spectral: This refers to the number and width of the wavelength bands detected by a sensor. A panchromatic sensor has poor spectral resolution, as it does not distinguish different wavelengths. A standard red-green-blue (RGB) sensor would have better spectral resolution and a hyperspectral sensor, typically with hundreds to thousands of bands with some standard width (such as 10nm) would be considered to have a high spectral resolution.

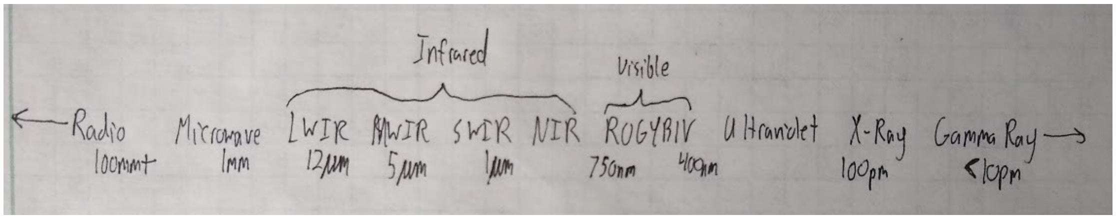
Radiometric: This refers to the number of distinct light levels detectable by the sensor. In digital imagery this is usually 2 to the power of the number of bits used to store the data, but is also limited by the sensitivity of the sensor itself.

Temporal: This refers how frequently the sensor revisits the same location. For geostationary (GEO) satellites, this is only limited by the capture rate of the sensor and the bandwidth of the satellite downlink. For individual low earth orbit (LEO) satellites with common fields-of-view (FOV), it is more commonly in the range of 10-20 days.

Regarding tradeoffs, spatial and temporal are the most closely linked. High spatial resolution usually requires a relative close proximity of the sensor to the target, such as LEO (~200km – 2000km altitude). This however means a smaller FOV and a longer period of time between revisits. More continuous imagery can be obtained at GEO (~35,000km altitude) but the significantly greater distance to target results in worse spatial resolution. There is also a link between spatial resolution and spectral resolution. Wider bands enable more light per pixel to be collected, increasing the signal-to-noise ratio (SNR). As a result, panchromatic sensors typically have better spatial resolutions than multispectral or hyperspectral sensors. Spectral and radiometric resolutions are more typically limited by hardware complexity, sensitivity, and data processing rate limitations. A higher spectral resolution means that some method is required to distinguish each band. For hyperspectral sensors, this is commonly done using a push-broom sensor grid, where each row captures a different wavelength. This is significantly more complex than a multispectral sensor and also generates data at a much higher rate. Radiometric resolution is similarly limited by the bits available per pixel for imagery, but is also sensitive to noise. A very high radiometric resolution is sensitive to slight variations in radiance intensity, particularly when looking at darker targets. Counteracting this requires noise suppression methods such as cooling.

In general, the set of requisite resolutions required for an application depend on the scale of the phenomena in each of this dimensions. Changes in climate operate at large, even global spatial scales, over the course of years, and are primarily involving relatively small changes in average radiance levels over time. As a result, spatial and temporal frequency are not as important as large FOVs and consistent, well calibrated imagery, meaning that radiometric and spectral resolutions need to be reliable. On another extreme, urban traffic patterns vary significantly over the course of a single day and require a sufficiently high spatial resolution to detect automobiles. These combined requirements of high spatial and temporal resolutions (which usually are at odds with one another) have historically made this application unsuitable for satellite monitoring. Vegetation species identification usually requires a high spectral resolution (so as to be able to distinguish different species) and reasonably high spatial resolution (so as to reasonably capture areas that contain distinct species).
It should be noted that in some forms of sensing, particular active sensing, phase and polarization are two other forms of resolution that may be relevant.

2. **Describe the electromagnetic (EM) spectrum and how it relates to remote sensing.**



The electromagnetic (EM) spectrum refers to the various wavelengths/frequencies (the two are inversely proportional to one another) of light, including (from longest wavelength to shortest) from radio, microwave, infrared, visible, ultraviolet, x-ray, and gamma ray, as seen in the figure below. These different wavelengths are generated in different amounts by different sources, interacting with media in different ways, and are detectable in different ways. Each of these three elements are relevant in remote sensing of Earth.

Regarding light sources, passive sensors rely on light generated by other sources and are thus limited in detecting such light. The sun, the primary source of light on Earth, emits primarily in the infrared-through-ultraviolet spectrum (though ultraviolet is largely stopped by the atmosphere), limiting their use to this range. The surface of Earth meanwhile emits primarily blackbody radiation in the infrared range. Other frequencies, particularly microwave and radio, largely require the use of active sensors that generate their own light. X-rays and gamma rays are not usually relevant in an Earth sensing context.

Regarding media interaction, different media absorb, scatter, reflect, and transmit light of various wavelengths in differing amounts. In order for a sensor to measure, it must receive light. Unless they are directly looking at a light-emitting source, this requires that the target reflected the light, and that the light was able to pass through an intermediate media. Wavelength bands must thus be appropriately chosen to generate some meaningful measurement with regards to the target and to avoid extinction in the intervening media.

Regarding detection, generally the higher the intensity of light and the shorter the wavelength are, the higher the resolution (spatial and radiometric) will be. This is partially due to noise generated by blackbody radiation of the target, the intervening media, and the sensor itself. If the sensor is trying to measure dim sources with long wavelengths, noise suppression methods will be required.

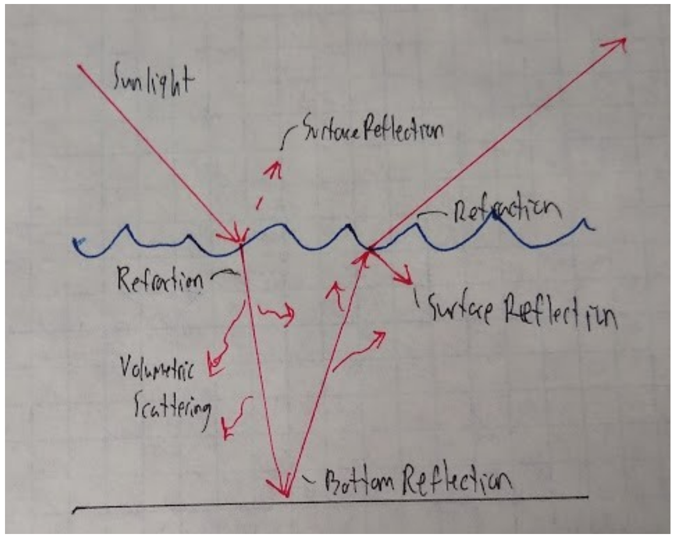
3. **Discuss how sections of the EM spectrum interact with different objects including the atmosphere, land, and water. Be sure to consider the ways light moves through a medium and what parts of the spectrum are best suited for terrestrial and aquatic applications and why. Use figures to help explain.**

As stated in the previous section, matter tends to do some combination of absorb, scatter, reflect, transmit, and emit light. The upper atmosphere effectively blocks most frequencies higher than visible (ultraviolet, x-ray, etc.), either absorbing or reflecting it back to space. It allows visible light to be transmitted for the most part (nuances to this are discussed in Question 5). In the infrared and microwave ranges, the atmosphere transmits some bands and blocks others, largely dependent on the absorption bands of water vapor. This means that, in these regimes, bands must be chosen carefully. The K-band of microwaves, for instance (12-28 GHz) is split into a Ku (K under, 12-20 GHz) and a Ka (K above, 24-28 GHz) sections, to avoid the water vapor absorption band centered around 22 GHz. Radio waves shorter than 10m are generally transmitted, with those longer often reflected by the ionosphere.

Land is opaque to most forms of light and thus doesn’t transmit. What parts of the EM spectrum it reflects or absorbs varies significantly depending on the landcover type. That said, in general land tends to reflect longer wavelengths and absorb shorter wavelengths. This is relative however, and even a significant portion of fairly short wavelength visible light is reflected by most landcover. The primary variation in reflectivity/absorption of different landcover types takes place in the visible through infrared region, meaning that spectral resolution in this regions are key to distinguish and monitoring most terrestrial systems. The reflectivity of land in the microwave and radio regimes does mean that these are fruitful areas for active sensing, particularly of factors such as elevation and geometry.

Water, as a fluid, sits somewhere between the atmosphere and land with regards to light. Like the atmosphere, it is not completely opaque, though it is much more so than air. It reflects and transmits some light in the ultraviolet through visible portions of the spectrum (particularly around blue), but tends to absorb anything lower frequency than that. This means that bathymetry measurements are typically focused on the green-to-blue area, as these will penetrate water further than other frequencies. Water also has an emittance of near 1 in the infrared regime, meaning that is effective blackbody temperature is quite close to the ideal blackbody temperature, making infrared-based measurements of surface water temperature quite straightforward.

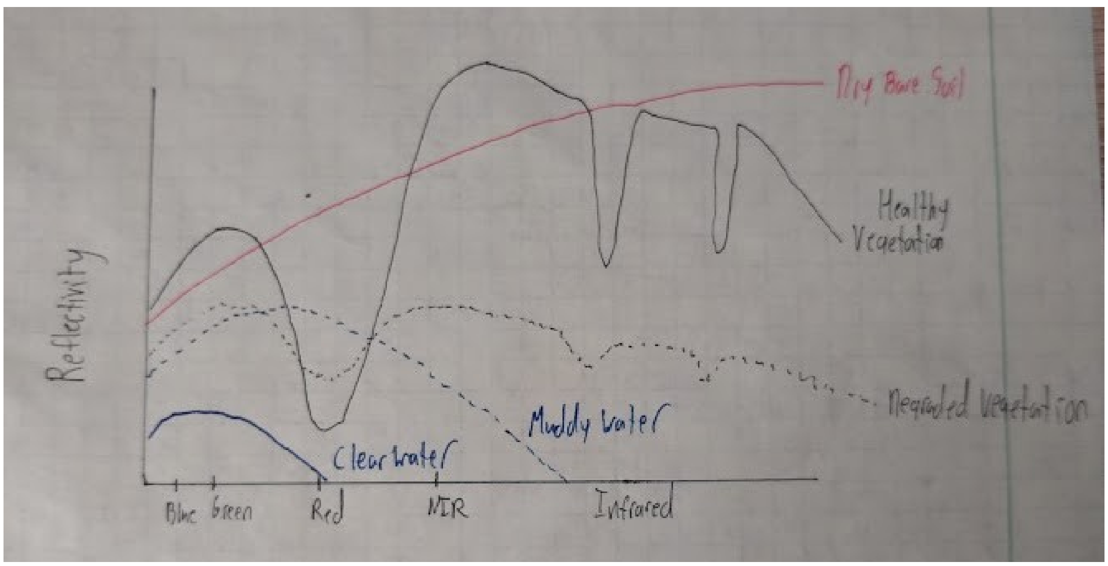
For both air and water, some light will be reflected upon impact with a surface, as shown in the below figure. The light will then refract and, as it continues, some will be lost to volumetric scattering and absorption before striking the next surface and continuing back upwards.



With both water and the atmosphere, the addition of other components (smoke, aerosols, particulate matter in air; suspended minerals, chlorophyll, dissolved organic matter in water) alter their behavior with regards to light. In air, the addition of pollutants tends to scatter or absorb shorter wavelengths (such as the visible spectrum). This means that these pollutants can be detected with such wavelengths (a blue is commonly used for aerosols) and that, if you desire to observe the surface through pollutants, longer wavelengths are required (such as infrared beds that are strongly correlated with red). In water, the addition of chlorophyll increases the green reflectivity while decreasing other wavelengths. Suspended minerals tend to make water more reflective (like land) and move its peak reflectivity towards red (rather than blue).

4. **Thoroughly explain how the optical EM spectrum interacts with vegetation. Use figures to help explain, and draw typical EM signatures of 1) healthy vegetation, 2) degraded vegetation, 3) clear water, 4) muddy water, 5) dry bare soil**

There are three primary factors that drive the EM response of vegetation. The first is the presence of various pigments (or lack thereof), the most notable of which is chlorophyll. It is chlorophyll, contained in the palisade mesophilial cells on the outside of leaves, that grants vegetation its characteristic green reflectivity. Other pigments are more reflective of reds and yellows, as seen in the fall trees in the New England area when chlorophyll is withdrawn for the winter. The second factor is the significant water content of plants, resulting in the characteristic infrared and microwave absorption bands that water has. The third are the numerous water-air interfaces in the spongy mesophilial cells in the interior of leaves. These tend to scatter and diffuse near infrared (NIR), reducing the heat absorbed by the plants and generated a high NIR reflectivity characteristic of healthy vegetation, as seen in the figure below. As vegetation degrades, its visible reflectivity shifts towards red due to the loss of chlorophyll. Its NIR peak lowers and its IR water absorption troughs diminish due to the lower water content.



The reflectance characteristics of clear and muddy water, as well as land, were discussed in the response to Question 4 and can also be seen in the above figure. In general, muddy water tends to pull the water reflectance curve towards that of soil.

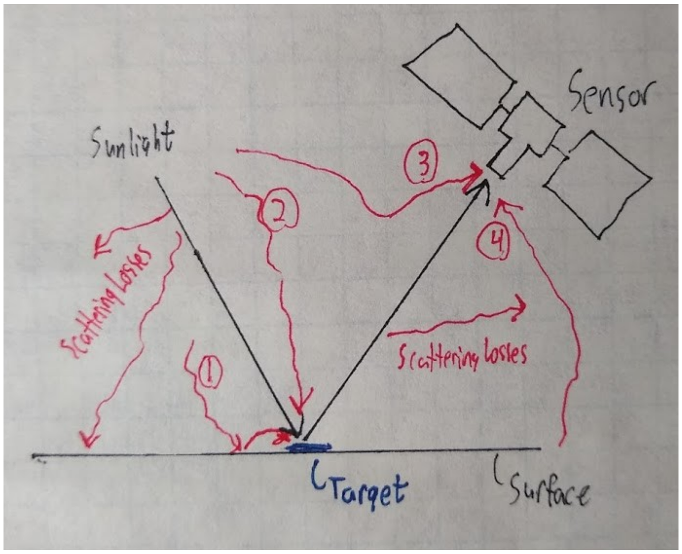
One notable use of these differing curves, plus the particular phenological trajectory of most vegetation in this space, means that vegetation and soil can be mapped as a sort of ‘tasseled cap’ in green, red, NIR space that can be used to readily identify vegetation and determine its health.

5. **Why is the sky blue and the sunset orange/red? Why is atmospheric correction needed for satellite imagery?**

As briefly discussed in Question 3, the atmosphere transmits, scatters, and absorbs light in a frequency-dependent way. One of the two primary ways in which the atmosphere does this is Rayleigh scattering (the other is aerosol/Mies scattering). The degree of

Rayleigh scattering is inversely proportional with the fourth power of wavelength. Longer wavelengths are thus scattered less and significantly so. Blue light, the shortest wavelength of the visible spectrum, is thus scattered more than any other visible light. This results in sunlight being scattered differentially, with the reds, yellows, and even greens, largely proceeding in straight lines, but the blue scattering every which way, thereby giving the entire sky that doesn't contain the sun and blue appearance. This same explanation holds for the reddish orange of the sunset. When the sun is setting, its light passes through more of the atmosphere than at midday. There is thus more opportunity for shorter wavelengths to be scattered in different directions. As a result, most of the blue and green has been scattered by the time the light reaches your way, distributed across the rest of the sky, and leaving only the red and orange light.

Atmospheric correction is needed because, except for atmospheric scientists, most earth scientists are interested in the surface of the Earth, not the air. In particular, scientists are typically interested in the portion of light reflected by a target. Remote observation sensors, however, are directly measuring the light that reaches them, not the value of interest. For passive daytime sensors, as seen in the figure below, the source light was originally generated by the sun, passed through the atmosphere (with portions of it being scattered and absorbed), it strikes the surface (the actual component of interest for measurements), then passes through the atmosphere again on the way to the surface. This introduces all sorts of error. Not only does the extinction coefficient of the atmosphere (the scattering losses and the atmospheric absorption) need to be taken into account, but so do sky irradiance (red lines 1 and 2) and path radiance (3 and 4). These are dependent on the amount of atmosphere along the path from sun-to-surface-to-sensor (which in turn depends on their relative angles) and atmospheric composition, temperature, and humidity. Only by subtracting these can we determine the portion of sunlight reflected by the target. Even passive sensors looking at Earth-emitted light and active sensors must deal with this problem, though obviously the exact configuration will be somewhat different.



6. **Describe the differences between active and passive sensors. What are some different applications for each sensor type? What are some tradeoffs between active and passive satellite platforms?**

As alluded to in the previous responses, passive sensors detect light generated by other sources, such as the sun, the Earth itself, or objects on the surface of the earth (fires, nightlights, etc.). Passive sensors are thus limited to observing phenomena detectable in the bands generated by these outside sources. Active sensors themselves generate light of some form and then measure the response. This allows for a wider range of bands of light to be used, including microwave and radio waves. It also allows for polarization, phase, and return time to be used to generate additional insights. Most light sources emit unpolarized light, so polarization carries no information for passive sensors. Active sensors can intentionally polarize the light they emit however, then measure differences in the polarization of the return signal. This can be used for such purposes as distinguishing the relative amounts of vertical and horizontal components in the structure of vegetation. Phase differences allow for interferometry, a whole branch of imaging in its own right. Return time allows for distance to be measured, enabling active sensors to measure the elevation of a target.

The benefits of active sensors do come at a cost, however. Generating light requires additional hardware complexity and higher power requirements. For these reasons, a given instrument is usually limited to emitting only a small number (commonly one) of wavelengths, while a passive sensor can easily contain detectors for a plethora of wavelengths. Furthermore, active sensors usually are only able to illuminate a small area at a time, particularly if using shorter wavelengths such as the visible spectrum. The sun generates an immense amount of light that enables a passive sensor to monitor a huge FOV with high precision.

In general, these tradeoffs lead to active sensors only being used for those things that they are uniquely capable of doing: elevation, media movement, structural analysis, etc. Passive sensors are then relied upon for all other forms of measurement.

7. **Describe the fundamental aspects of spectral and textural indices. What are some common examples, why are they used, and what does the metric value represent and why?**

The idea being indices is to have some quantitative method of distinguishing targets and measuring change over time. Spectral indices rely on the fact that most media and targets have unique spectral responses to light. Most remote observation sensors do not have sufficient spectral resolution to conduct such a unique identification and their spatial resolution means that a given pixel usually contains some mix of landcover (such as multiple species of trees) rather than a specific type. In light of this, spectral indices are simple arithmetic spectral comparisons that are considered highly characteristic of some phenomena of interest. Perhaps the most commonly used of these is the Normalized Difference Vegetation Index (NDVI), shown below, which relies on the characteristic difference in red and NIR found in healthy vegetation of most species. It varies from -1 to 1, with values greater than 1 indicate both the presence of vegetation with increasing likelihood and the health of that vegetation.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Other vegetation-related spectral indices include the Simple Ratio, Triangular Vegetation Index, and the Atmospheric Resilient Vegetation Index. Other spectral indices include the Normalized Difference Water Index for the presence of water, the Normalized Built Up Index for the presence of human buildings, and the Normalized Difference Snow Index to distinguish clouds from snow and ice.

Textural indices serve to quantify spatial variation in a local area. The most basic of these are template-based methods that calculate the mean, standard deviation, or some other statistic of the pixels surrounding a target. A high standard deviation would mean that there is significant variation in the area, suggesting that it isn't a smooth surface or consistent landcover type. Other forms of textural indices are based on the frequency of spatial repetition of pixels of the same intensity level. These include the Grey Level Correlation Matrix (GLCM), average semivariance, and entropy. These can be used to estimate the noise of the sensor and can also be used as inputs in machine learning land cover classification systems.

8. **What are various ways one conduct a land cover classification and estimate the final map accuracy? Consider the types of algorithms used as well as what errors in the final map product mean.**

   The three primary ways of conducting a landcover classification are (1) in-situ surveying, (2) human interpretation of remote observation imagery, and (3) computer-automated forms of land cover classification. The last of these itself comes in a variety of forms:

   - Supervised Learning: A set of previously identified training data is provided and the computer uses this to develop distinguishing factors in the pattern space. Numerous methods for this exist, including maximum likelihood, minimum distance, parallepiped, k nearest neighbors, genetic algorithms, and neural networks.
   - Unsupervised Learning: A set of *unidentified* data is provided to the computer which then seeks to sort into clusters in the pattern space. These clusters may or may not corresponded to information classes on a one-to-one basis. Numerous algorithms for this exist, including iterative means, single pass, agglomerative hierarchy, and histogram peak identification.
   - Knowledge-based / Expert Systems: A set of decision rules, probabilistic or deterministic, are pre-coded as a decision tree that the computer then uses to sort pixels or objects.

It should be noted that for land cover classification, the above are usually, but not always, applied on a per-pixel basis, though commonly with various additions to help take into account spatial context.

For assessing map accuracy, the most common method is to use a confusion matrix, a simple example of which is shown below. From this various error statistics of interest can be calculated.

- Total accuracy rate: the total number of accurate classifications over the total number of pixels, which is here (70+98)/183 = 92%.
- User Accuracy Rate: the likelihood that, given a classification, the landcover is what the classifier says. For Vegetation this is 70/73 = 96% and for Soil is 98/110 = 89%.
- Producer Accuracy Rate: the likelihood that, given a type of landcover, the classifier will identify it correctly. For Vegetation this is 70/82 = 85% and for Soil is 98/101 = 97%.
- Kappa Coefficient: A more holistic, though more complicated, measurement that accounts of differences in the prevalence of different land cover types (which the above do not) and can also be used to estimate the likelihood that two different classifiers are, in fact, different to a statistically significant degree.

		Classifier		
		Vegetation	**Soil**	**Total**
Ground Truth	**Vegetation**	70	12	82
	Soil	3	98	101
	Total	73	110	183