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ESTIMATING BIOGENIC NON-METHANE HYDROCARBON EMISSIONS FOR

THE WASATCH FRONT THROUGH A HIGH-RESOLUTION, GRIDDED,

BIOGENIC VOLATILE ORGANIC COMPOUND EMISSIONS

INVENTORY

by

Jeremy V. Oldham

A thesis submitted in partial fulfillment
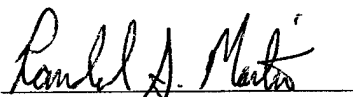of the requirements for the degree

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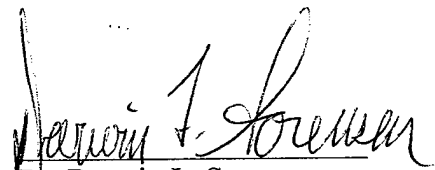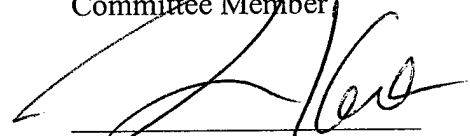
in

Civil and Environmental Engineering

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Logan, Utah

2002

ABSTRACT

Estimating Biogenic Non-Methane Hydrocarbon Emissions for

the Wasatch Front Through a High-Resolution, Gridded,

Biogenic Volatile Organic Compound Emissions

Inventory

by

Jeremy V. Oldham, Master of Science

Utah State University, 2002

Major Professor: Dr. Randal S. Martin
Department: Civil and Environmental Engineering

During the summers of 2000, 2001, and 2002, monitoring sites along the Wasatch

Front reported ground-level concentrations of ozone exceeding both the 1-hour and

proposed 8-hour National Ambient Air Quality Standards. Reactive biogenic (natural)

volatile organic compounds emitted from plants have been shown to have the potential to

increase the formation of ozone and other photochemical products.

In order to better estimate and spatially characterize the vegetative emissions of

photochemically reactive hydrocarbons along the Wasatch Front, a high-resolution, 30-

meter gridded biogenic emissions inventory was created for the Wasatch Front using

remotely sensed data. Local vegetative survey information was used to help reduce some

of the uncertainty in predicting plant species composition and frequency.

Isoprene emissions computed for the study area from the project's high-resolution gridded inventory were 65% higher than isoprene estimates from the second version of the U.S. E.P.A's currently recommended inventory, Biogenic Emissions Landcover Database (BELD 2), while monoterpene and other reactive volatile organic compound emission rates were almost 26% and 28% lower, respectively. This high-resolution emissions inventory also characterized the spatial distribution of biogenic hydrocarbon emissions within the study area at a 30-meter resolution, whereas BELD 2 assumes homogenous, countywide emissions.

This high-resolution model could potentially increase the accuracy of model predictions that utilize biogenic hydrocarbon emission estimates as input for air quality modeling and assist regulators in developing control strategies for ozone formation.

(118 pages)

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Jeremy V. Oldham

DISCLAIMER: The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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INTRODUCTION

Timeliness of Study

The state of Utah's largest population center, which includes Salt Lake City, is located along the western front of the Wasatch Mountains, locally known as the Wasatch Front. During the summers of 2000 and 2001, monitoring sites within the airshed reported high ground level concentrations of ozone (O_3) exceeding the National Ambient Air Quality Standard (NAAQS) 1-hour and proposed 8-hour standards of 120 and 80 ppb, respectively (Figures 1 and 2). Additionally, preliminary data indicate that nine exceedances of the 8-hour standard also occurred during the summer of 2002 (Figure 3) (Olson, 2002).
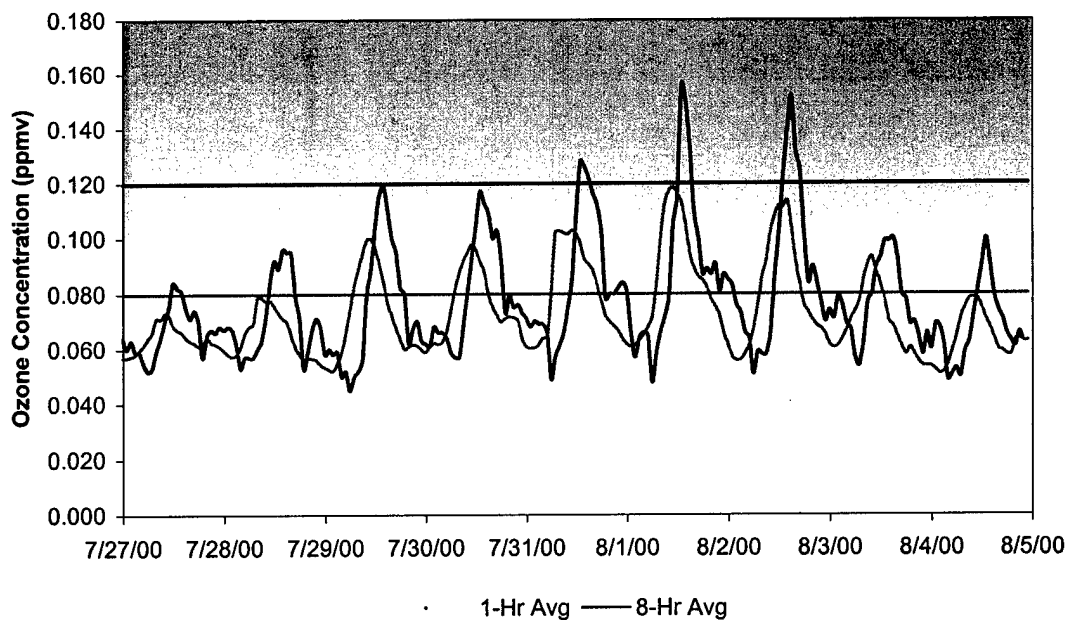
Figure 1. Composite high 1-hour and 8-hour average ozone concentrations for the Wasatch Front's ozone episode, summer 2000.
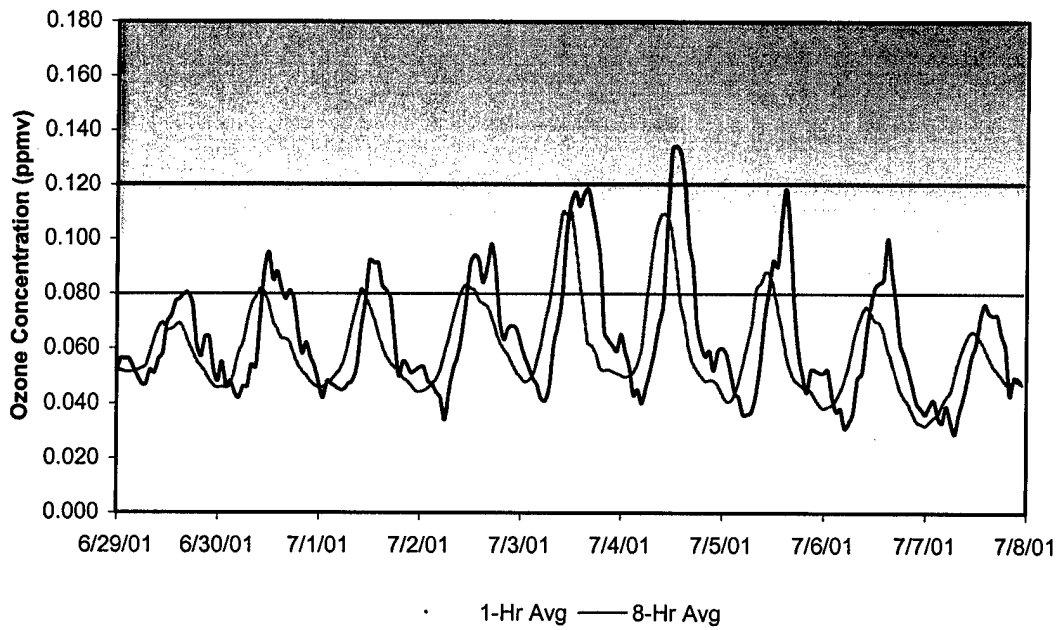
Figure 2. Composite high 1-hour and 8-hour average ozone concentrations for the Wasatch Front's ozone episode, summer 2001.
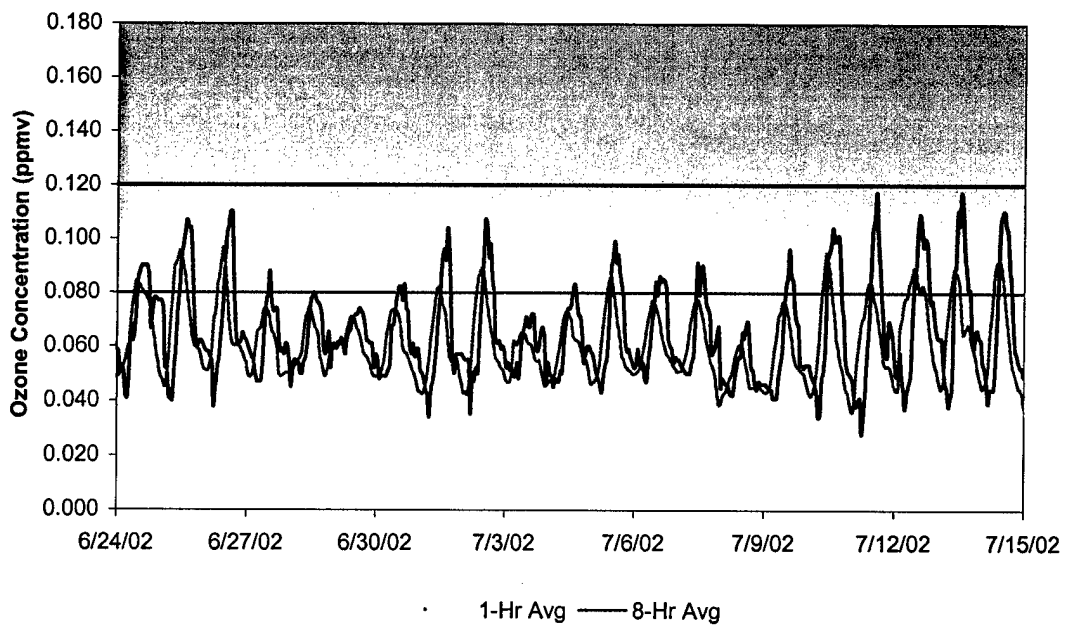
Figure 3. Composite high 1-hour and 8-hour average ozone concentrations for the Wasatch Front's ozone episode, summer 2002.

In order to remain in attainment with the 1-hour standard, the second highest daily maximum 1-hour average ozone concentration in a year cannot exceed 120 ppb averaged over three consecutive years (EPA, 2002a). Attainment of the proposed 8-hour standard is determined in a similar manner except the fourth highest daily maximum 8-hour average is averaged over three consecutive years and must be lower than 80 ppb. Although 7 exceedances of the 1-hour standard and 15 exceedances of the proposed 8-hour standard have occurred at various monitoring sites in the air shed over the past three years, no monitoring site is currently considered in non-attainment of the standard because these exceedances have not always occurred at the same location in the airshed (King, 2002).

Ozone is a strong oxidant and high ambient concentrations cause deleterious effects on human health and welfare. Reductions in lung function can occur within five minutes of exposure to concentration in the range of 20-150 ppb and chronic exposure to elevated concentrations can accelerate lung aging (Cooper and Alley, 1994). Ozone is also an eye, nose, and throat irritant, causes accelerated deterioration of synthetic rubbers, and causes crop damage at an estimated annual cost of one billion dollars in the United States (Cooper and Alley, 1994).

Photochemistry of Ozone Formation

Ozone is not emitted directly but is formed in the atmosphere through reactions of volatile organic compounds (VOCs) in the presence of oxides of nitrogen (NO_x) and sunlight. Although there are many pathways and complex reactions involved, a

somewhat simplified overview of a common pathway for ozone formation through reactions involving the VOC isoprene is presented herein.

As shown in Equations 1-3, in the presence of solar energy, ambient nitrogen dioxide (NO_2) is photolyzed by light (h = Plank's constant and v = light frequency) at wavelengths less than 400 nm to nitric oxide (NO) and ground-state atomic oxygen atoms ($O(^3P)$) (Cooper and Alley, 1994; Finlayson-Pitts and Pitts, 2000). $O(^3P)$ then quickly reacts with ambient molecular oxygen (O_2) to form O_3 which in turn reacts with NO to regenerate NO_2 and O_2.

$$NO_2 + hv \rightarrow NO + O(^3P) \qquad (1)$$
$$O(^3P) + O_2 \rightarrow O_3 \qquad (2)$$
$$O_3 + NO \rightarrow NO_2 + O_2 \qquad (3)$$
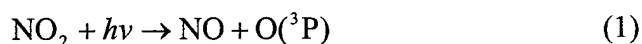
Because the rate of Reaction 1 is dependant on sunlight and the rates of Reactions 2 and 3 are temperature dependant, these reactions explain why O_3 concentrations typically show a diurnal pattern. However, they do not explain how elevated ambient O_3 concentrations occur because as equilibrium is reached, the net O_3 formation should be zero (O_3 is formed in Reaction 2 but destroyed in Reaction 3). However, alkylperoxy ($ROO\bullet$) and hydrogen peroxy ($HOO\bullet$) radicals formed by the oxidation of VOCs in the atmosphere provide a pathway for conversion of NO to NO_2 which does not destroy O_3 while allowing for additional $O(^3P)$ formation (Cooper and Alley, 1994).

Equation 4 shows how isoprene (C_5H_8), a common naturally occurring VOC, is oxidized by the hydroxyl radical ($\bullet OH$) via addition at one of the double bonded carbons to form an alkyl radical (Finlayson-Pitts and Pitts, 2000). Molecular oxygen then reacts

with the alkyl radical to form an alkylperoxy radical (Equation 5). As previously mentioned, the alkylperoxy radical then reacts with NO to form NO_2 and an alkoxy radical (Equation 6). It is important to note that the alkoxy radical undergoes further reactions which in turn produce additional byproducts including more alkylperoxy radicals. Hence, the oxidation of a single VOC molecule in the atmosphere can result in the conversion of many NO molecules to NO_2. This conversion of NO to NO_2 without destroying O_3 is what allows for an increase in net O_3 formation (Cooper and Alley, 1994).

$$C_5H_8 + \cdot OH \rightarrow \cdot C_5H_8OH \qquad (4)$$
$$\cdot C_5H_8OH + O_2 \rightarrow \cdot OOC_5H_8OH \qquad (5)$$
$$\cdot OOC_5H_8OH + NO \rightarrow NO_2 + \cdot OC_5H_8OH \qquad (6)$$

Contribution of Biogenic Volatile Organic Compounds to Ozone Formation

Biogenic volatile organic compounds (BVOCs) are VOCs emitted to the atmosphere from natural sources such as plants, animals, and microbes. Several thousand different BVOCs have been identified, some of the most well known and most abundant being methane, isoprene, and monoterpenes such as α- and β-pinene (Hewitt, 1999; Finlayson-Pitts and Pitts, 2000). Globally, emissions of VOCs by vegetation far exceed emissions from anthropogenic sources (Hewitt, 1999). Vegetation emissions also exceed anthropogenic emissions in the U.S. (Guenther et al., 1995; Kinnee, Geron, and Pierce, 1997). Estimations of global anthropogenic (human-caused) non-methane VOC emissions are on the order of 90-213 Tg per year, while estimations of global non-

methane BVOC emissions are on the order of 1150 Tg per year (Guenther et al., 1995; Hewitt, 1999). For the purposes of this paper, the term BVOC will exclude biogenic emissions of methane due to its low reactivity.

BVOCs are also generally more reactive in terms of O_3 production than VOCs from anthropogenic sources (AVOCs) (Chameides et al., 1988). The reactivity of a VOC in terms of O_3 production is based on the fact that for most VOCs, oxidation by the OH radical is predominantly responsible for VOC consumption and subsequent alkylperoxy radical formation (Finlayson-Pitts and Pitts, 2000). The rate constant for the reaction of the OH radical and the VOC then reflects the overall reactivity of the VOC. Other indicators of reactivity are the atmospheric half-life ($\tau_{1/2}$), which represents the time needed for the concentration of the VOC to fall to one-half of the original concentration due to oxidation by the OH radical, and the atmospheric lifetime (τ_L), which is the time needed for the concentration to fall to $1/e$ of the initial concentration ($e = 2.718$) (Finlayson-Pitts and Pitts, 2000). Isoprene and monoterpenes, for example, have an atmospheric half-life of around 1-2 hours as compared to toluene and propane which both have a half-life on the order of 1-10 days (Harley, Monson, and Lerdau, 1999; Finlayson-Pitts and Pitts, 2000). Prior studies have shown that in some areas, VOCs from natural vegetation contribute the major fraction of reactive hydrocarbons responsible for ozone formation. For example, Chameides et al. (1988) found that in the Atlanta area at current NO_x levels, ambient ozone concentrations would still exceed the NAAQS, even if all anthropogenic VOCs were eliminated due to the dominance of the biogenic fraction.

Regulatory Implications of BVOC Emissions

Accurate estimates of the contribution of ozone precursors by various sources are necessary so that the most efficient emission reduction plans can be implemented (Hewitt, 1999). For example, when the VOC to NO_x ratio is high (NO_x limiting conditions) reductions in VOCs, keeping NO_x levels constant, will only result in modest ozone concentration reductions, while reducing NO_x at constant VOC levels would result in larger ozone reductions (Finlayson-Pitts and Pitts, 2000). On the other hand, at low VOC to NO_x ratios (VOC limiting conditions) reducing VOC emissions at constant NO_x levels will reduce ozone concentrations, while reducing NO_x at constant VOC can initially increase ozone concentrations (Finlayson-Pitts and Pitts, 2000). Even though only anthropogenic sources are considered for reduction, BVOCs are potentially more abundant than anthropogenic VOCs and are typically more reactive, therefore, effective ozone control strategies require an understanding of biogenic as well as anthropogenic emissions of its precursor compounds (Chameides et al., 1988). Understanding what fraction of the ozone precursor compounds is natural and what fraction is anthropogenic allows regulators to make a more informed decision about what sources can feasibly be reduced. Additionally, BVOC estimates are used as inputs to some air quality models that are also used as decision-making tools (Pierce et al., 1998).

Methods for Modeling BVOC Emissions

A BVOC emissions inventory is a database of BVOC emission estimates for a target area. BVOC emissions are generally estimated as a mass flux per area for a given compound. The general form for modeling the BVOC flux (F) from a landscape is

shown in Equation 7 and involves multiplying a standardized emission factor (ε, µg C g^{-1} h^{-1}) representative of the emission rate at standardized activity level, the activity factor (γ) to correct for variations from the standardized conditions in the activity level, and a source factor (D), usually foliar density (Geron, Guenther, and Pierce, 1994; Hewitt, 1999).

$$F = \varepsilon \cdot \gamma \cdot D \qquad (7)$$

Emission factors, ε

Landscape average BVOC emission factors can be estimated using two different approaches. The first, referred to as a "bottom-up" approach involves creating a weighted average of BVOC emission factors associated with vegetation species present in the landscape (Hewitt, 1999). Emission factors for specific plant species can be estimated using leaf or branch enclosure systems and doing a mass balance of the BVOC in the enclosure system to estimate an emission rate (Winer et al., 1992; Arey et al., 1995; Guenther et al., 1996b). The emission rate is then divided by the mass of foliage enclosed in the system (usually dry weight), and by an emission activity factor, reflecting the environmental conditions at which the emission measurements were made, to determine the standardized BVOC emission factor for the species (Hewitt, 1999). Emission factors have been determined for over 1300 plant species using these methods (Hewitt et al., 1997).

Another approach for estimating landscape average BVOC emission factors, the "top-down" approach, involves determining the BVOC flux from a landscape as a whole

using tracers, relaxed eddy accumulation (REA) systems, or inverse modeling techniques and dividing the flux by the landscape foliar density and an emissions activity factor (Davis, Lenschow, and Zimmerman, 1994; Guenther et al., 1996a, 1996b; Hewitt, 1999).

Activity factors, γ

Emissions of BVOCs have been shown to vary depending on environmental conditions such as leaf temperature, available photosynthetically active radiation (PAR), plant stress, and many other factors (Lamb et al., 1987; Guenther et al., 1993; Hewitt, 1999). Guenther et al. (1993) developed algorithms to model effects of PAR and temperature on BVOC emissions using nonlinear regression of measured data . Biogenic emissions of isoprene, specifically, have shown well-documented effects of both PAR and temperature. Emission activity factors for the effects of light or PAR ($\gamma_{I,L}$) and temperature ($\gamma_{I,T}$) on isoprene emissions are shown in Equations 8 and 9, respectively. The variable L (μmol m^{-2} s^{-1}) represents the ambient PAR flux, α (0.0027) and C_{L1} (1.066) are empirical coefficients, T (K) is the ambient leaf temperature, T_s (K) is leaf temperature at standard conditions, R (8.314 J K^{-1} mol^{-1}) is the ideal gas constant, and C_{T1} (95,000 J mol^{-1}), C_{T2} (230,000 J mol^{-1}), C_{T3} (0.961), and T_M (314 K) are all empirical coefficients. Most of the recent literature define standard conditions as an ambient temperature of 303.15 K or 30 °C and 1000 μmol m^{-2} s^{-1} PAR (Geron, Guenther, and Pierce, 1994; Benjamin et al., 1996; Kinnee, Geron, and Pierce, 1997; Diem and Comrie, 2000).

$$\gamma_{I,L} = (\alpha C_{L1} L)/[(1 + \alpha^2 L^2)^{0.5}] \tag{8}$$

$$\gamma_{I,T} = [\exp\{C_{T1}(T - T_s)/(RT_s T)\}]/[C_{T3} + \exp\{C_{T2}(T - T_M)/(RT_s T)\}] \tag{9}$$

In addition to isoprene, monoterpenes and a number of potentially important other volatile organic compounds (OVOCs) with an atmospheric lifetime of less than a day are emitted by vegetation (Guenther, Zimmerman, and Wildermuth, 1994). Some examples of OVOCs are ethylene, acetaldehyde, and compounds from the hexanal family (Hewitt, 1999). Natural emissions of monoterpenes and OVOCs have shown dependence on temperature but not on PAR. An activity factor modeling the temperature dependence of these compounds emissions ($\gamma_{M,T}$) is shown in Equation 10 where β is an empirical coefficient with a recommended value of 0.09 K^{-1} (Guenther et al., 1993).

$$\gamma_{M,T} = \exp(\beta[T - T_s]) \tag{10}$$

Although other factors such as leaf age, leaf nitrogen content, water status, and stress can also influence biogenic emissions, there are currently no reliable algorithms to describe these effects on activity for all landscapes (Hewitt, 1999).

Foliar density, D

Foliar density is generally defined as the dry weight foliar mass per unit area of ground. Although foliar densities for a landscape are generally not constant throughout the year, the peak or seasonal maximum foliar density for a given species tend to be fairly uniform (Hewitt, 1999). For purposes of this study, the term foliar mass will generally refer to the peak foliar mass.

Estimates of foliar mass for vegetation types have been determined through destructive sampling or leaf fall collection (Geron, Guenther, and Pierce, 1994). Foliar

density estimates have also been made using optical satellite measurements and techniques which combine optical measurements with microwave, lidar, and other sensors (Guenther et al., 1996a; Hewitt, 1999).

Current BVOC Emissions Modeling by the Utah Division of Air Quality

The Utah Department of Environmental Quality currently uses the PC-BEIS 2 model, developed by the EPA, to estimate biogenic reactive hydrocarbon emissions for the Wasatch Front. This model uses the light and temperature corrections developed by Guenther et al. (1993) as well as the second version of the Biogenic Emissions Landcover Database (BELD 2) to estimate the three previously defined categories of BVOC emissions on a county-level basis for the contiguous United States (Kinnee, Geron, and Pierce, 1997; Pierce et al., 1998). Hourly emissions from vegetation of isoprene, monoterpenes, and OVOCs with a typical atmospheric lifetime of less than one day are estimated based on county-level land use/land cover data and standardized emission factors contained in BELD 2 (for a more detailed description of PC BEIS 2 and BELD 2, refer to Review of Literature) (Pierce et al., 1998).

Figure 4 shows emission rate estimates of isoprene, monoterpenes, and OVOCs for Salt Lake County based on meteorological data for a high ozone day (31 July 2000). These emission rate estimates were produced using the EPA's most current version of the model PC-BEIS 2.3 (EPA, 2001) which estimated nearly 76,000 kg of isoprene and 128,000 kg of total BVOCs were emitted that day by vegetation in Salt Lake County alone. The inclusion of Davis and Utah Counties, to the north and south, respectively, would significantly increase the estimated emissions for the Wasatch Front airshed.
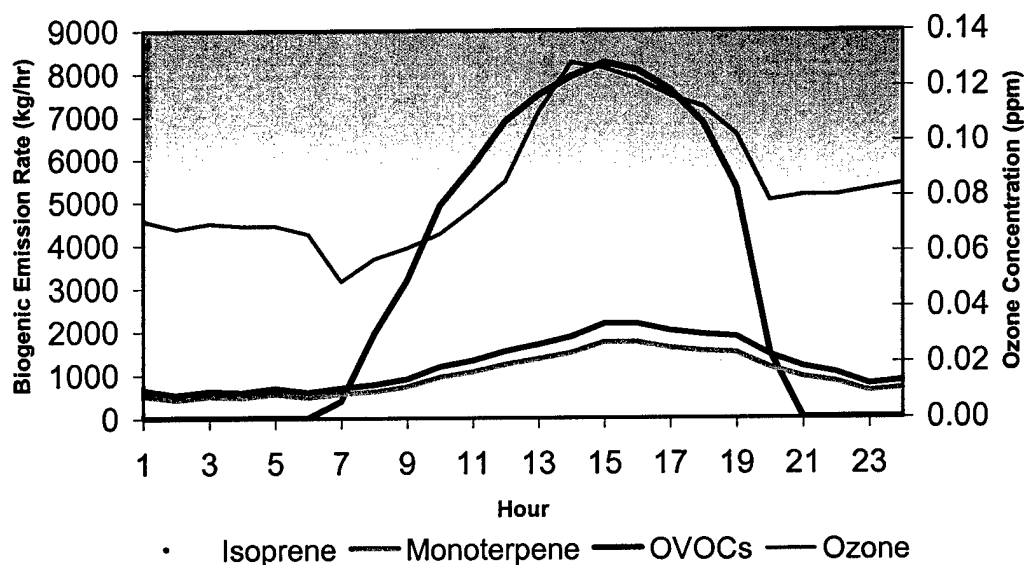
Figure 4. BVOC emission rate estimates from PC BEIS 2.3 for Salt Lake County and composite 1-hour average ozone concentrations, 31 July 2000.

Although it cannot be inferred that BVOC emissions are the sole cause of this high-ozone episode, it is important to note that BVOC emission rates are approaching their maximum near the same time of day that rates of photochemical oxidation are highest. The dependence of BVOC emissions on light and temperature explains why emission rates are highest during the same time when photochemical-oxidant formation rates are high.

Although BVOC emissions estimates from the PC BEIS 2/BELD 2 model are available, there may be potential for better BVOC emissions estimates using locally specific vegetation data in place of BELD 2 (Pierce, Kinnee, and Geron, 1998; Diem and Comrie, 2000). In BELD 2, urban areas along the Wasatch Front are assumed to consist of 11% forested areas and 89% urban-other (Pierce et al., 1998). The urban forest composition is assumed to be identical to the non-urban forest composition; the urban-

other land use type is assumed to have 20% grass coverage and be 80% barren (Kinnee, Geron, and Pierce, 1997; Pierce et al., 1998). These assumptions may not represent the actual vegetation composition of urban areas along the Wasatch Front. Emission estimates are also based on national data sets and do not allow for as much variation in vegetation types as a local data set would (Kinnee, Geron, and Pierce, 1997). In addition, emission estimates are averaged throughout the county and no differentiation can be made between areas of high emissions and areas of low emissions within the county.

Figures 5-7 show the spatial distribution of standardized BVOC emission estimates from BELD 2 along the Wasatch Front. Although there is some differentiation in emission estimates between counties, there is no differentiation within an individual county. It is also important to point out that unvegetated areas, such as the Great Salt Lake, are shown to have the same BVOC emission flux as highly vegetated areas within the same county. This is because, as mentioned previously, emission estimates are an average for the whole county area and are distributed homogenously throughout the county regardless of whether the county area is a water body, barren, or vegetated area.

Objectives and Scope of Project

The Wasatch Front is currently believed to be VOC limited in terms of ozone formation (Barickman, 2002). In this case, ozone formation would be more sensitive to BVOC emissions. Accurate estimates of these emissions are necessary in order to determine the best control strategy for the area. A higher resolution inventory, combined with more accurate local vegetation data, increases the accuracy of BVOC estimates.
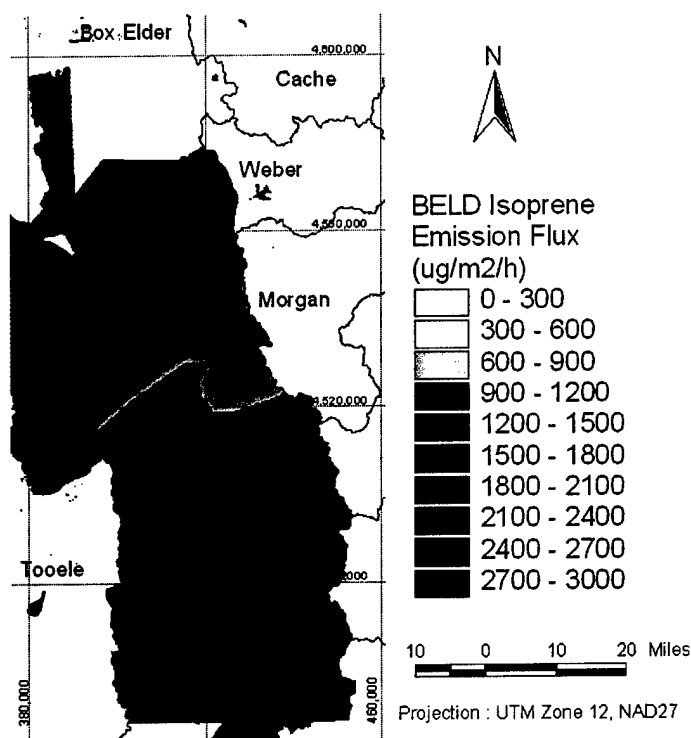
Figure 5. Spatial distribution of isoprene emission estimates from BELD 2.
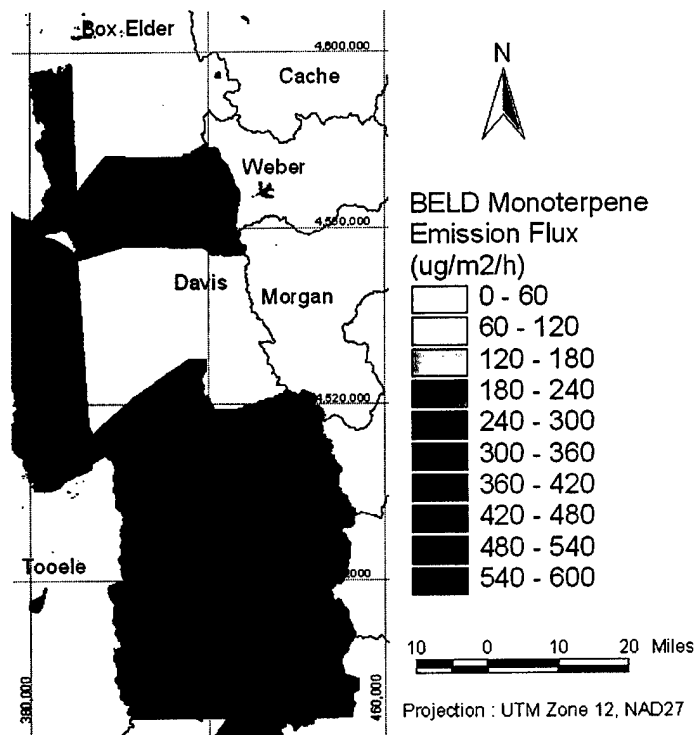
Figure 6. Spatial distribution of monoterpene emission estimates from BELD 2.
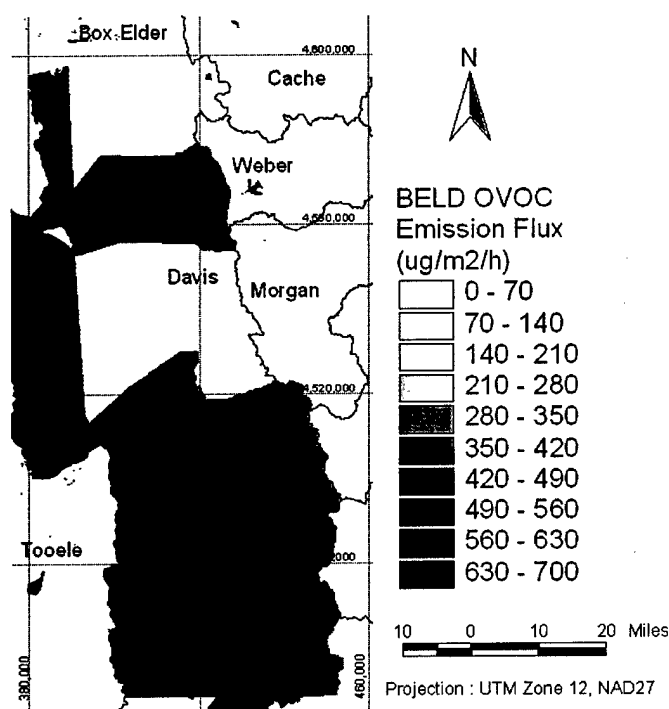
Figure 7. Spatial distribution of OVOC emission estimates from BELD 2.

The purpose of this study was to increase the accuracy in estimating BVOC

emissions for the Wasatch Front by creating a high-resolution (30-m spatial resolution)

standardized BVOC emissions inventory for the Wasatch Front study area using locally

specific vegetation information, estimate standardized emissions of isoprene,

monoterpenes, and OVOCs from vegetation, compare these results to estimates from PC-

BEIS's BELD 2, and evaluate the implications of any differences. Because isoprene and

monoterpene emissions account for a vast majority of reactive BVOC emissions, the

scope of this inventory was limited to estimates of emissions of these compounds and a

broad third class, OVOCs with an atmospheric lifetime of less than one day (Hewitt,

1999). The scope of this project was also limited to vegetative emissions of the three

groups of compounds and did not examine possible contributions from non-vegetative

biogenic sources such as emissions from soils. For comparative purposes, emission estimates were standardized to 30 $^\circ$C and 1000 μmol m^{-2} s^{-1} PAR and reflect emissions at the peak growing season biomass. Seasonal variations in biomass were not investigated.

REVIEW OF LITERATURE

Studies Leading to the Development of BEIS/BELD 2

Many studies have been made to estimate BVOC emissions for large portions of the United States. These studies have developed the framework for BEIS 2, the EPA's current model for estimating emissions of BVOCs.

Lamb et al. (1987) compiled a national inventory of BVOCs on a county scale. They used the Geocology Data Base, which contains a number of environmental parameters at county resolution such as land use area, agricultural areas and yields, natural vegetation areas, average monthly temperatures, and growing seasons (Olson, Emerson, and Nunsgesser, 1980). This information was combined with emission factors from Zimmerman (1979), leaf biomass density factors, and temperature correction curves developed by Tingey (1981) to model isoprene, α-pinene, and other non-methane hydrocarbon emissions for the United States. The model results had an uncertainty of a factor of three, meaning actual measurements should be within a factor of three of the estimated values (Lamb et al., 1987).

Pierce and Waldruff (1991) adapted BEIS for use on personal computers. This version computed hourly emission rates of isoprene, α-pinene, other monoterpenes, and unidentified hydrocarbons for any county in the United States using land use areas, leaf biomass factors, emission factors and environmental factors (Pierce and Waldruff, 1991). Equation 11 illustrates the emissions model where ER_i is the emission rate ($\mu g\ h^{-1}$) for chemical species i, A_j is the area (m^2) in the county of land use class j, BF_i is the leaf biomass factor ($g\ m^{-2}$), EF_{ij} is the emission factor ($\mu g\ g^{-1}\ h^{-1}$), and $F_i(S,T)$ is a unitless

environmental adjustment factor to account for the effects of solar radiation and leaf

temperature on emission rates (Pierce and Waldruff, 1991).

$$ER_i = \sum_j \left[A_j BF_j EF_{ij} F_i(S, T)\right] \qquad (11)$$

Land use data for this model were derived from the Oak Ridge National Laboratory's

Geocology Data Base and biomass and emissions factors were adapted from Lamb et al.

(1987).

Guenther, Zimmerman, and Wildermuth (1994) used genus specific emission

factor estimates based on previous research and species composition and foliar mass data

to estimate landscape level emission rates for woodland areas covering about half of the

contiguous United States. This study used a 1.1 km resolution land-cover database

compiled by the EROS Data Center (EDC) using AVHRR satellite imagery and ancillary

data (Loveland et al., 1991). All woodland landscapes in the database were assigned area

averaged isoprene, monoterpene, and OVOC emission rates based on the dominant

genera and estimated leaf biomass for each landscape (Guenther, Zimmerman, and

Wildermuth, 1994). The apportionment of leaf biomass was based on the assumptions

that the dominant genera in a land cover type made up a fixed percentage of the total leaf

biomass in the cover type and that the biomass associated with the dominant genera is

evenly divided between each tree genera. The authors point out that while this

apportionment is somewhat arbitrary, this method is adequate for a first order

approximation (Guenther, Zimmerman, and Wildermuth, 1994). Results from this study

indicated a higher relative contribution of isoprene and lower contribution of

monoterpenes to total BVOC emissions in woodland areas than previous studies (Lamb et al., 1987; Pierce and Waldruff, 1991).

In addition to estimating woodland BVOC emissions for the contiguous United States, Guenther, Zimmerman, and Wildermuth (1994) used the Eastwide Forest Inventory Database (EFID or EWDB in subsequent reports) to obtain more accurate leaf biomass estimates for two study areas in the southeastern United States. They report that although the vegetative species that are dominant in the EDC are the same as those in the EFID, the relative contribution of these species is quite variable and databases such as the EFID should be used where available (Guenther, Zimmerman, and Wildermuth, 1994).

Geron, Guenther, and Pierce (1994) used information from the EWDB to estimate hourly regional BVOC emissions from forests for the 37 easternmost states. Tree crown-coverage data for plot areas in the database were allocated by genus using empirical relationships and foliar mass for the canopy coverage was determined using published foliar density values (Geron, Guenther, and Pierce, 1994). The database of genus level standardized BVOC emission factors created by Guenther, Zimmerman, and Wildermuth (1994) was then used to assign emission rates to each genus. Temperature and light correction algorithms developed by Guenther et al. (1993), as well as a simple canopy model to account for shading at different levels within the canopy, were used to adjust emission rates based on ambient temperature and PAR (Geron, Guenther, and Pierce, 1994). Resulting isoprene and total BVOC emission estimates were 5 to 10 times greater under a range of environmental conditions than BVOC emission estimates produced by BEIS (Geron, Guenther, and Pierce, 1994).

Kinnee, Geron, and Pierce (1997) used a GIS to combine the EDC's land cover data, data from the U.S. Forest Service's EWDB, and other land cover data to create the BELD 2 covering the entire contiguous United States. The BELD 2 was created to estimate biogenic emissions of isoprene, monoterpenes, and OVOCs from vegetation and nitric oxide (NO) from soils on a countywide basis for the United States. The BELD 2 is a GIS layer of county boundaries throughout the United States with information on the total area of each county and the percentage of each land use type within the county (Kinnee, Geron, and Pierce, 1997). There are 158 land use types in BELD 2 that are grouped into nine land use classes (urban areas, coastal and inland water, forest, urban forest, agriculture, barren, scrub, grass, and other) based on the data source used to assign land-use types (Kinnee, Geron, and Pierce, 1997). County percentage of urbanized area was calculated using the U.S. Census urbanized-area polygons and percentage of water was determined using the EDC land cover database with other information (Kinnee, Geron, and Pierce, 1997). Barren, scrub, and grass areas, as well as forest cover areas for the western United States, were also determined using the EDC land cover database while forest area for the eastern United States was obtained from the Forest Inventory and Analysis (FIA) Eastwide Data Base (EWDB) as described by Geron, Guenther, and Pierce (1994). Urbanized forest areas were assigned to be 32% of urban areas in forested regions and 22 and 10% of urban areas in grass and rangeland/dessert regions, respectively, and are assumed to be composed of the same genera as non-urban forest component (Kinnee, Geron, and Pierce, 1997). Agricultural areas and crop types were obtained from the 1987 Census of Agricultural data.

Standardized emission rates for land classes derived from the EDC data were determined using methods and emission factors from Guenther, Zimmerman, and Wildermuth (1994) while emissions from classes derived from the EWDB were based on work by Geron, Guenther, and Pierce (1994). Agricultural types were assumed to have constant biomass and were assigned BVOC emission factors based mostly on work by Lamb et al. (1993).

The U.S. EPA updated BEIS to BEIS 2, the current version for modeling BVOC emissions. BEIS 2 uses the BELD 2 as well as updated PAR and temperature correction algorithms developed by Guenther et al. (1993) and a simple canopy model to model hourly BVOC emissions on a county level resolution for the contiguous United States (Kinnee, Geron, and Pierce, 1997; EPA, 2001).

Higher Resolution BVOC Emission Inventories

Pierce, Kinnee, and Geron (1998) outline the methods they used to develop a 1-km resolved vegetation cover database for the contiguous United States that is referred to as BELD 3. In order to create BELD 3, the Biogenic Emissions Landuse Database described by Kinnee, Geron, and Pierce (1997) was modified by incorporating Forest Inventory Analysis data for the entire contiguous U.S. rather than just the eastern portion and using updated agricultural data from the 1992 Agricultural Census (Pierce, Kinnee, and Geron, 1998). One-kilometer resolved estimates of forest density from work by Zhu and Evans (1994) and data from the U.S. Geological Survey's (USGS) land cover characteristics database (EDC in previous reports) were also used in the process. The methodology to create BELD 3 involved assigning 100% of the area of each county in

the U.S. to one of four broad vegetation categories (water, agriculture, forest, and other) and then assigning each 1-km grid cell in the county to one or more vegetation types (Pierce, Kinnee, and Geron, 1998). Although the spatial accuracy of BELD 3 has not been validated with independent vegetation cover surveys, this model shows much more spatial variability in BVOC emissions than BEIS's current land use database (Pierce, Kinnee, and Geron, 1998). Although a preliminary version of BELD 3 is available from the EPA for research purposes, it has not yet been validated.

Diem and Comrie (2000) presented a method for creating high-resolution BVOC emissions inventory by using multispectral satellite data and local vegetation information. They asserted that 1-km resolution land cover and vegetation information was not sufficient to model the heterogeneous vegetation in the region of Tucson, Arizona and created a high-resolution (30-m resolution) BVOC emissions inventory for the area (Diem and Comrie, 2000). To create the inventory, the region was separated into urban and peripheral areas and an unsupervised classification of a Landsat thematic mapper (TM) satellite image was performed for both areas. Aerial photographs were then used to identify agricultural areas and golf courses and forest class was divided into two classes based on elevation resulting in a total of 21 land cover classes (Diem and Comrie, 2000). Existing vegetation surveys as well as a project specific survey were then used to determine vegetative species composition, frequency, canopy area or volume in each land cover class. Leaf biomass constants, foliar density values, and isoprene, monoterpene, and OVOC standardized emission factors were then assigned to each species in the database based on work by Benjamin et al. (1996), Chinkin et al. (1996), and Geron, Guenther, and Pierce (1994). Emission fluxes were then calculated for each class based

on published methods described previously (Geron, Guenther, and Pierce, 1994; Chinkin et al., 1996). Results of the Diem and Comrie study yielded regionwide isoprene and monoterpene fluxes that were about 4 and 2 times greater, respectively, than those calculated using BEIS 2 information (Diem and Comrie, 2000).

Baugh et al. (2001) also used Landsat TM data to characterize the emissions of biogenic hydrocarbons. They performed a supervised classification of multi-temporal satellite imagery for a study area near Oak Ridge, Tennessee. Field measurements made for previous studies consisted of 10 m by 10 m plots where detailed vegetation inventories were made (Baugh et al., 2001). These plots were used as training sites for each of the 10 land cover classes identified. Isoprene emission flux values were then assigned to each land cover class based on empirical vegetation emissions data for the area from a previous study (Guenther et al., 1996b). Isoprene emissions modeled using the land cover classification were then compared to isoprene emissions measured by Guenther et al. (1996b). Baugh et al. (2001) report that modeled results were within a factor of two of measured isoprene fluxes and that was considered good given the heterogeneity of the sources within the region.

The results from these studies illustrate the potential benefits of creating a higher resolution BVOC inventory to model biogenic emissions along the Wasatch Front. The higher spatial resolution combined with more accurate local vegetation data should increase the accuracy of BVOC emission estimates.

METHODS OF PROCEDURE

Project Study Area

The study area for this project (hatched) is mapped in Figure 8. The Wasatch

Front study area contains most of Salt Lake and Davis Counties as well as parts of Utah,

Weber, and Box Elder Counties. It extends roughly from Brigham City in the north to

Provo in the south. The study area is bounded on the east by the Wasatch Mountains and

extends into the Great Salt Lake on the west, along the county boundaries. The study

area covers approximately 6,700 km^2 or nearly 7.5 million individual 30-m grid cells.
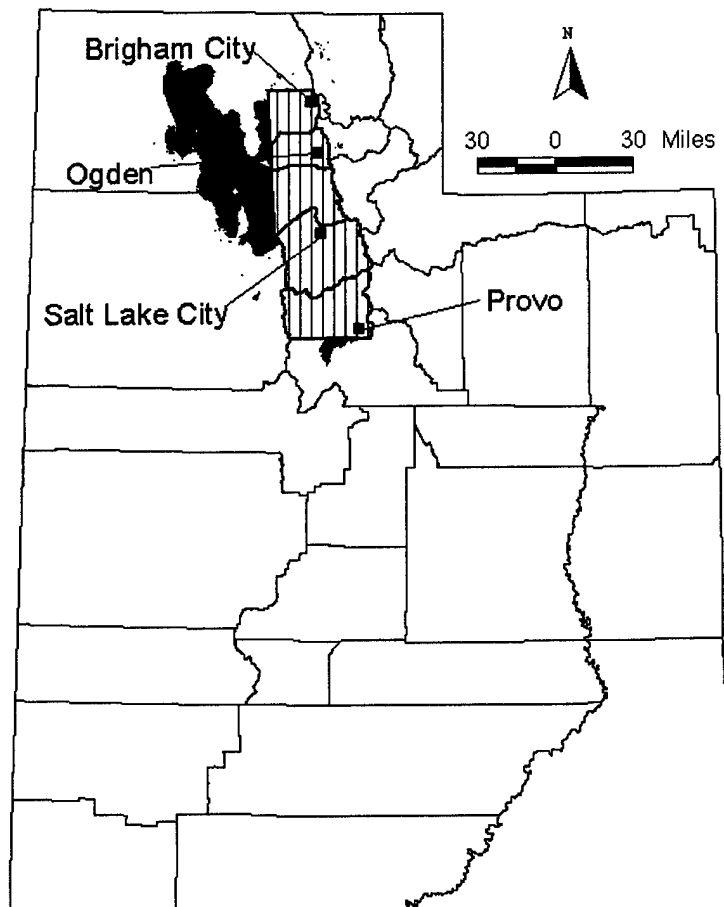
Figure 8. Location of the Wasatch Front study area.

Data Sources

Data used to create the emissions inventory for this project consisted of the Utah Geographical Approach to Planning (GAP) Analysis vegetation classified image, the Utah Division of Water Resources Water Related Land Use geographic information system (GIS) coverage, the Utah portion of the National Land Cover Data (NLCD), two Landsat Enhanced Thematic Mapper (ETM) satellite images, GIS coverages representing physical and political features, leaf biomass constants, foliar density values, BVOC emission factors, data from the 1997 Census of Agriculture, and vegetation survey information.

Existing data

The Utah GAP Analysis vegetation classified image is a 30-m resolution classified image denoting vegetation and land use classes for the entire state of Utah. It was derived using an Isodata algorithm to create an unsupervised classification from a mosaic of satellite imagery. The Isodata algorithm generated unsupervised spectral clusters and an iterative approach was used to find the point at which the decrease in the average standard deviation of all clusters versus the increase in the number of clusters was maximized. Aerial photographs and data collected at training sites were then used to determine the cover type of each spectral class. This file is projected in zone 12 of the Universal Transverse Mercator (UTM) coordinate system, NAD 27 (Edwards et al., 1995).

The Water-Related Land Use shape file was acquired from the state of Utah's Automated Geographic Reference Center (AGRC) as an ArcInfo coverage. The Water-

Related Land Use file is a polygon coverage of much of the state of Utah and represents a number of different water related land use areas such as various croplands, commercial, and residential areas (Division of Water Resources, 1999). This coverage was created using aerial photos as well as field data to identify land use boundaries. This coverage has a scale of 1:24,000 which corresponds to 30-meter grid resolution in UTM projection (USGS, 2001c). Shape files representing city and county boundaries, water bodies, roads, and other geographical features were also acquired from the AGRC.

The NLCD is a 21-class land cover data layer for the conterminous United States developed as part of a cooperative program between the USGS and the EPA (USGS, 2001b). This data set was derived from Landsat Thematic Mapper (TM) satellite imagery as well as ancillary data and has a spatial resolution of 30-meters in the Albers Conic Equal Area projection, NAD 83 (USGS, 2001b). The data set covering Utah was downloaded for this project.

Two geo-rectified Landsat ETM satellite images were necessary to cover the study area. The images available covering the northern and southern portions of the study area were taken 26 April and 28 May 2000, respectively. They were acquired from the College of Natural Resources at Utah State University.

Leaf biomass constants (g dry foliar mass m^{-3}), foliar density values (g dry foliar mass m^{-2}), and standardized BVOC emission factors (30 °C, PAR = 1000 μmol m^{-2} s^{-1}) for isoprene, monoterpenes, and OVOCs (μg g^{-1} dry mass h^{-1}) were obtained from previous research done on biogenic emissions (Horie, Sidawi, and Ellefsen, 1991; Lamb et al., 1993; Geron, Guenther, and Pierce, 1994; Benjamin et al., 1996; Chinkin et al., 1996; Hewitt et al., 1997; Pierce et al. 1998) (see Appendix A).

The Census of Agriculture is a compilation of data and statistics about the United States agricultural production (National Agricultural Statistics Service, 1997). It contains county level crop production by area and numbers of farms for each county in the U.S.

Data collected at training sites for the Utah GAP project included vegetation species composition and percent cover for the species present (Edwards et al., 1995). An ERDAS™ Imagine image and attribute table containing this information for up to the three most prevalent species at each site was acquired from the Utah GAP Analysis team at Utah State University.

The Interior West Forest Inventory and Analysis (IWFIA) Program conducts forest resource inventories in the Interior West States of Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming (IWFIA, 2002). The percent foliar crown coverage as well as percent basal area for the three most prevalent forest species was provided by the IWFIA for forested field sample plots within the study area. Although the IWFIA do not release actual plot location data, they provided field plot data and the land use class that each plot fell within using the land use classes developed as part of this study (Frescino, 2002).

Project specific vegetation survey

In order to obtain information about vegetation composition in residential areas along the Wasatch Front, a project specific vegetation survey of 45 residential property lots within the study area was conducted within about a 2-week period. The total area surveyed was over 33,000 m^2.

Fifteen survey locations were randomly selected from a grid of residential areas within the study area. Upon arrival at the predetermined location, permission of the nearest property owners was sought and the three nearest property lots were selected based on the availability and cooperation of the property owner (Figure 9).
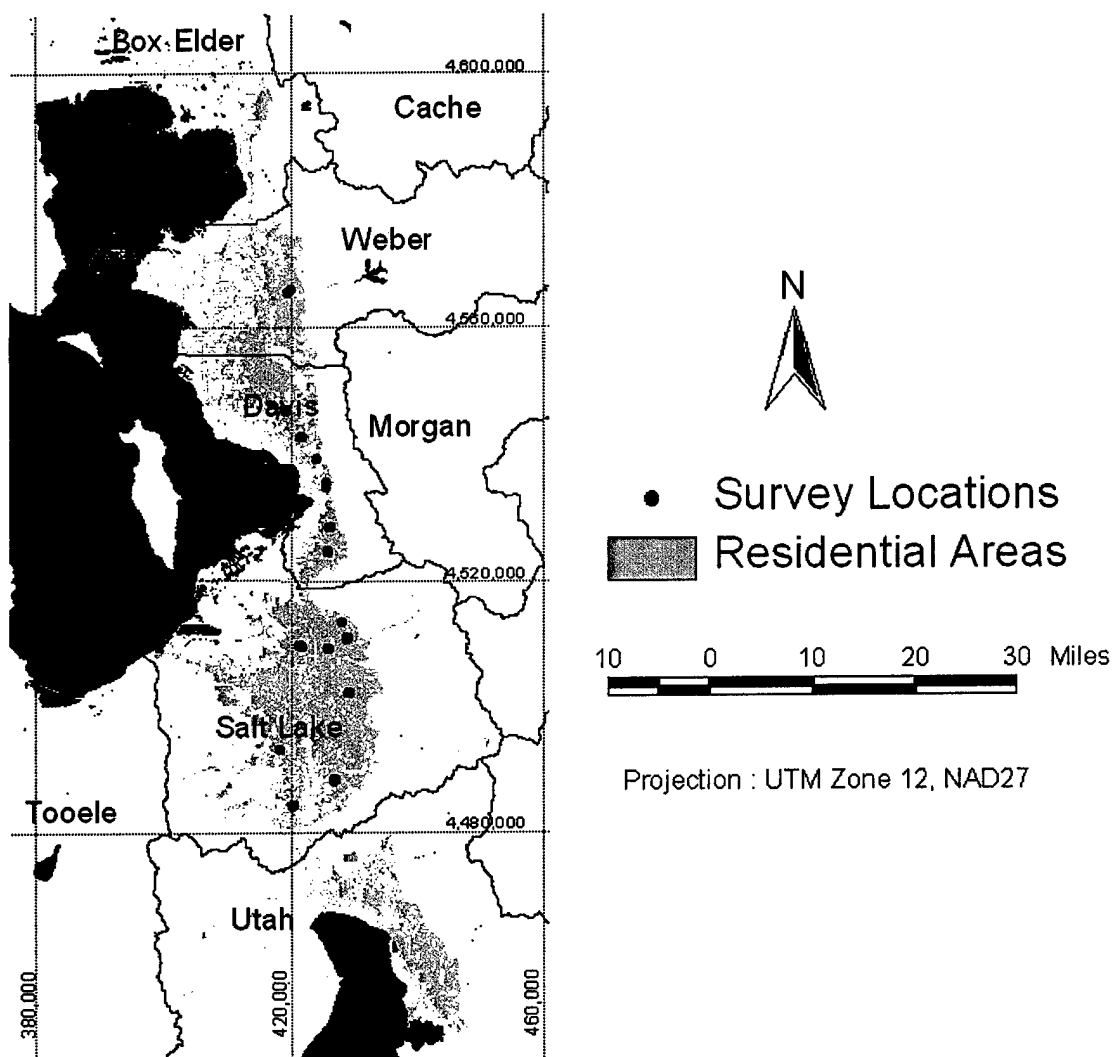
Figure 9. Residential vegetation survey locations.

After obtaining permission to survey a residential lot, property boundaries were identified, the lot area was measured and the UTM coordinates of the lot were determined using a Magellan GPA 4000 hand held global positioning system (GPS). Vegetative species present in the residential yard were then identified at least to the genus level. This was considered sufficient because within some genera, individual species can be hard to distinguish and many BVOC emission factors are based on genus or family level data and do not vary within the genera (Horie, Sidawi, and Ellefsen, 1991; Benjamin et al., 1996; Kinnee, Geron, and Pierce, 1997). In order to expedite the identification process, if a species could not be identified in the field, a leaf and/or flower sample was collected and the species was identified at a later time. For mixed beds of flowers, weeds, or garden plants where there was more than two species present, areas were identified as mixed flowers, mixed garden, or weeds.

All species were then recorded and measurements were made to assess the volume (area in cases of ground covers) of each species. Assumptions and methods described by Horie, Sidawi, and Ellefsen (1991) were used to make measurements and to determine foliar volumes.

In order to determine the foliar volume for each tree and tree like shrub, measurements of the crown height and diameter of each species were made under the assumption that the trees were radially symmetric. A shape factor was also assigned to each tree ranging from 0 to 1 to describe the actual shape of the tree crown. A value of 0.33 represented a cone-like crown, 0.67 a spherical crown, and 1.0 a cylindrical crown but any value within this range could be used to describe the shape. The crown volume

was then calculated by multiplying the crown area by the crown height and the shape factor.

Measurements of length, width, and height of other shrub species were made and volumes were approximated as prisms. Only length and width measurements were made for groundcovers such as grass because emission factors for theses species are normally given on a per area basis.

In order to be able to determine the area of just the vegetated portion of the area surveyed, an asterisk was placed next to tree and shrub species which were not occupying the same area as lawn or other ground cover areas. The crown area of these specimens was then added to the lawn and ground cover areas in order to determine the vegetated area surveyed.

Measurements of tree crown diameters, lawn areas, areas of uniform ground cover, and shrub dimensions were performed using a measuring tape (Figure 10). A Bushnell Yardage Pro Compact 600 optical range finder was used for estimating the heights of tall trees and determining the total area of the lot surveyed (Figure 11).

In the instance where a tree or shrub species within a lot would tend to have a fairly uniform shape and size, other specimens were assumed to have the same dimensions. In order to expedite the survey process, one specimen was measured and the remaining specimens were simply counted and recorded. Figure 12 shows an example of the form used to record the data collected at each survey site.

Figure 10. Measurement of tree crown diameter as part of the residential vegetation
survey.

Figure 11. Estimation of tree crown height using an optical range finder as part of the
residential vegetation survey.

Land Cover Class __RESIDENTIAL__ GPS Coordinates: X __419449__

Y __4565614__

Site # __2__   Total Area Sampled __750 m²__

Species	#	Length	Width	Height	Diameter	Shape Factor
ACER PSEUDOPLATAN	2			8	6.1	.67
"	1			11.04	9.75	.33
ILEX SP.		1.52	3.17	1.07		
PICEA PUNGENS				1.62	1.07	.33
ROSA SP.	13			1.25	.73	1
PRUNUS PERSICA	2			2.38	1.83	.67
AESCULUS SP.	2			6.7	6.8	.67
QUERCUS SP.				7.7	6.64	1
LIGUSTRUM		4.91	1.37	1.07		
CATALPA				3.35	3.35	.67
MYRTUS	3			2.13	1.83	.67
JUNIPERUS				13.8	9.14	.33
GRASS		91.66 m²				
		51.5 m²				
		360.8 m²				

Shape Factor: Cone = 0.33, Ellipsoid = 0.67, Cylinder = 1.0

Figure 12. Sample data collection sheet used for residential vegetation survey.

Figure 13 outlines the methodology used to create a BVOC emissions inventory

for the Wasatch Front study area. The following subsections provide more detail on the

methods that were used in the creation of the inventory.
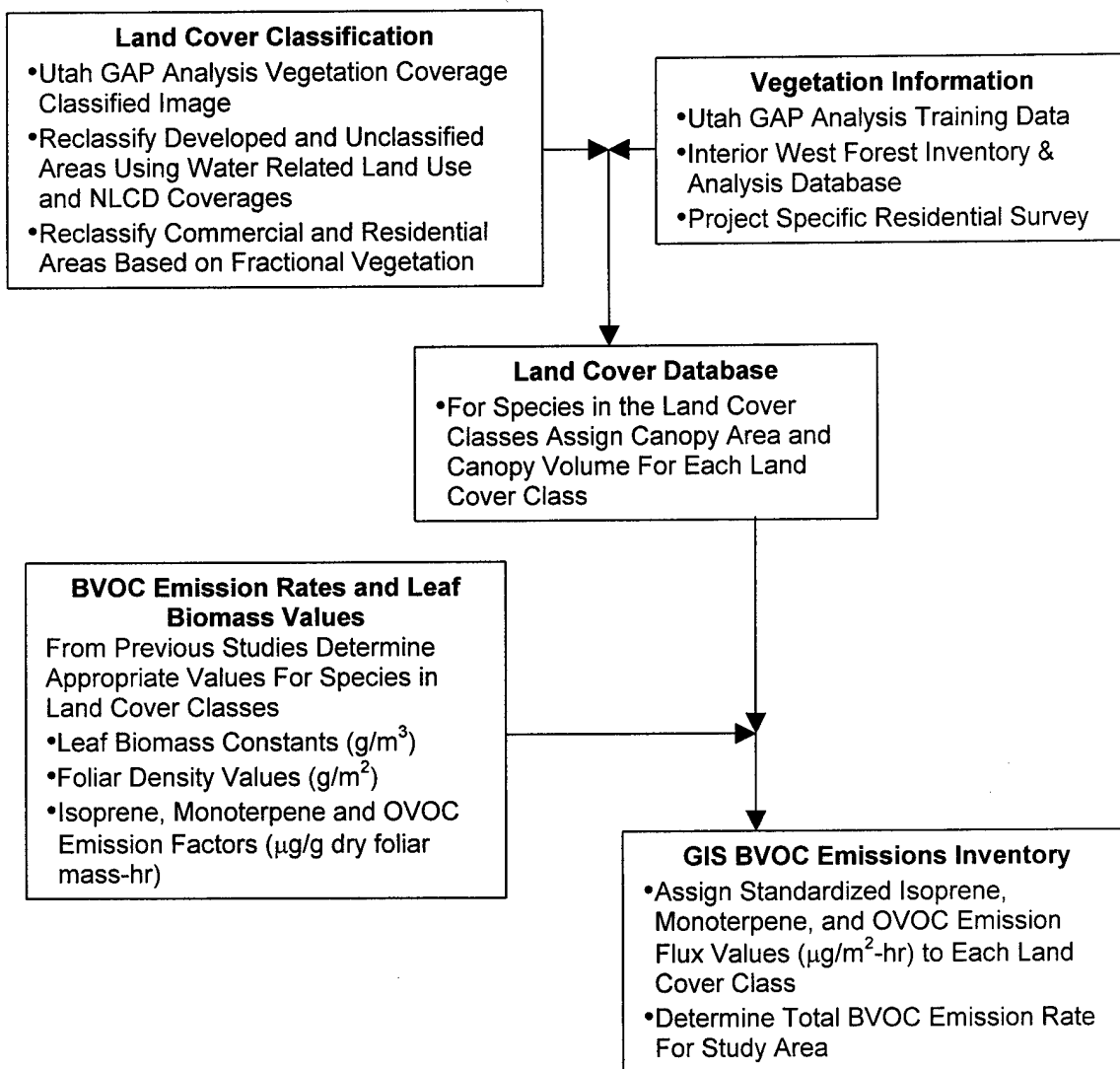
Figure 13. Methodology for creating a high-resolution, gridded BVOC emissions
inventory.

Land cover classification

The Utah GAP Analysis vegetation classified image was the foundation for creating a land cover classification for the study area. Within the study area, the GAP image contained 32 of the 38 listed land cover classifications. For use in this project, this image was converted to an integer grid to be used with the GIS software ArcView, version 3.2. One inadequacy of the GAP classified image for this project was the lack of differentiation in the agriculture and urban classes in the image. When the classified image was created, these areas were masked in order to reduce spectral variability (Edwards et al., 1995). Although this procedure allowed for a more accurate classification of nondeveloped areas, there was no attempt to separate out vegetated and nonvegetated areas within the urban class nor to separate types of agriculture within the agriculture class. Another minor issue was that a small number of grid cells within the study area were unable to be accurately classified due to the ground being obstructed from the satellite by cloud cover (cloud) or holes in the mosaic of satellite images (background).

In order to increase the spatial resolution for the urban and agricultural classes in the GAP image, the Water-Related Land Use shape file was converted to a grid format (30-m resolution) and was clipped to correspond to the areas covered by the urban and agricultural classes resulting in 46 different cover types. The land cover types in the clipped Water-Related Land Use grid were then reclassified to 18 project specific land classes based on cover type descriptions provided in the Water-Related Land Use Summary Report of the State of Utah (Table 1) (Division of Water Resources, 1999).

Table 1. Reclassification of water-related land use cover types

Water-related land use cover type [a]	Project land cover class
Evaporation Pond	Water
Open Water	Water
Other Water	Water
Ponds & Lakes	Water
Reservoirs	Water
Salt Water	Water
Sewage Lagoon	Water
Streams	Water
Temporary Flood	Water
Excavated Lands	Barren
Riparian	Lowland Riparian
Cattail / Bullrush Aspect	Wetlands
Grass / Turf	Urban Grasses
Open Spaces (Parks, Golf Courses)	Urban Grasses
High Density Buildings / Homes	High Intensity Residential
Buildings / Homes	Low Intensity Residential
Farmsteads	Low Intensity Residential
Low Density Buildings / Homes	Low Intensity Residential
Residential	Low Intensity Residential
Commercial	Commercial/Industrial/Transportation
Industrial	Commercial/Industrial/Transportation
Commercial/Industrial Open Space	Commercial/Industrial/Transportation
Transportation & Utilities	Commercial/Industrial/Transportation
Idle (Overgrown Agricultural Land)	Pasture
Pasture	Pasture
Fallow	Miscellaneous Crops
Grain / Beans/ Seeds	Miscellaneous Crops
Non-Irrigated Cropland	Miscellaneous Crops
Vegetables	Miscellaneous Crops
Grain	Grain
Fruit (Orchards)	Orchards
Other Horticulture	Orchards
Berries	Berries
Corn	Corn
Sorghum	Sorghum
Potatoes	Potatoes
Onions	Onions
Beans	Beans

Table 1. Continued

Water-related land use Cover type [a]	Project land cover class
Tomatoes	Tomatoes
Alfalfa	Alfalfa
Grass Hay	Hay
Safflower	Safflower
Idle Spaces	No Data
Open Spaces (Feed Lots)	No Data
Wet / Vegetation	No Data
Wet Flats	No Data

[a] Division of Water Resources (1999)

The purpose of reclassifying these cover types was to reduce the number of project land cover classes by aggregating similar land use classes and to group land cover types into land cover classes developed for this study. Four land cover types from the Water-Related Land Use data set were not classified but were assigned a "No Data" value during this process because sufficient information on the land cover types was not available to adequately assign them to one of the project's land cover classes.

Because portions of the agricultural and urban areas were not completely covered spatially by the Water-Related Land Use data and because some cover types were not used, the NLCD land cover grid was down loaded and re-projected to UTM zone 12, NAD 27, coordinates to conform with the GAP and Water-Related Land Use data. A sub-set of the NLCD grid corresponding to the urban and agricultural classes in the GAP data set was constructed and the resulting 20 land cover classes were reclassified (Table 2) to conform to the project's land cover classes.

Table 2. Reclassification of NLCD land cover classes

NLCD land cover class [a]	Project land cover class
Open Water	Water
Perennial Ice/Snow	Water
Low Intensity Residential	Low Intensity Residential
High Intensity Residential	High Intensity Residential
Commercial/Industrial/Transportation	Commercial/Industrial/Transportation
Bare Rock/Sand/Clay	Barren
Quarries/Strip Mines/Gravel Pits	Barren
Transitional	Barren
Deciduous Forest	Urban Deciduous Forest
Evergreen Forest	Urban Coniferous Forest
Mixed Forest	Urban Mixed Forest
Shrubland	Sagebrush
Orchards/Vineyards/Other	Orchards
Grasslands/Herbaceous	Pasture
Pasture/Hay	Pasture
Row Crops	Miscellaneous Crops
Small Grains	Grain
Urban Recreational Grasses	Urban Grasses
Woody Wetlands	Lowland Riparian
Emergent Herbaceous Wetlands	Wetlands

[a] USGS (2001b)

The Water-Related Land Use grid was then merged on top of the NLCD sub-set

which, in turn, was merged on top of the GAP data set resulting in the creation of 21 land

cover classes taking the place of the GAP agricultural and urban classes.

In order to reclassify grid cells classified as cloud or background in the GAP data,

another subset of the NLCD grid corresponding to these areas was made and overlaid on

the merged land cover classes. This resulted in an intermediate land cover classification

with a total of 50 land cover classifications for the study area (Table 3).

Table 3. Intermediate project land cover classes

Project land cover classes	
1 Water	26 Desert Grassland
2 Spruce-Fir	27 Greasewood
3 Ponderosa Pine	28 Pickleweed Barrens
4 Mountain Fir	29 Wetland
5 Juniper	30 Urban Grasses
6 Pinyon	31 High Intensity residential
7 Pinyon-Juniper	32 Low Intensity residential
8 Mountain Mahogany	33 Commercial/Industrial/Transportation
9 Aspen	34 Pasture
10 Oak	35 Miscellaneous Crops
11 Maple	36 Grain
12 Mountain Shrub	37 Orchards
13 Sagebrush	38 Berries
14 Sagebrush/Perennial Grass	39 Corn
15 Grassland	40 Sorghum
16 Alpine	41 Potatoes
17 Dry Meadow	42 Onions
18 Wet Meadow	43 Beans
19 Barren	44 Tomatoes
20 Spruce-Fir/Mountain Shrub	45 Alfalfa
21 Mountain Fir/Mountain Shrub	46 Hay
22 Aspen/Conifer	47 Safflower
23 Mountain Riparian	48 Developed Deciduous Forest
24 Lowland Riparian	49 Developed Coniferous Forest
25 Salt Desert Scrub	50 Developed Mixed Forest

Although the NLCD data set alone could probably be used for land cover classifications for this study and would work well for a national inventory, both the GAP and the Water Related Land Use data sets were developed using local data and were therefore given preference in characterizing the study area (Pierce et al., 2002).

The fractional vegetation cover (the percent of each grid cell that is covered by vegetation) for the study area was determined using the satellite images and methods first described by Gillies and Carlson (1995). Digital numbers (DN) collected for the visible

band (0.63-0.69 μm) and near infra-red (NIR) band (0.75-0.9 μm) of the Landsat ETM

images (bands 3 and 4) were converted to at-sensor radiance (W m^{-2} sr^{-1} μm^{-1}) using

ERDAS Imagine 8.5 software as shown by Equation 12 where the Gain (W m^{-2} sr^{-1} μm^{-1})

and Bias (W m^{-2} sr^{-1} μm^{-1}) for each band are supplied in the Landsat ETM header files

(Crombie et al., 1999; NASA, 2002).

$$Radiance = DN \times Gain + Bias \qquad (12)$$

Radiance values for each band were then converted to a unitless at-sensor

reflectance (a) using Equation 13 where d is the earth-sun distance in astronomical units,

ESUN$_\lambda$ (W m^{-2} μm^{-1}) is the mean solar exoatmospheric irradiance for the band of

interest, and β is the solar elevation angle. Values for ESUN$_\lambda$ and d were given or

interpolated from tables in the Landsat 7 Science Data Users Handbook (NASA, 2002)

and β is given in the Landsat image header file (Crombie et al., 1999).

$$a = \frac{\pi \cdot Radiance_\lambda \cdot d^2}{ESUN_\lambda \cdot \sin \beta} \qquad (13)$$

The normalized difference vegetation index (NDVI) was then calculated using the

at-sensor reflectance for bands 3 and 4 (Equation 14) (Gillies et al., 1997).

$$NDVI = \frac{(a_4 - a_3)}{(a_4 + a_3)} \qquad (14)$$

Although NDVI, strictly speaking, is in terms of surface reflectance rather than at-sensor reflectance, corrections for atmospheric effects require specification of atmospheric makeup. In order to account for atmospheric variations over the study area, the NDVI was scaled between the fully vegetated ($NDVI_s$) and bare soil ($NDVI_0$) values (Equation 15) (Crombie et al., 1999). Fractional vegetation (Fr) was then calculated as a function of the scaled NDVI (N*). As reflected in Equation 16, analysis from previous studies consistently indicate that Fr is equal to N* squared (Gillies et al., 1997).

$$N* = \frac{NDVI - NDVI_0}{NDVI_s - NDVI_0} \qquad (15)$$

$$Fr = (N*)^2 \qquad (16)$$

The fractional vegetation Imagine files were then converted to grid format, re-projected to UTM Zone 12 coordinates, and merged to form a single grid covering the study area. This grid was then clipped to correspond to the intermediate high and low intensity residential and commercial/industrial/transportation classes and the distribution of fractional vegetation values for these classes was determined by making a histogram of percent vegetation values in each class (Figures 14-16). There was no apparent difference between the distribution of fractional vegetation values in the high intensity and low intensity residential classes (Figures 14 and 15). The vast majority of the grid cells in the commercial/industrial/transportation class had 10% or less vegetation coverage. This was expected because these areas include roads, parking lots, industrial areas, etc. and are mostly impermeable surfaces.
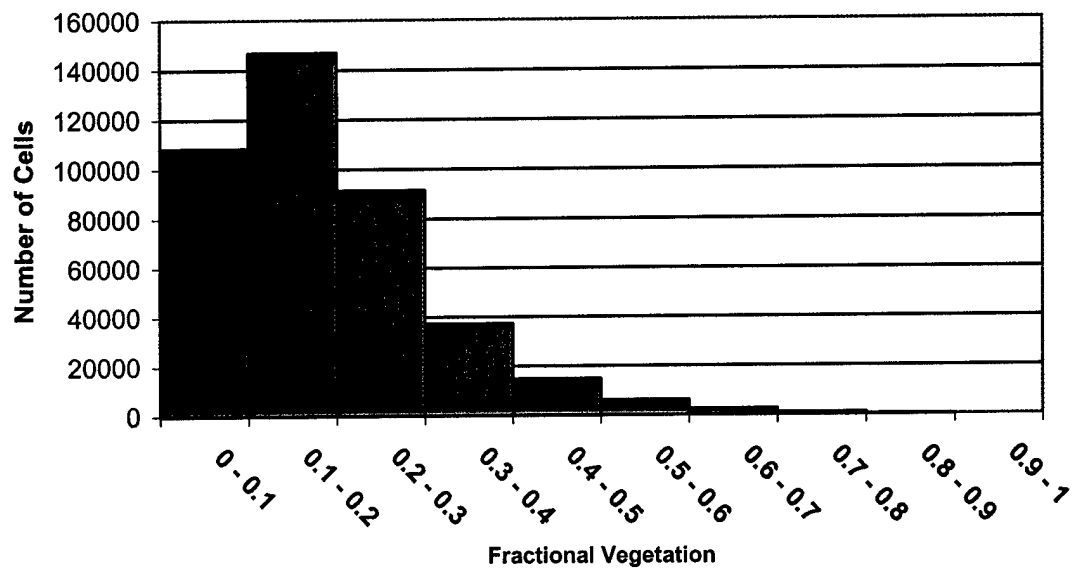
Figure 14. Histogram of fractional vegetation values for the high-intensity residential intermediate land cover class.
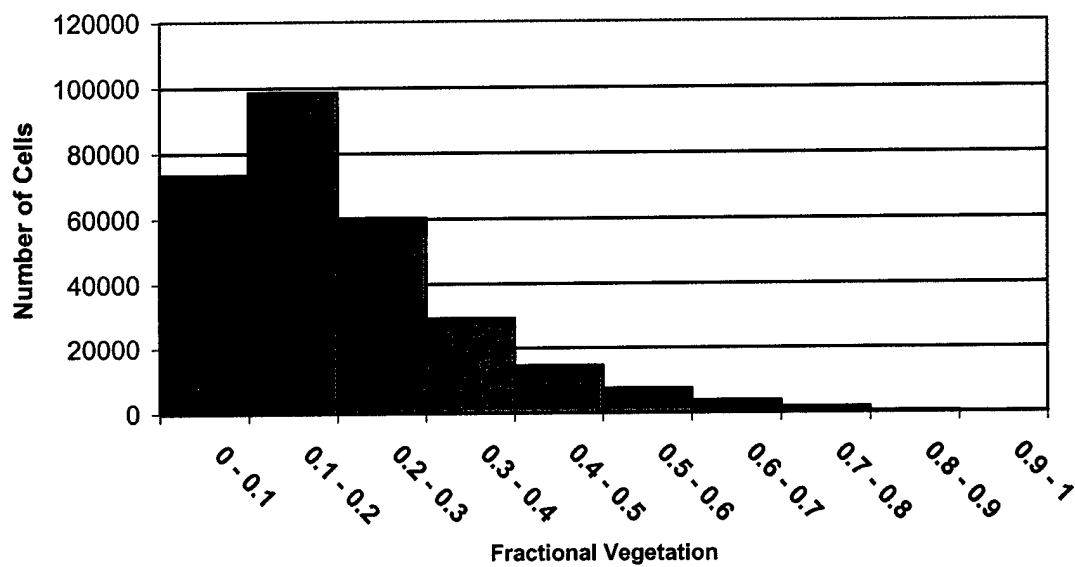
Figure 15. Histogram of fractional vegetation values for the low-intensity residential intermediate land cover class.
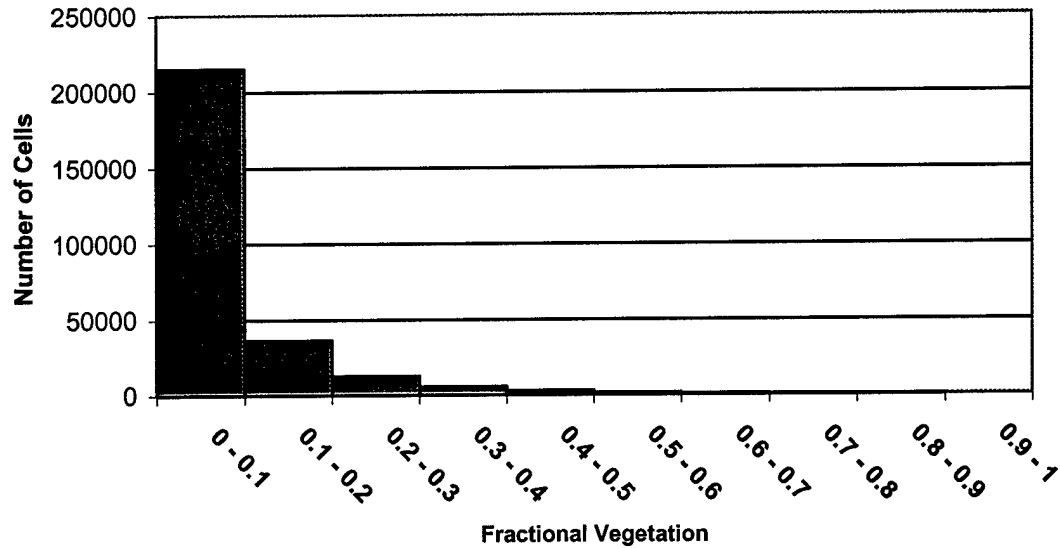
Figure 16. Histogram of fractional vegetation values for the commercial/
industrial/transportation intermediate land cover class.

In order to obtain better characterization of residential areas in terms of the

amount of vegetation present, the high- and low-intensity residential classes, as well as

portions of the commercial class corresponding to areas with fractional vegetation greater

than 10%, were merged together and a histogram of fractional vegetation values for the

class was made (Figure 17). Based on theses results, the residential area was then

reclassified into four new classes: residential areas with 10% or less fractional

vegetation, residential areas with between 10% and 20% fractional vegetation, residential

areas with between 20% and 40% fractional vegetation, and residential areas with greater

than 40% fractional vegetation.
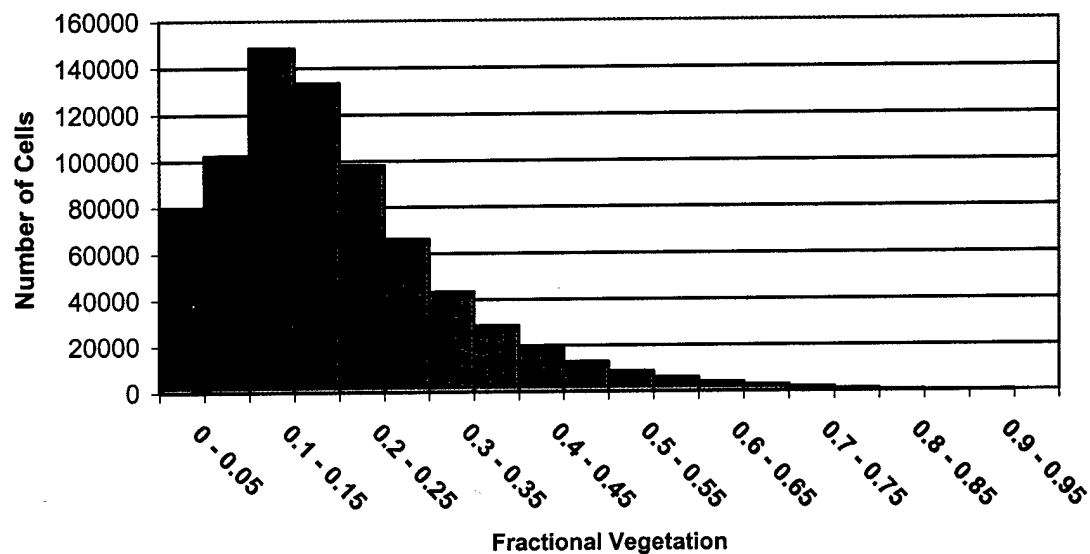
Figure 17. Histogram of fractional vegetation values for the merged residential and portions of commercial/industrial/transportation class.

The completed land cover classification consists of 52 land cover classes covering the study area (Figure 18 and Table 4). Of the 52 classes, the first 29 correspond to non-developed areas, while the remaining 23 characterize developed areas such as the agricultural and urban classes. Nearly all of the classes for the undeveloped areas are based on the Utah GAP image, while the developed classes are taken from the Water Related Land Use and NLCD land cover data sets. The last three classes (developed forest classes) correspond to forested areas in the NLCD data set that corresponded to developed areas in the GAP image.
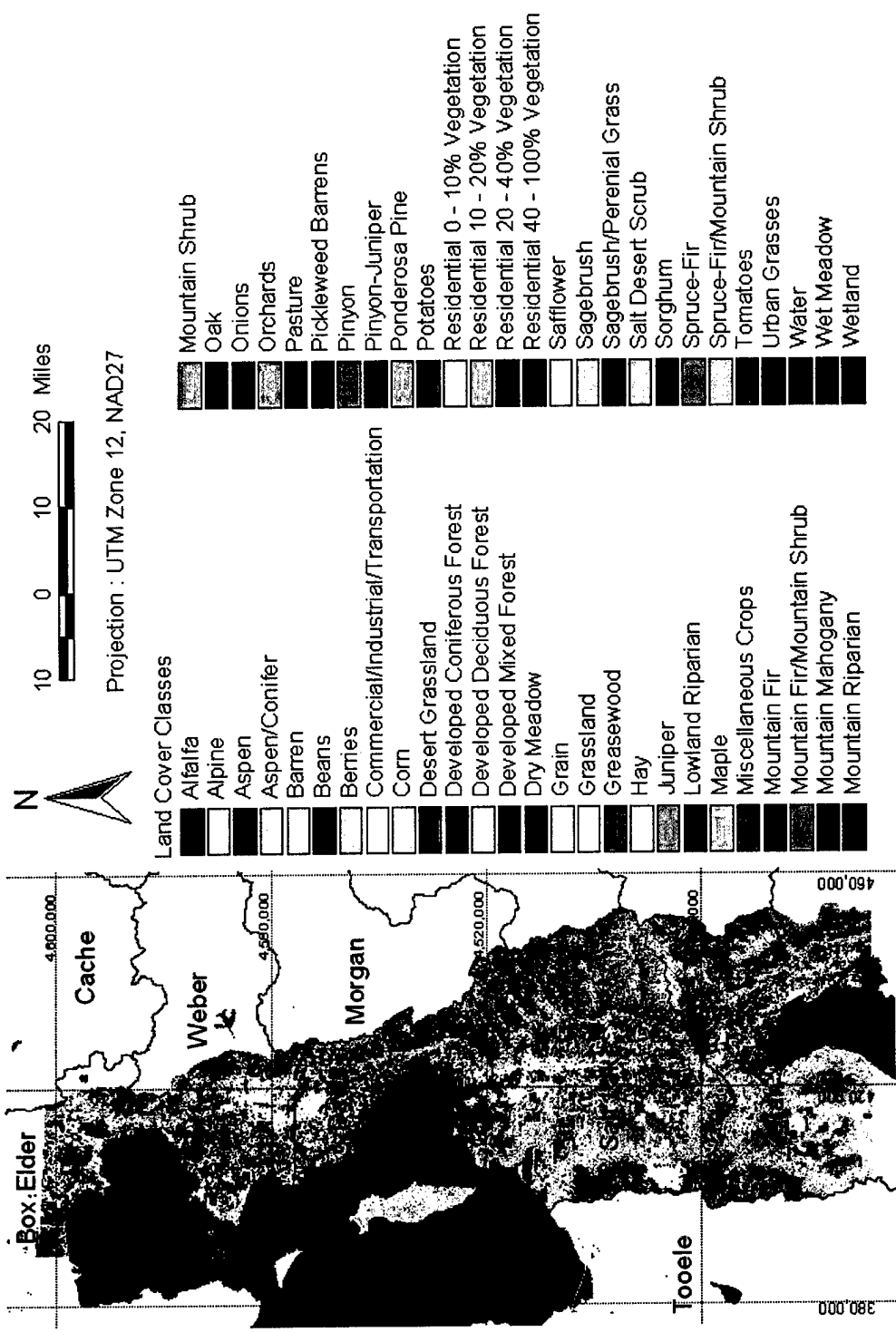
Figure 18. Final project land cover classes.

Table 4. Final project land cover classes

Project land cover classes	
1 Water	27 Greasewood
2 Spruce-Fir	28 Pickleweed Barrens
3 Ponderosa Pine	29 Wetland
4 Mountain Fir	30 Urban Grasses
5 Juniper	31 Residential 0-10%
6 Pinyon	32 Residential 10-20%
7 Pinyon-Juniper	33 Residential 20-40%
8 Mountain Mahogany	34 Residential 40-100%
9 Aspen	35 Commercial/Industrial/Transportation
10 Oak	36 Pasture
11 Maple	37 Miscellaneous Crops
12 Mountain Shrub	38 Grain
13 Sagebrush	39 Orchards
14 Sagebrush/Perennial Grass	40 Berries
15 Grassland	41 Corn
16 Alpine	42 Sorghum
17 Dry Meadow	43 Potatoes
18 Wet Meadow	44 Onions
19 Barren	45 Beans
20 Spruce-Fir/Mountain Shrub	46 Tomatoes
21 Mountain Fir/Mountain Shrub	47 Alfalfa
22 Aspen/Conifer	48 Hay
23 Mountain Riparian	49 Safflower
24 Lowland Riparian	50 Developed Deciduous Forest
25 Salt Desert Scrub	51 Developed Coniferous Forest
26 Desert Grassland	52 Developed Mixed Forest

Land cover database

In order to determine vegetation species composition for the 29 nondeveloped

land cover classes in the study, training site locations from the GAP project were

converted to grid format and associated with the land cover classes they were located

within. IWFIA field site data for forested plots were associated with the project's non-

developed land cover classes by the IWFIA. Percent canopy coverage for tree species at

each IWFIA site was determined by multiplying the total percent canopy coverage by the percent basal area for the species. A weighted average percent coverage for each species in a land cover class was then calculated by weighting the species canopy coverage by the area of the field site (see Appendix B). Thus, the more area represented by a site, the more weight it carried in characterizing the vegetation composition of a land cover class. Because some of the GAP field sites did not fall completely within one land cover class, only sites where a majority of the area of the site fell within the land cover class were used to characterize the class. When weighting these sites, only the area that was contained in the land cover class was considered. In addition, when weighting the percent cover for non-forest species, only the area for the GAP field sites was considered because data reported for the IWFIA field sites did not contain information for non-forest species.

In order to estimate what percentage of the land cover class was covered by each crop for the land cover classes that represented more than one crop (grain and orchards), county-level crop statistics from the 1997 Census of Agriculture were used (National Agricultural Statistics Service, 1997). The grain class consisted of approximately 71% wheat, 26% barley, and 3% oats. The make up of the orchard class was about 39% apple, 28% cherry, 26% peach, 3% apricot, 3% pear, and 1% grape. Other agricultural classes were assumed to only consist of one vegetative type.

The vegetative makeup of residential and commercial areas was determined using information collected during the project specific field survey and fractional vegetation values determined previously. For each species recorded in the residential survey, a total foliar volume (or area for ground covers) was calculated and normalized by the total area

surveyed that was covered by vegetation yielding a volume or area of a species per unit

vegetated area average for each species (see Appendix B). An average of the fractional

vegetation values within each of the four residential classes and the commercial class was

calculated yielding values of 5.3%, 14.8%, 27.4%, 51.4% vegetation coverage for

residential classes and 2.5% vegetation coverage for the commercial/industrial/trans-

portation class (Figures 19-23). The vegetative composition of each class was then

estimated by multiplying the average fractional vegetation by the average foliar volume

(area for ground covers) per unit vegetated area for each species from the survey.
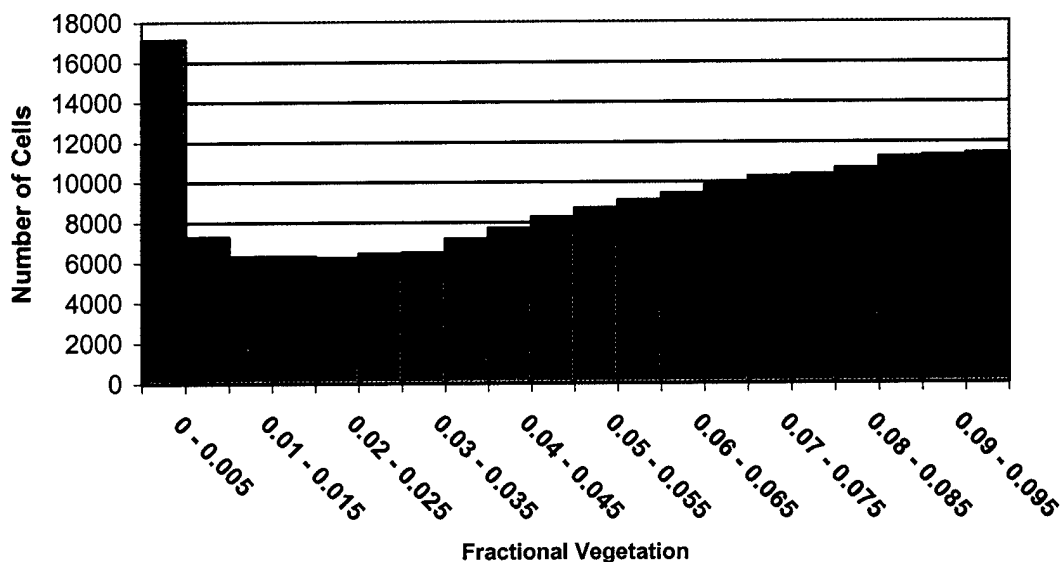
Figure 19. Histogram of fractional vegetation values for the residential 0-10% vegetation
class.
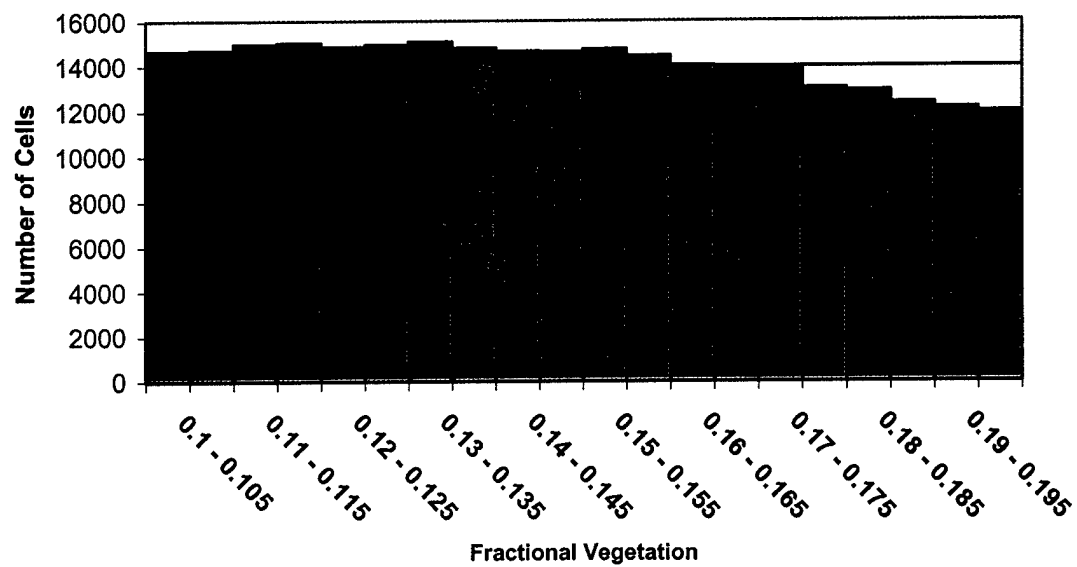
Figure 20. Histogram of fractional vegetation values for the residential 10-20% vegetation class.
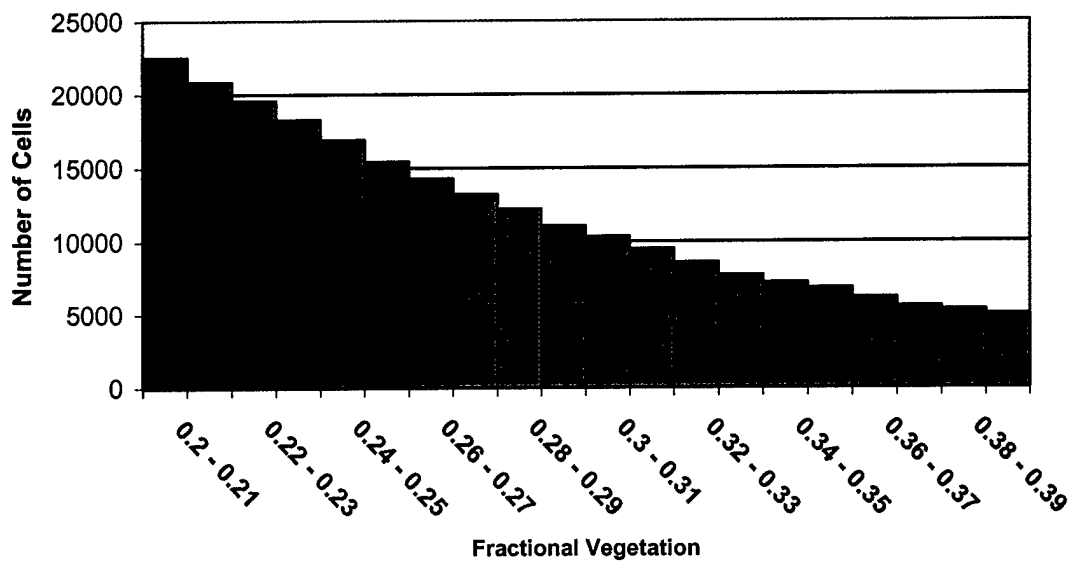
Figure 21. Histogram of fractional vegetation values for the residential 20-40% vegetation class.
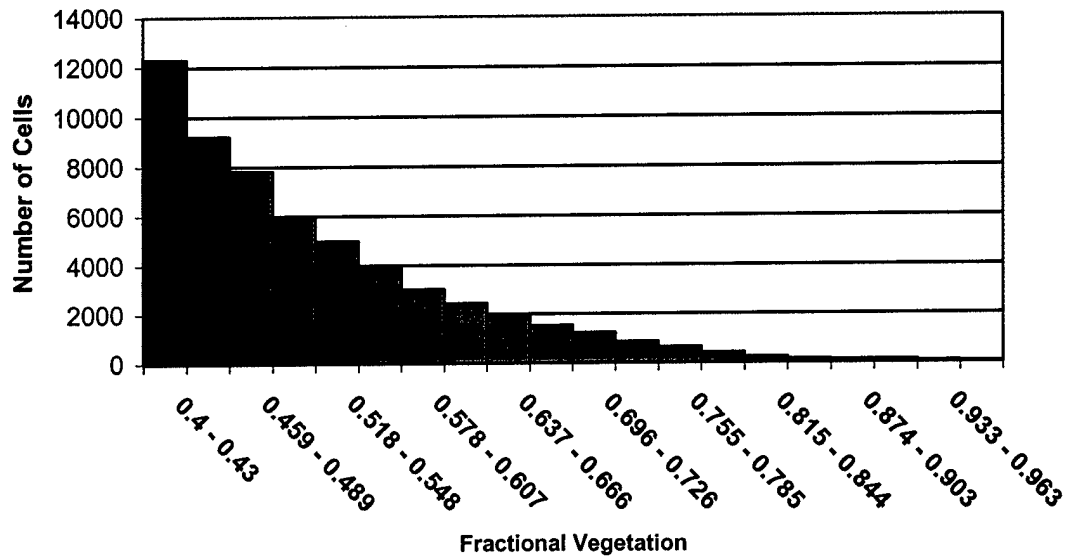
Figure 22. Histogram of fractional vegetation values for the residential 40-100% vegetation class.
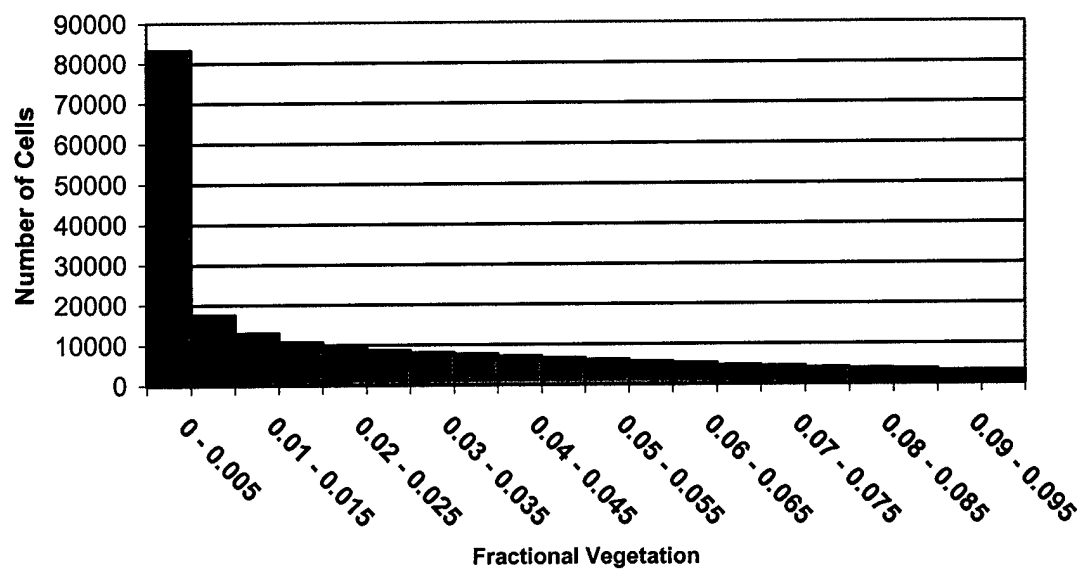
Figure 23. Histogram of fractional vegetation values for the commercial/ industrial/transportation class.

Because there was no species-specific vegetation information available about the

developed deciduous, coniferous, and mixed forest classes and the fact that these classes

collectively only makeup about 0.2% of the study area, no further effort was made to

verify species composition for these classes and the species composition assumed for

BELD 2's hardwood, western coniferous, and western mixed forest classes was applied

to these areas (Guenther, Zimmerman, and Wildermuth, 1994; Kinnee, Geron, and

Pierce, 1997).

GIS BVOC emissions inventory

Using published values, leaf biomass constants, foliar density values, and

standardized isoprene, monoterpene, and OVOC emission factors were assigned to each

species in the database (see Appendix A).

Foliar density values (g dry weight m^{-2}) for species in non-developed classes were

taken mostly from Geron, Guenther, and Pierce (1994) where broad leaf genera were

given a value of 375 g m^{-2}, 1500 g m^{-2} for *Abies*, *Picea*, and *Pseudotsuga* genera, and 700

g m^{-2} for *Pinus* and other coniferous genera. The majority of leaf biomass values (g dry

weight m^{-3}) used for species in residential and commercial areas were taken from Horie,

Sidawi, and Ellefsen (1991) and Chinkin et al. (1996). For ground covers where no

biomass value was reported, a value of 100 g m^{-2} was assumed based on Horie, Sidawi,

and Ellefsen (1991). Crop biomass density factors for agricultural vegetation were taken

mostly from Lamb et al. (1993).

Standardized isoprene, monoterpene, and OVOC emission factors (μg g^{-1} h^{-1})

were taken from a number of sources (Horie, Sidawi, and Ellefsen, 1991; Winer et al.,

1992; Lamb et al., 1993; Geron, Guenther, and Pierce, 1994; Benjamin et al., 1996;

Chinkin et al., 1996; Hewitt et al., 1997; Pierce et al., 1998). Some emission factors were reported under different PAR and temperature conditions and were standardized to 30 ° C and PAR of 1000 μmol m^{-2} s^{-1} using the activity factor corrections mentioned previously (Guenther et al., 1993). For species where no information about emission factors was reported, methods described by Benjamin et al. (1996) were used to assign BVOC emission factors. This method consisted of using the average of measured emission factors for species in the same genus for species without measured values. If values were not available for species of the same genus, the average of emission values from species in the same family was used. For species or genera that were reported as isoprene or monoterpene emitters but no emission factors were reported, an emission factor of 0.1 μg C g^{-1} h^{-1} was assigned (Pierce et al., 1998). All species were assumed to emit OVOCs if there were no genus or family values indicating otherwise. These species were also assigned an OVOC emission factor of 0.1 μg C g^{-1} h^{-1} and an average OVOC molecular mass to carbon mass ratio of 1.23 as used in BELD 2 (Kinnee, Geron, and Pierce, 1997).

Standardized isoprene, monoterpene, and OVOC fluxes (μg m^{-2} h^{-1}) were then calculated for each land cover class. For all of the non-developed land cover classes except water, barren, and wetland, emission fluxes for each class were calculated by multiplying the average percent canopy coverage for each species in the class by the corresponding foliar density and emission factors. The products for each species in the land class were then summed to give total isoprene, monoterpene, and OVOC emission fluxes for the class. This procedure followed the methods outlined by Geron, Guenther, and Pierce (1994). Standardized BVOC emission fluxes for the water, barren, and

wetland classes were assigned using emission flux values from the BEIS 2/BELD 2

model for these cover types (Pierce et al., 1998).

Standardized BVOC emission fluxes for pasture, miscellaneous crops, corn,

sorghum, potatoes, alfalfa, and hay agricultural classes were also assigned using emission

flux values from the BEIS 2/BELD 2 model (Pierce et al, 1998). Because the grain class

consisted of more than one crop type (wheat, barley, and oats), the standardized BVOC

flux was calculated by multiplying the BELD 2 emission fluxes by the percent area

occupied by each crop and summing these numbers for all crop types present in the class.

For agricultural classes that were not contained in the BEIS 2/BELD 2 model,

standardized BVOC emission fluxes were developed by multiplying the crop's emission

factor by the appropriate foliar density (for orchard class) or aboveground biomass per

area estimates.

BVOC emission flux values for the residential classes and the commercial/in-

dustrial/transportation class were calculated by multiplying the leaf biomass values for

each species in the class by the species average crown volume per area (area per area for

ground covers) and by the BVOC emission factor and summing the products for all

vegetation species in the class. The urban grasses class was given the emission flux value

for grass from BELD 2 (Kinnee, Geron, and Pierce, 1997). BVOC emissions flux values

for the developed deciduous, coniferous, and mixed forest classes were also assigned

based on values reported in BELD 2 for hardwood, western coniferous, and western

mixed forest classes. Resulting BVOC emission flux values for each land cover class are

presented in Table 5.

Table 5. BVOC emission flux values for project land cover classes at standardized conditions of 30 °C and 1000 μmol m^{-2} s^{-1} PAR

Class	Isoprene (μg m^{-2} h^{-1})	Monoterpene (μg m^{-2} h^{-1})	OVOC (μg m^{-2} h^{-1})
Water	0	0	0
Spruce-Fir	7330	2620	1450
Ponderosa Pine	2170	980	690
Mountain Fir	3230	2750	1700
Juniper	117	319	579
Pinyon	243	1090	708
Pinyon-Juniper	46.7	628	548
Mountain Mahogany	610	70.5	498
Aspen	18800	142	545
Oak	17500	219	558
Maple	8110	318	547
Mountain Shrub	2860	187	422
Sagebrush	36.1	135	335
Sagebrush/Perennial Grass	88.3	94.0	204
Grassland	33.8	138	125
Alpine	146	594	331
Dry Meadow	230	725	405
Wet Meadow	471	354	198
Barren	0	0	0
Spruce-Fir/Mountain Shrub	1500	1780	1110
Mountain Fir/Mountain Shrub	3780	1550	1210
Aspen/Conifer	12300	1485	1150
Mountain Riparian	5190	332	385
Lowland Riparian	2650	142	333
Salt Desert Scrub	24.9	217	183
Desert Grassland	35.9	115	99.2
Greasewood	383	191	273
Pickleweed Barrens	0	50.7	106
Wetland	1050	660	770
Urban Grasses	56.2	140.5	84.3
Residential 0-10% Vegetation	113	29.1	54.5
Residential 10-20% Vegetation	316	81.6	153
Residential 20-40% Vegetation	584	151	282
Residential 40-100% Vegetation	1100	283	529
Commercial/Industrial/Transportation	53.8	13.9	26.0

Table 5. Continued

Class	Isoprene ($\mu g\ m^{-2}\ h^{-1}$)	Monoterpene ($\mu g\ m^{-2}\ h^{-1}$)	OVOC ($\mu g\ m^{-2}\ h^{-1}$)
Pasture	56.2	140.5	84.3
Miscellaneous Crops	7.6	19.0	11.4
Grain	13.0	10.0	10.0
Orchards	40.8	48.7	697
Berries	66.0	132	1220
Corn	0.5	0	0
Sorghum	7.8	19.5	11.7
Potatoes	9.6	24.0	14.4
Onions	0	0	12.3
Beans	0	0	17.4
Tomatoes	0	5330	192
Alfalfa	19.0	7.6	11.4
Hay	37.8	94.5	56.7
Safflower	0.0	11.3	375
Developed Deciduous Forest	8730	436	882
Developed Coniferous Forest	4270	1120	1320
Developed Mixed Forest	5720	620	530

This completed the high-resolution BVOC emissions inventory which consists of a grid file containing standardized emission flux values of isoprene, monoterpenes, and OVOCs for every 30-m cell in the Wasatch Front study area. Total standardized isoprene, monoterpene, and OVOC emission rates (kg h^{-1}) were also calculated for the study area by multiplying the emission flux for each cell by the area of the cell (900 m^2) and summing the products across the entire study area. This sum was compared to results from BELD 2.

RESULTS AND DISCUSSION

Comparison of High-Resolution Inventory with BELD 2

Comparison of land cover

Because of the larger number of land cover classes in the high-resolution BVOC

inventory, direct comparison of some land cover classes to corresponding classes in

BELD 2 was not always possible but where feasible, general groups of classes within the

two databases were compared. Tables 6 and 7 show what percentage of the study area is

covered by each land cover class for BELD 2 and the high-resolution BVOC inventory,

respectively.

Table 6. Percentage of study area for land cover classes in BELD 2

Land cover class	% study area
Water	20.27%
Barren	1.64%
Miscellaneous Cropland	4.56%
Woodland/Cropland	3.64%
Hay	1.28%
Wheat	0.97%
Barley	0.20%
Corn	0.17%
Oats	0.02%
Western Woodlands	14.98%
Southeast/Western Deciduous Forest	2.22%
Hardwood Forest	0.10%
Western Coniferous Forest	11.10%
Boreal Forest	0.10%
Western Mixed Forest	15.50%
Scrub	2.87%
Grass	7.37%
Urban Other	13.01%

Table 7. Percentage of study area for land cover classes in the high-resolution BVOC inventory

Land cover class	% study area	Land cover class	% study area
Water	24.22%	Mountain Fir/Mountain Shrub	0.78%
Barren	1.88%	Developed Coniferous Forest	0.17%
Miscellaneous Crops	2.00%	Aspen/Conifer	0.26%
Grain	1.19%	Developed Mixed Forest	0.01%
Berries	0.00%	Mountain Mahogany	0.16%
Corn	0.90%	Mountain Shrub	2.92%
Sorghum	0.02%	Sagebrush	5.23%
Potatoes	0.00%	Sagebrush/Perennial Grass	1.89%
Onions	0.08%	Salt Desert Scrub	4.28%
Beans	0.01%	Greasewood	0.75%
Tomatoes	0.00%	Pickleweed Barrens	0.14%
Alfalfa	2.14%	Grassland	3.20%
Hay	0.33%	Dry Meadow	0.14%
Safflower	0.07%	Wet Meadow	0.01%
Aspen	4.34%	Desert Grassland	0.02%
Oak	9.27%	Urban Grasses	1.06%
Maple	0.23%	Pasture	5.58%
Orchards	0.22%	Residential 0-10% Vegetation	2.44%
Developed Deciduous Forest	0.04%	Residential 10-20% Vegetation	3.79%
Spruce-Fir	1.45%	Residential 20-40% Vegetation	3.17%
Ponderosa Pine	0.00%	Residential 40-100% Vegetation	0.76%
Mountain Fir	1.88%	Commercial/Industrial/Transportation	2.89%
Juniper	3.81%	Alpine	0.09%
Pinyon	0.15%	Mountain Riparian	0.74%
Pinyon-Juniper	0.79%	Lowland Riparian	1.61%
Spruce-Fir/Mountain Shrub	0.16%	Wetland	2.70%

The high-resolution model indicates that a slightly larger portion of the study area

is covered by water than is reflected in BELD 2. One reason for this difference could be

that the Great Salt Lake dropped roughly 7 feet in elevation between 1987 and 1990

(USGS, 2001a). While the satellite images for the Utah GAP project were collected

between 1988 and 1989, the data used to create BELD 2 was collected in 1990. A

problem with this explanation is that BELD 2 should have a greater barren area from where the lake had receded. Another more likely reason could be that the 30-m spatial resolution used for this project would reflect smaller bodies of water that would not be detected at the coarser spatial resolution used to create BELD 2.

Barren and agricultural classes occupied roughly the same amount of area in both databases and the urban other class from BELD 2 covered approximately the same percentage of the study area as the residential and commercial land cover classes combined. Forested areas in the high-resolution BVOC inventory occupied a smaller percentage of area than those in BELD 2 while grasslands and shrub areas occupied a greater portion. This is probably because large forested portions of Utah, Weber, and Box Elder counties did not fall within the study area but, due to the fact that BELD 2 uses county resolution data, all forested areas would, in effect, be evenly distributed throughout the county. This would cause the parts of the counties within the study area to have a higher percentage of forested areas and a smaller percentage of other areas than what is actually in the study area. Comparison on a county-by-county basis rather than at the study area level would probably be more appropriate for a more exhaustive comparison of land cover databases.

Comparison of study area level
standardized emission rates

The total standardized BVOC as well as isoprene, monoterpene, and OVOC emission rate estimates calculated for the study area using BELD 2 and the project's high-resolution BVOC inventory are shown in Table 8.

Table 8. Standardized BVOC emission rates for the study area using BELD 2 and the
high-resolution BVOC inventory

Inventory	Isoprene Emission Rate (kg/h)	Monoterpene Emission Rate (kg/h)	OVOC Emission Rate (kg/h)	Total BVOC Emission Rate (kg/h)
BELD 2	11978	2103	2617	16698
High-Resolution	19769	1554	1885	23208

The emission rate of isoprene calculated for the study area using the high-resolution inventory was 65% higher than the emission rate estimated by BELD 2. Pierce et al. (1998) noted that isoprene concentrations modeled using emission estimates from the BEIS 2/BELD 2 model were about 50% lower than measured values. This would support the conclusion that the higher isoprene emission rate determined by the high-resolution model is more accurate. Emission rates for monoterpenes and OVOCs were about 26% and 28% lower than the BELD 2 estimates, respectively. The total BVOC emission rate estimated by the high-resolution inventory was 39% higher than the BELD 2 estimate. The differences in isoprene emissions are explainable by noting that although forested areas in the BELD 2 are greater than in the high-resolution BVOC inventory, the vegetative species composition data acquired from field sites for forested areas included a greater percentage of high isoprene emitting species, such as aspen and oak, than was assumed in BELD 2. These areas had isoprene emission fluxes 2 to 4 times the values for forested areas in BELD 2. These high isoprene emitting species also tended to have lower monoterpene emissions than the species composition assumed in BELD 2. This coupled with the fact that BELD 2 included more forested area explain why monoterpene

emissions were greater in BELD 2 than in the high-resolution BVOC inventory. The

lower OVOC emissions in the high-resolution BVOC inventory are also explained by the

smaller forested area reflected in the inventory.

Comparison of spatial resolution

Figures 24-26 show a comparison of the spatial distribution of the standardized

isoprene, monoterpene, and OVOC emission flux estimates from the high-resolution

BVOC emissions inventory and BELD 2 within the Wasatch Front study area.
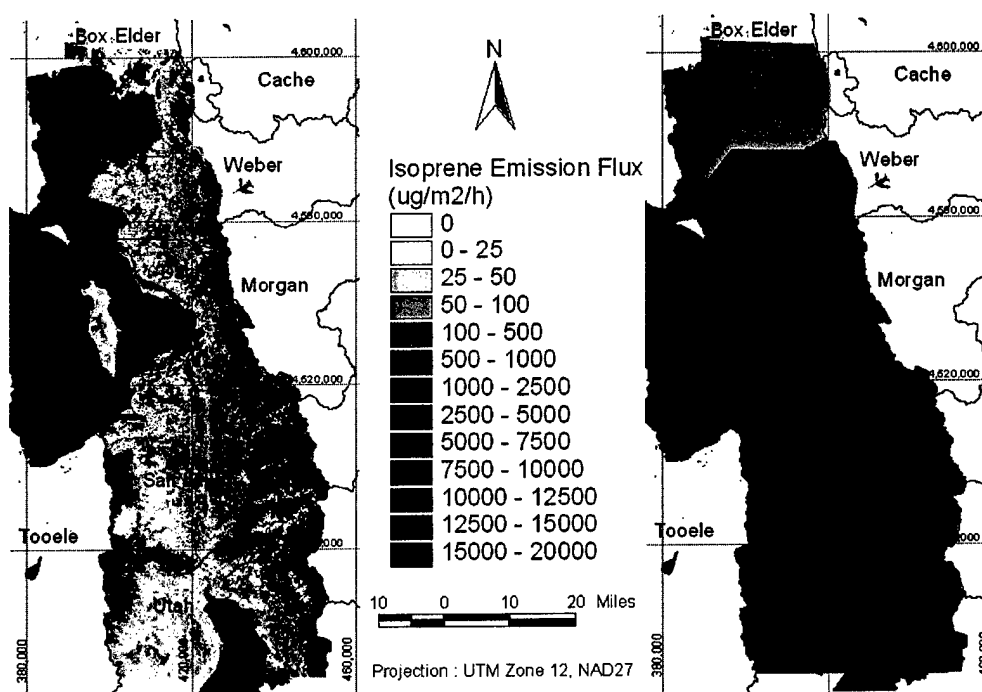
Figure 24. Comparison of the spatial distribution of isoprene emission fluxes in the
project BVOC emissions inventory and BELD 2.
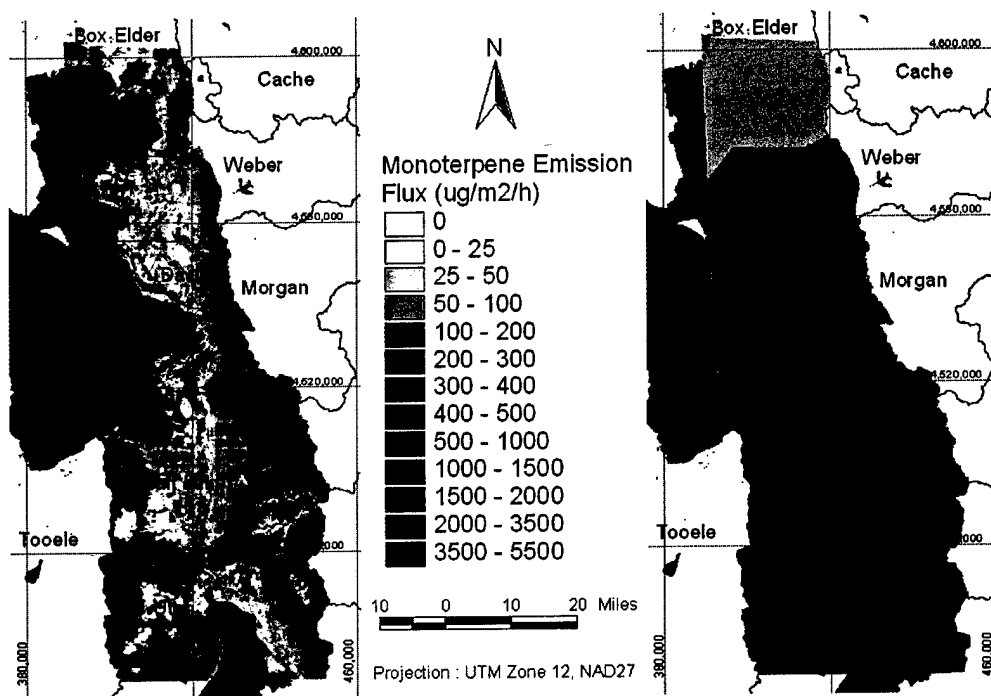
Figure 25. Comparison of the spatial distribution of monoterpene emission fluxes in the project BVOC emissions inventory and BELD 2.
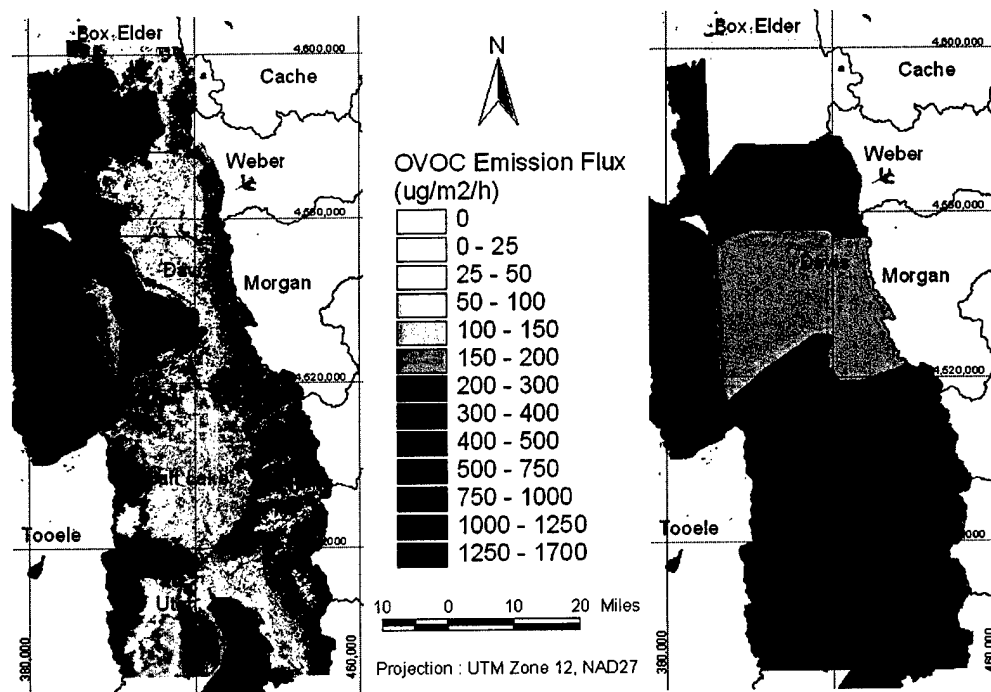
Figure 26. Comparison of the spatial distribution of OVOC emission fluxes in the project BVOC emissions inventory and BELD 2.

From these figures, the advantages of using higher resolution data for spatially characterizing BVOC emissions are readily apparent. The high-resolution inventory shows that a large portion of the BVOC emissions come from the eastern portion of the study area corresponding to the forested mountainous areas while emissions are lower in more developed areas. This is reasonable because less developed areas in the mountains have more vegetation. However, due to its coarser resolution, BELD 2 does not reflect these differences.

Although standardized isoprene, monoterpene, and OVOC emission rates for the study area from the high-resolution BVOC inventory and BELD 2 were well within a factor of 2 of each other, within the study area, some areas in the high-resolution BVOC inventory had emission flux values 20 times greater than the values reflected in BELD 2. Once again, this is due to the fact that BVOC emissions in BELD 2 are averaged over the whole county. The fact that in the high-resolution BVOC inventory, BVOC emissions are averaged over a 30-m by 30-m area rather than the entire county results in a more defined spatial characterization of emissions.

Comparison of model uncertainty

Most of the uncertainty associated with BVOC emission models is due to variations in measured emission rates (Kinnee, Geron, and Pierce, 1997). Geron, Guenther, and Pierce (1994) report that emission rates of isoprene and monoterpenes for most vegetative species within a genus have been shown to fall within ± 50% of a genus level average value. Benjamin et al. (1996), however, report that differences in isoprene and monoterpene emission rates from species within a genus are more on the order of a factor of 10 while species within a family can vary by as much as a factor of 32.

Estimates of OVOCs have been reported to vary by a factor of 10 (Guenther, Zimmerman, and Wildermuth, 1994). Foliar mass values reported by Guenther, Zimmerman, and Wildermuth (1994) differed by as much as a factor of 5 for some cover types but the majority differed by less than a factor of 2.

Because the majority of the BVOC emission rate values and nearly all of the foliar mass values were taken from the same sources as are used in BELD 2 (Lamb et al., 1987; Geron, Guenther, and Pierce, 1994; Guenther, Zimmerman, and Wildermuth, 1994), the uncertainty in estimating BVOC emissions associated with these factors is basically the same for the high-resolution BVOC inventory and BELD 2.

The main difference in the uncertainty between the two models is the vegetation composition assigned to land cover classes and the land cover data used. Guenther, Zimmerman, and Wildermuth (1994) point out that species composition estimates that were used to assign emission rates to land cover classes in the portion of BELD 2 corresponding to the western United States are a first approximation and should only be used in the event that more detailed species composition data is not available. The local specific data collected for the Utah GAP Analysis project, forest inventory information from IWFIA, and data collected during the project specific residential survey have reduced some of the uncertainty involved in assigning species composition to each land class. Rather than assuming the vegetative composition based solely on remotely sensed data, remotely sensed information has been coupled with local vegetative field surveys to construct this high-resolution BVOC inventory.

There is a good deal of uncertainty in the estimates of species composition of urban vegetation. Unlike vegetation in natural areas, the composition in urban areas is

not homogenous and difficult to predict based on environmental factors (Horie, Sidawi, and Ellefsen, 1991). Although questions may arise as to whether a residential vegetation survey of a small portion of the total area can adequately characterize the species composition for these areas it is important to note that the alternative current approach is to assume that 89% of urban areas are 20% grass and 80% hardened surface. The other 11% is assumed to have the same species composition and frequency as the forested areas in the county (Kinnee, Geron, and Pierce, 1997). Kinnee, Geron, and Pierce (1997) report that more resolved land use and vegetation cover data are needed for urban areas and that urban vegetation surveys can help to address this problem. Based on this information, the composition of urban vegetation derived from the project specific survey conducted for this study was considered more adequate for characterizing BVOC emissions than the assumptions used in BELD 2.

Another source of uncertainty is the land cover data used to generate a BVOC emissions inventory. Edwards et al. (1995) report that overall map accuracy of the GAP vegetation classified image, as determined through field validation, was 75.3%. As mentioned previously, this image was the basis for the majority of the land cover classes. Although no estimates of uncertainty were given for the Water Related Land Use GIS coverage, it is note worthy that one of the final steps in the creation of the Water Related Land Use coverage was the validation of boundaries and cover types by technicians in the field (Division of Water Resources, 1999). Accuracy assessment of the region of the NLCD data set containing the study area has not been completed but reported accuracies for other regions ranged from 38 to 81% but were generally around 50 to 60% (USGS, 2001b). Loveland et al. (1991) report that the only verification of the EDC land cover

data used for the western portion of the United States in BELD 2 was a comparison to preexisting data sets. However, no information on the results of the comparison were presented. Field validation of data sets used to create the high-resolution BVOC emissions inventory help reduce some of the uncertainty involved in accurately characterizing vegetative land cover.

Loveland et al. (1991) also state that due to the coarse resolution of the EDC data, land cover classes are based on mosaics of land cover rather than on homogeneous landscape regions. The finer resolution of the data used for this project should help to reduce some of the uncertainty in the land cover classes.

There is a small degree of uncertainty involved during the process of computing the fractional vegetation in selecting the bare soil NDVI value ($NDVI_0$). Ideally, if a pixel in the image is known to correspond to bare soil, its NDVI value can be used. However, this is not always possible. A more general approach involves looking at the histogram of values and extrapolating the bare soil value. Bare soil values are usually around 0.08 while urban surfaces like concrete will be around 0.04 (Gillies, 2002). While an $NDVI_0$ value of 0.08 was used to derive the fractional vegetation for this project, the actual $NDVI_0$ value would be in the range of $\pm$ 50% of the value used. Figure 27 shows the variability involved in the calculated fractional vegetation values depending on the value of $NDVI_0$.

Based on this figure, actual fractional vegetation values should not differ from calculated values by more than 0.026. This is relatively small compared to other uncertainties involved in estimating BVOC emissions. In addition, the purpose in calculating fractional vegetation was to reclassify urban areas to get better spatial

0.04 —0.08 —0.12
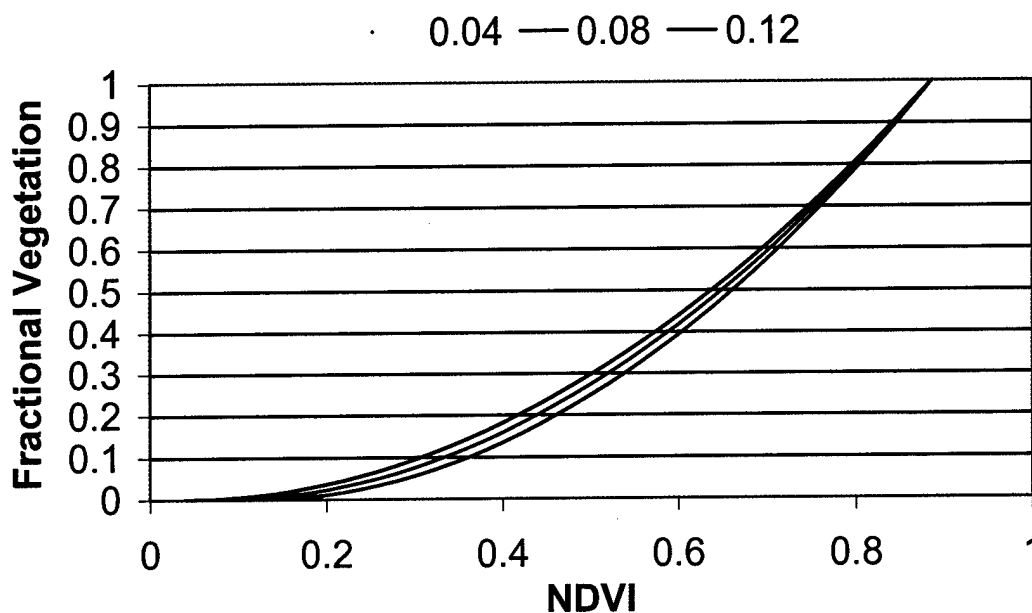
Figure 27. Variability in calculated fractional vegetation values based on $NDVI_0$ values of 0.04, 0.08, and 0.12.

resolution for these areas so the spatial distribution of values was more important than the actual value itself. This process of determining the fractional vegetation for urban areas provided more information on the amount of vegetation present in these areas and helped reduce some of the uncertainty involved in estimating BVOC emissions from urban areas.

The methods and datasets used to create the high-resolution BVOC emissions inventory should help to reduce some of the uncertainty involved in estimating vegetative emissions of VOCs. Although much work is needed in reducing the uncertainty involved in vegetative species BVOC emission rates, the use of vegetation surveys as well as higher resolution data has reduced some of the uncertainty involved in modeling the vegetative composition and land cover of the study area.

Implications of Inventory Differences

The incremental reactivity (IR) of a VOC is defined as the amount of ozone formed per unit VOC added to an initial atmospheric reaction mixture of VOC and NO_x (Finlayson-Pitts and Pitts, 2000). This value varies depending on the compound and the VOC/NO_x ratio of the air mass into which the compound is entering (Finlayson-Pitts and Pitts, 2000). The peak, or maximum IR (MIR) occurs at a VOC/NO_x ratio of about 6 (Finlayson-Pitts and Pitts, 2000). Reported MIR values for representative compounds for the three classes of BVOCs modeled in this project are shown in Table 9.

The BVOC class representative MIR averages were used to estimate the maximum amount of ozone that could be produced in the study area by hourly BVOC emissions at standard conditions. It was estimated that the hourly maximum amount of ozone that could by produced for the study area at standard conditions based on hourly BVOC estimates from BELD 2 was about 137,400 kg while BVOC estimates from the high-resolution model would produce 200,700 kg ozone, a difference of over 63,000 kg.

Table 9. Maximum incremental reactivity (MIR) values for representative BVOCs

BVOC	MIR [a] (g O^3 formed per g VOC added)
ISOPRENE	9.1
MONOTERPENE (Average)	3.8
α-Pinene	3.3
β-Pinene	4.4
OVOC (Average)	7.8
Ethene	7.4
Propene	9.4
1-Butene	8.9
Acetaldehyde	5.5

[a] Carter (1994)

Due to the dynamic nature of the mixing height, the spatial heterogeneity of emissions and mass transport issues, it is difficult to extrapolate these calculations to differences in ground-level ozone concentrations without more complex atmospheric models. These calculations, however, do serve to show that the ozone production due solely to BVOC emissions is estimated to be roughly 45% greater than the current model, BELD 2, would indicate. It is important to note that this percent difference is not in the total ozone production but only in the fraction that could potentially be produced due to BVOCs. Differences in the estimated potential total ozone production would be less when anthropogenic VOCs are also included and the previous calculations are only intended for model comparison.

Figure 28 shows isopleths of one hour average ozone concentrations during an ozone episode (1 August 2000) superimposed on the distribution of isoprene emissions within the study area. Data from 11 monitoring sites were available to interpolate the ozone concentrations shown. Due to the small number of monitoring sites available, the confidence in the modeled concentrations decreases for areas where there are few or no monitoring sites (e.g., on the eastern slope of the mountain ridge defining the boundary of the study area). These calculations did, however, help identify areas of elevated ozone concentrations. Although accurate meteorological information and other modeling parameters are necessary to determine whether BVOCs contributed significantly to the elevated ozone concentrations, the high-resolution BVOC inventory better identifies areas that are emitting higher levels of BVOCs that may contribute to ozone formation.
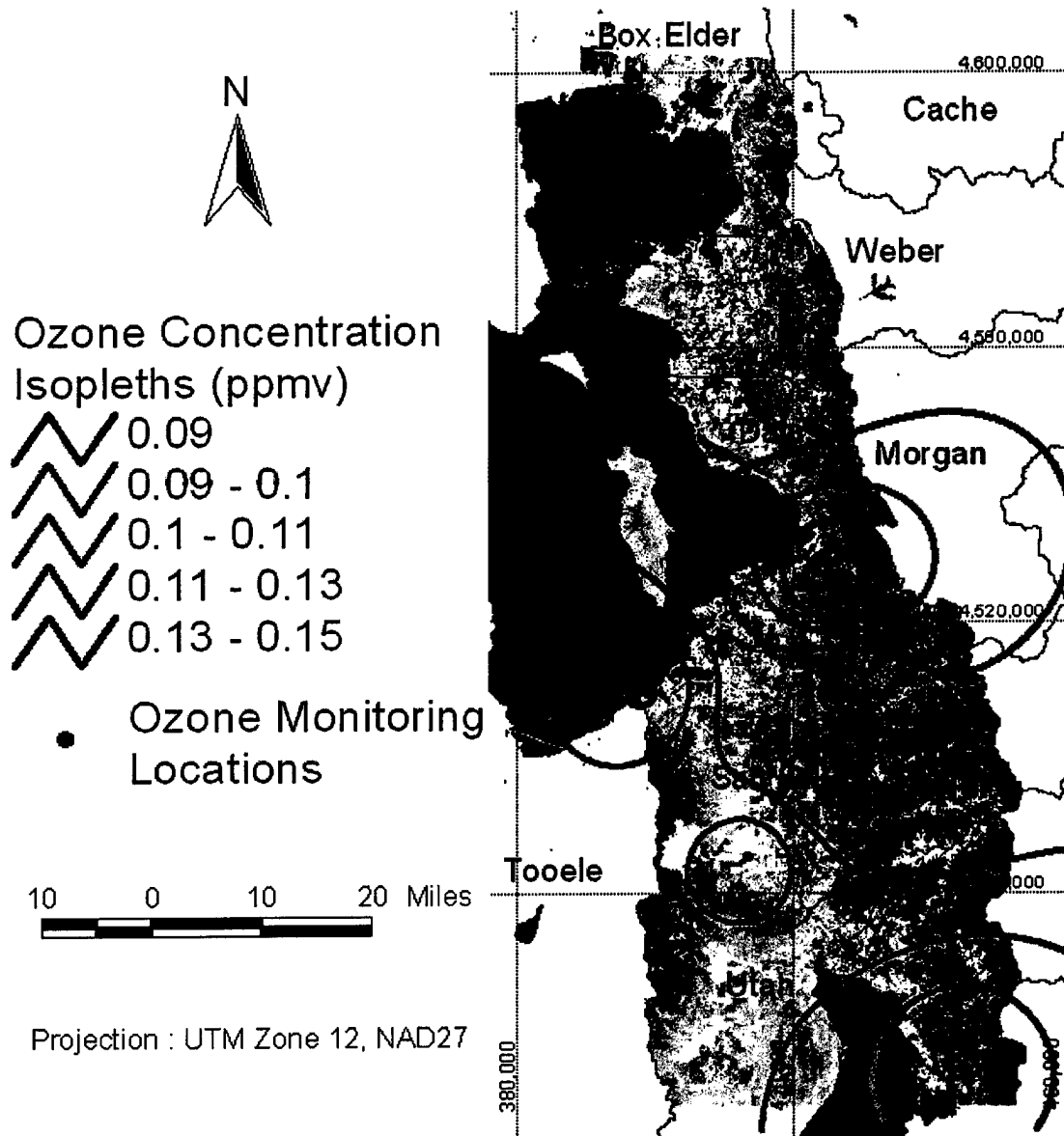
Figure 28. Ozone concentrations along the Wasatch Front during an ozone episode superimposed on isoprene emissions for the study area.

SUMMARY AND CONCLUSIONS

Project Summary

The Wasatch Front is Utah's most populated and fastest growing urban area. In the past few years, ambient concentrations of ground-level O_3 have exceeded the NAAQS at monitoring sites within the airshed. Because BVOCs are very reactive in terms of O_3 production and the Wasatch Front airshed is VOC limited, it is important to accurately estimate and characterize emissions of non-methane, photochemically reactive hydrocarbons emitted from vegetation along the Wasatch Front. Better estimates of these compounds will enable regulators to make more informed decisions about strategies for reducing emissions of ozone precursor compounds

In order to accomplish this task, a locally accurate 30-m resolution gridded BVOC emissions inventory was created using remotely sensed data, vegetative species composition information from field surveys, and plant biomass and BVOC emission rate factors from previous research. A more spatially representative and complete land cover classification was generated using the Utah GAP Analysis vegetation classified image, the Utah Division of Water Resources Water Related Land Use GIS coverage, and the NLCD land cover data. Fractional vegetation values derived from Landsat TM satellite imagery were used to define the extent of vegetation cover in residential and commercial classes. The vegetative species composition of each land cover class was estimated using information from the GAP and IWFIA field surveys, the Census of Agriculture, and a project specific residential field survey. Based on the vegetative species composition, standardized emission fluxes of isoprene, monoterpenes, and OVOCs were assigned to

each land cover class using standardized BVOC emission factors and biomass constants. The high-resolution BVOC inventory was then compared to BELD 2, the current land cover database used to model BVOC emissions for the Wasatch Front.

While some similarities in land cover classes between BELD 2 and the high-resolution BVOC inventory occurred, forested areas in the study area were less in the high-resolution BVOC inventory than in BELD 2. Other undeveloped areas such as shrub and grasslands were more predominant in the high-resolution BVOC inventory than in BELD 2. These differences are due to the differing spatial resolutions of both inventories.

Even though forested areas were lower in the high-resolution BVOC inventory, standardized hourly isoprene and total BVOC emissions for the study area were 65% and 39% higher than BELD 2 estimates, respectively. Differences between the two inventories in emission estimates were a result of the differences in vegetative species composition assigned to land cover classes and the difference in the spatial resolution of both models. For purposes of estimating the spatial distribution of BVOC emissions, the high-resolution model was superior to BELD 2 in showing areas of differing BVOC emission fluxes within the study area.

Although there is a large amount of uncertainty involved in estimating BVOC emissions, methods used in this study have characterized the spatial heterogeneity in vegetation composition and distribution. A more thorough characterization of this nature helps to better delineate one of those factors which are responsible for the spatial distribution of BVOC emissions. Assuming that emission factors and biomass constants associated with differing plant species are correct, the methodology used in this project to

develop a more thorough characterization of the landscape should reduce some of the uncertainty in estimating VOC emissions and the resulting ozone pollution.

Using maximum incremental reactivity (MIR) values, the potential ozone production due to BVOC emissions was estimated. Based on these estimates, potential ozone production due to BVOC emissions in the study area was 45% greater than BVOC estimates from the current model would indicate.

Future Study

This study shows some of the advantages of coupling high-resolution, remotely sensed data with local vegetation information for characterizing BVOC emissions from an area. However, results from this study are only a comparison to the current BVOC emissions inventory. No field validation of emission estimates from the high-resolution BVOC inventory has been made and future work should include field measurements of the area flux of BVOC emissions to verify emission estimates from this inventory. Other methods of verification could include using the inventory as input data for photochemical models and assess whether BVOC estimates from this study increase the accuracy in modeling observed ozone concentrations.

Future work could also include the creation of an emissions inventory for the whole state of Utah using the methodologies developed in this study. For this, the most current data sets available should be used. A large portion of the data used in this study was collected around the early 1990's. Updated versions of the vegetation classification of Utah by the Southwest Regional GAP Analysis Project, the Utah Division of Water Resources Water Related Land Use coverage, and the NLCD are all currently underway

(Division of Water Resources, 2001; USGS, 2001b; EPA, 2002b). Upon completion of these data sets, they would contain a more up-to-date characterization of land cover for Utah. The largest anticipated difference would probably be an increase in the extent of residential areas and a decrease in nondeveloped areas due to population growth.

As more measurements of BVOC emissions are made for different vegetative species, they should be incorporated into this or future inventories to help reduce some of the uncertainty involved in the estimation process. In addition, seasonal changes to plant biomass could be modeled using remotely sensed data as described by Zhu and Evans (1994).

Engineering Significance

As the population along the Wasatch Front grows and elevated concentrations of ambient ozone become more prevalent, control strategies for reducing emissions of ozone precursor compounds (VOCs and NO_x) will require a better understanding of the magnitude and sources of these compounds. Improvements in estimating BVOC emissions will help in making regulatory decisions to control ozone production (Kinnee, Geron, and Pierce, 1997). Results from this project will help better estimate BVOC emissions and characterize their spatial distribution along the Wasatch Front.

According to current estimates, the Wasatch Front is currently believed to be VOC limited in terms of ozone formation (Barickman, 2002). In this case, ozone formation would be more sensitive to BVOC emissions. As mentioned previously, for VOC limiting conditions, reductions in VOCs would be targeted to reduce ozone formation. However, some areas have such high BVOC emission rates that reductions in

AVOC emissions are not sufficient to achieve the NAAQS (Chameides et al., 1988). For decision making purposes, this high-resolution BVOC emissions inventory could be used as input to photochemical oxidant formation models to assess the feasibility of reducing VOC emissions sufficiently to meet the ozone standards and the sensitivity of ozone formation to BVOC emissions. Better decisions on control strategies of NO_x and VOCs could then be made based on the results.

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APPENDICES

Appendix A

Values Used to Assign BVOC Emission Flux Estimates

Table 10. Standardized BVOC emission factors and foliar density values used for vegetative species in the undeveloped classes

Vegetation Species	Isoprene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Monoterpene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		OVOC Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)	Ref.	Foliar Density (g m-2)	
Abies concolor	1.4	B	2.9	B	1.85	A	1500	A
Abies lasiocarpa	0.11	A	3.4	A	1.85	A	1500	A
Acer glabrum	0.11	A	2.8	B	1.85	A	375	A
Acer grandidentatum	0.11	A	1.8	A	1.85	A	375	A
Acer spp.	0.11	A	1.8	A	1.85	A	375	A
Achillea spp.	0	C2	4.8	C2	1.85	A	375	A
Agoseris rostrata	0	C2	4.8	C2	1.85	A	375	A
Agropyron cristatum	0	D	0	D	0.06	E	873	D
Allenrolfea occidentali	0	C	1	C2	1.85	A	375	A
Alnus spp.	0.11	F	0.11	F	1.85	A	375	A
Amelanchier utahensis	0.11	F	0.11	F	1.85	A	375	A
Arctostophylos spp.	0	C	0	C	1.85	A	375	A
Artemisia spp.	0	C	0.2	C	1.85	A	375	A
Artemisia campestris	0	C	0.2	C	1.85	A	375	A
Artemisia nova	0	C	0.2	C	1.85	A	375	A
Artemisia tridentata	0.1	C	0.2	C	1.85	A	375	A
Atriplex canescens	1.0	C	3.0	C	1.85	A	375	A
Atriplex confertifolia	0	C	3.0	C1	1.85	A	375	A
Baccharis salicina	0.1	C1	0.1	C1	1.85	A	375	A
Betula spp.	0.11	A	0.23	A	1.85	A	375	A
Bromus spp.	0	D	0.015	E	0.06	E	873	D
Carex geophila	0	C2	0	D2	0.06	E2	873	D
Carex spp.	0	C2	0	D2	0.06	E2	873	D
Ceanothus spp.	0	B1	2.4	B1	1.85	A	375	A
Ceratoides lanata	0.13	C2	1.0	C2	1.85	A	375	A
Cercocarpus ledifolius	0	B	0	B	1.85	A	375	A
Cercocarpus montanus	1.0	C	0.2	C	1.85	A	375	A
Chrysopis villosa	0	C2	4.8	C2	1.85	A	375	A

Table 10. Continued

Vegetation Species	Isoprene Emission Factor (μg g^{-1} h^{-1})		Monoterpene Emission Factor (μg g^{-1} h^{-1})		OVOC Emission Factor (μg g^{-1} h^{-1})		Foliar Density (g m-2)	
Chrysothamnus spp.	1.0	C	3.0	C	1.85	A	375	A
Cowania mexicana	0.01	C2	0.7	C2	1.85	A	375	A
Elymus cinereus	0	C2	0	D2	0.06	E2	873	D
Ephedra spp.	3.0	D	3.0	D	1.85	A	375	A
Family Compositae Forb spp.	0	C2	4.8	C2	1.85	A	375	A
Family Rosacea Shrub spp.	0.28	C2	0.55	C2	1.85	A	375	A
Festuca thurberi	0	D	0	D	0.06	E2	873	D
Gutierrezia sarothrae	0	C2	4.8	C2	1.85	A	375	A
Halogeten glomeratus	0.1	C2	1.0	C2	1.85	A	375	A
Helianthus annuus	0.05	C	0.5	C	1.85	A	375	A
Juncus compressus	0	C1	0	C1	0.06	E2	873	D
Juniperus ssp.	0.11	A	0.68	A	1.85	A	700	A
Juniperus osteosperma	0.11	A	0.68	A	1.85	A	700	A
Juniperus scopulorum	0.11	A	0.68	A	1.85	A	700	A
Kochia vestita	0.13	C2	1.0	C2	1.85	A	375	A
Lupinus spp.	2.0	C2	0.9	C2	1.85	A	700	A
Physocarpus spp.	0.01	C2	0.7	C2	1.85	A	375	A
Picea engelmannii	15.9	A	3.4	A	1.85	A	1500	A
Picea pungens	15.9	A	3.4	A	1.85	A	1500	A
Picea spp.	15.9	A	3.4	A	1.85	A	1500	A
Pinus contorta	0.11	A	3.4	A	1.85	A	700	A
Pinus edulis	0.11	A	3.5	B	1.85	A	700	A
Pinus flexilis	0.11	A	3.4	A	1.85	A	700	A
Pinus monophylla	0.11	A	3.4	A	1.85	A	700	A
Pinus ponderosa	0.11	A	3.4	A	1.85	A	700	A
Poa spp.	0	D	0	D	0.06	E2	873	D
Populus angustifolia	79	A	0.11	A	1.85	A	375	A
Populus fremontii	79	A	0.11	A	1.85	A	375	A
Populus tremuloides	79	A	0.11	A	1.85	A	375	A
Potentilla spp.	0.01	C2	0.7	C2	1.85	A	375	A
Prunus virginiana	0.11	A	0.11	A	1.85	A	375	A

Table 10. Continued

Vegetation Species	Isoprene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Monoterpene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		OVOC Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Foliar Density (g m-2)	
Pseudotsuga menziesii	1.4	B	2.9	B	1.85	A	1500	A
Purshia tridentata	0	C	0.7	C2	1.85	A	375	A
Quercus gambelii	79	A	0.23	A	1.85	A	375	A
Rosa woodsii	0	B	0.1	B	1.85	A	375	A
Salix spp.	40	A	0.11	A	1.85	A	375	A
Salsola iberica	0.1	C2	1	C2	1.85	A	375	A
Sarcobatus vermiculatus	0.1	C2	1	C2	1.85	A	375	A
Shepherdia canadensis	0	C2	1	C2	1.85	A	375	A
Symphoricarpos orbiculatus	1.0	C1	0.2	C1	1.85	A	375	A
Symphoricarpos oreophilus	1.0	C1	0.2	C1	1.85	A	375	A
Symphoricarpos vaccinioides	1.0	C1	0.2	C1	1.85	A	375	A
Tamarix pentandra	0	C	0.04	C1	1.85	A	375	A
Taraxacum officinale	0	C2	4.8	C2	1.85	A	375	A
Tetradymia canescens	0	C2	4.8	C2	1.85	A	375	A
Wyethia amplexicaulis	0	C	4.8	C2	1.85	A	375	A

A = Geron, Guenther, and Pierce (1994), B = Benjamin et al. (1996), C = Hewit et al. (1997), D = Horie, Sidawi, and Ellefsen (1991), E = Winer et al. (1992), F = Pierce et al. (1998)
1 = genus average, 2 = family average

Table 11. Standardized BVOC emission factors and foliar density values used for agricultural species

Vegetation Species	Isoprene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Monoterpene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		OVOC Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Foliar Density (g m-2)	
Allium cepa (onion)	0	D	0	D	0.123	E	100	D
Carthamus tinctorius (safflower)	0	B	0.03	B	1	E	375	A
Lycopersicon lycopersicum (tomato)	0	B	35.5	B	1.28	E	150	D
Malus spp. (apple)	0.11	A	0.11	A	1.85	A	375	A
Phaseolus vulgaris (bean)	0	B	0	B	0.1	E	174	D
Prunus armeniaca (apricot)	0.11	A	0.11	A	1.85	A	375	A
Prunus domestica (plum)	0.11	A	0.11	A	1.85	A	375	A
Prunus persica (peach)	0.11	A	0.11	A	1.85	A	375	A
Prunus spp. (cherry)	0.11	A	0.11	A	1.85	A	375	A
Pyrus communis (pear)	0	B	0.6	B	1.85	A	375	A
Rubus spp. (berries)	0.1	B	0.2	B	1.85	A	660	F
Vitis vinifera (grape)	0.001	B	0.09	B	1.3	E	920	C

A = Geron, Guenther, and Pierce (1994), B = Hewit et al. (1997), C = Schreiner and Baham (2002), D = Horie, Sidawi, and Ellefsen (1991), E = Winer et al. (1992), F = Rempel (2002)

Table 12. Standardized BVOC emission factors and biomass constants used for residential tree and shrub species

Vegetation Species	Isoprene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Monoterpene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		OVOC Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Biomass Constant (g m-3)	
Abies sp.	0.11	A	3.4	A	1.85	A	435	D
Acer palmatum	0.11	A	2.8	B	1.85	A	44	D
Acer pseudoplatanus	0.11	A	2.8	B	1.85	A	44	D
Acer sp.	0.11	A	2.8	B	1.85	A	44	D
Aesculus hippocastanum	0.11	F	0.11	F	1.85	A	44	C2
Ailanthus altissima	0.11	F	0.11	F	1.85	A	44	C2
Alnus sp.	0.11	F	0.11	F	1.85	A	168	D
Antirrhinum majus	0	D	0	D	1.85	A	100	D
Aucuba japonica	3	D	3	D	1.85	A2	646	D
Berberis sp.	25	C2	0.2	C	1.85	A2	598	D2
Betula sp.	0.11	A	0.23	A	1.85	A	168	D1
Buddleia davidii	0	C2	0.11	3	1.85	A	646	D
Buxus sempervirens	10.75	C	0.067	C	1.85	A	646	D1
Castanea sativa	0.11	F	0.11	F	1.85	A	310	D2
Catalpa sp.	0.11	F	0.11	F	1.85	A	630	D2
Cotoneaster Franchetti	0	C1	0	C1	1.85	A	260	D1
Cotoneaster sp.	0	C1	0	C1	1.85	A	260	D1
Crataegus oxyacantha	0.11	F	0.11	F	1.85	A	168	D2
Elaeagnus Angustifolia	0	C	3	D1	1.85	A	646	D1
Euonymous sp.	3	D1	3	D1	1.85	A	646	D1
Fatsia sp.	0	D1	3	D1	1.85	A	646	D1
Forsythia sp.	0.016	C2	0.28	C2	1.85	A	646	D1
Fraxinus sp.	0.033	C1	0.033	C1	1.85	A	170	D1
Gleditsia triacanthos	0.11	F	0.11	F	1.85	A	150	D2
Hypericum sp.	0.11	3	0.5	C2	1.85	A	646	D
Ilex sp.	0.11	F	0.23	F	1.85	A	646	D
Juniperus Media	0.11	A	0.68	A	1.85	A	3700	D1
Juniperus sp.	0.11	A	0.68	A	1.85	A	3700	D
Laburnum sp.	0.11	F	0.11	F	1.85	A	150	D2
Ligustrum sp.	0	C1	0	C1	1.85	A	230	D
Lilium longiflorum	0	D	0	D	0.12	3	100	D
Magnolia sp.	0.11	F	3.4	F	1.85	A	350	D
Malus sp.	0.11	F	0.11	F	1.85	A	168	D
Myrtus communis	34	B	0.2	C	1.85	A	50	D

Table 12. Continued

Vegetation Species	Isoprene Emission Factor (μg g^{-1} h^{-1})		Monoterpene Emission Factor (μg g^{-1} h^{-1})		OVOC Emission Factor (μg g^{-1} h^{-1})		Biomass Constant (g m-3)	
Papaver sp.	0.11	C2	0.11	C2	1.85	A	360	D
Parthenocissus quinquefolia	0.001	C2	0.09	C2	1.3	E	150	D2
Philadelphus sp.	3	D	3	D	1.85	A	646	D
Picea pungens	16	A	3.4	A	1.85	A	435	D2
Pinus mugo	0.11	A	3.4	A	1.85	A	390	D1
Pinus nigra	0.11	A	3.4	A	1.85	A	390	D1
Pinus sp.	0.11	A	3.4	A	1.85	A	390	D1
Pinus sylvestris	0.11	A	3.4	A	1.85	A	390	D1
Populus tremuloides	79	A	0.11	A	1.85	A	168	D1
Prunus armeniaca	0.11	F	0.11	F	1.85	A	168	D
Prunus avium	0.11	F	0.11	F	1.85	A	168	D
Prunus domestica	0.11	F	0.11	F	1.85	A	168	D
Prunus lusitanica	0.11	F	0.11	F	1.85	A	394	D
Prunus persica	0.11	F	0.11	F	1.85	A	168	D
Prunus sp.	0.11	F	0.11	F	1.85	A	168	D
Pseudotsug menziesii	1.4	B	2.9	B	1.85	A	435	D1
Pyrus sp.	0	C	0.6	C	1.85	A	180	D
Quercus sp.	79	A	0.23	A	1.85	A	310	D
Rheum sp.	0.0011	C2	0	B2	1.85	A	340	D2
Rhus sp.	18	C1	0.55	C1	1.85	A	200	D
Rosa sp.	0	B	0.1	B	1.85	A	360	D
Salix sp.	40	A	0.11	A	1.85	A	110	D
Skimmia sp.	0.11	F2	1.81	F2	1.85	A	280	D2
Sorbus accuparia	0.11	F	0.11	F	1.85	A	168	D2
Spiraea arguta	0.1	C2	0.69	C2	1.85	A	646	D
Symphoricarpos sp.	1	C1	0.2	C1	1.85	A	646	D
Syringa vulgaris	0	C	0	C	1.85	A	646	D
Taxus baccata	0	C2	0.11	3	1.85	A	646	D
Thuja sp.	0.11	A	0.68	A	1.85	A	3700	D
Ulmus parvifolia	0.11	F	0.11	F	1.85	A	25	D
Ulmus sp.	0.11	F	0.11	F	1.85	A	646	D
Viburnum sp.	3	D	3	D	1.85	A	646	D
Wistaria sp.	0.11	C	0.033	G2	0.11	G2	100	D

A = Geron, Guenther, and Pierce (1994), B = Benjamin et al. (1996), C = Hewit et al. (1997), D = Horie, Sidawi, and Ellefsen (1991), E = Winer et al. (1992), F = Pierce et al. (1998), G = Lamb et al. (1993)

1 = genus average, 2 = family average, 3 = Assumed 0.1 μg C g^{-1} h^{-1}

Table 13. Standardized BVOC emission factors and biomass constants used for
residential ground cover species

Vegetation Species	Isoprene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Monoterpene Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		OVOC Emission Factor ($\mu g\ g^{-1}\ h^{-1}$)		Biomass Constant (g m-2)	
Achillea sp.	0	C2	4.8	C2	1.85	A	100	D
Aegopodium podagraria	0	C2	1.00	C2	1.85	A	100	D
Alyssum sp.	0	C2	0.12	C2	1.85	A	100	D
Begonia sp.	0	D	0	D	1.85	A2	100	D
Chrysanthemum praecox	0	C	0.3	C	1.85	A	100	D
Chrysanthemum sp.	0	C	0.51	C	1.85	A	100	D
Cucurbita maxima	0	D	0	D	1.85	A	100	D
Cucurbita sp.	0	D	0	D	1.85	A	100	D
Hedera Helix	0	D	0	D	1.85	A	100	D
Helianthus annuus	0.05	C	0.5	C	1.85	A	375	D2
Hemerocallis sp.	0	C2	0	C	0.12	3	100	D
Hosta sp.	0	C2	0	C2	0.12	3	100	D
Hyacinthus sp.	0	C2	0	C2	0.12	3	100	D2
Ipomoea tricolor	0.11	C	0.11	C	1.85	A	100	D
Lavandula sp.	0.1	C	5.9	C1	1.85	A	100	D
Lobelia sp.	0.11	3	0.11	3	1.85	A	100	D
Lycopersicon sp.	0	C	35.5	C	1.28	E	150	D
Mixed Flowers	0	D	0	D	1.85	A	100	D
Mixed Garden	0.0057	G	0.014	G	0.0085	G	1335	G
Petunia hybrida	0	C2	14.4	C2	1.85	A	100	D
Potentilla fruticosa	0.1	C2	0.69	C2	1.85	A	100	D
Primula sp.	0	D	0	D	1.85	A	100	D
Pteridium aquilinum	1.2	C	0.11	C	0.12	3	435	D
Rubus sp.	0.1	C	0.2	C	1.85	A	660	F
Sedum sp.	0	D	0	D	1.85	A	100	D
Trifolium sp.	0	C1	0	C1	0.11	G2	100	D
Tulipa sp.	0	C	0.1	C	0.12	E3	100	D
Vinca sp.	0	D	0	D	1.85	A	100	D
Viola sp.	0	D	0	D	1.85	A	100	D
Vitis vinifera	0.001	C	0.09	C	1.3	A	920	B
Weeds	0	D	0	D	1.85	A	100	D
Zinnia sp.	0	C2	4.8	C2	1.85	A	100	D

A = Geron, Guenther, and Pierce (1994), B = Schreiner and Baham (2002), C = Hewit et al. (1997), D = Horie, Sidawi, and Ellefsen (1991), E = Winer et al. (1992), F = Rempel (2002), G = Lamb et al. (1993)

1 = genus average, 2 = family average, 3 = Assumed 0.1 $\mu g\ C\ g^{-1}\ h^{-1}$

Table 14. Standardized hourly BVOC emission flux values for land cover classes taken from BELD 2

BELD 2 Land Cover Type	Isoprene [a] (μg m^{-2} h^{-1})	Monoterpene [a] (μg m^{-2} h^{-1})	OVOC [a] (μg m^{-2} h^{-1})
Water	0	0	0
Barren	0	0	0
Wetland	1050	660	770
Grasses	56.2	140.5	84.3
Alfalfa	19	7.6	11.4
Barley	7.6	19	11.4
Corn	0.5	0	0
Hay	37.8	94.5	56.7
Miscellaneous Crops	7.6	19	11.4
Oats	7.6	19	11.4
Pasture	56.2	140.5	84.3
Potatoes	9.6	24	14.4
Sorghum	7.8	19.5	11.7
Wheat	15	6	9
Developed Deciduous Forest	8730	436	882
Developed Coniferous Forest	4270	1120	1320
Developed Mixed Forest	5720	620	530

[a] Kinnee, Geron, and Pierce (1997)

Appendix B

Vegetation Species Frequency and Composition Used for Land Cover

Classes as Determined From the GAP, IWFIA, and

Project Residential Vegetation Surveys

Table 15. Average foliar volume of tree and shrub species per vegetated area for the residential and commercial/industrial/transportation classes

Species	Common Name	m^3 m^{-2} Vegetated Area
Abies sp.	Unidentified Fir	6.52E-05
Acer palmatum	Japanese Maple	1.56E-03
Acer pseudoplatanus	Sycamore	2.84E-02
Acer sp.	Unidentified Maple	3.48E-01
Aesculus hippocastanum	Horse Chestnut	1.60E-02
Ailanthus altissima	Tree of Heaven	1.58E-03
Alnus sp.	Unidentified Alder	3.29E-04
Antirrhinum majus	Snapdragon	7.73E-05
Aucuba japonica	Gold Dust	2.50E-04
Berberis sp.	Unidentified Barberry	7.17E-04
Betula sp.	Unidentified Birch	1.26E-02
Buddleia davidii	Butterfly Bush	1.09E-03
Buxus sempervirens	Dwarf Boxwood	9.76E-04
Castanea sativa	Chestnut	2.73E-02
Catalpa sp.	Unidentified Catalpa	2.43E-03
Cotoneaster Franchetti	Franchet Cotoneaster	7.78E-04
Cotoneaster sp.	Unidentified Cotoneaster	2.43E-04
Crataegus oxyacantha	Hawthorn	8.60E-04
Elaeagnus Angustifolia	Russian Olive	4.13E-02
Euonymous sp.	Unidentified Burning Bush	1.40E-03
Fatsia sp.	Unidentified Aralia	1.46E-03
Forsythia sp.	Forsythia	1.23E-03
Fraxinus sp.	Unidentified Ash	5.19E-01
Gleditsia triacanthos	Honeylocust	1.29E-01
Hypericum sp.	St. Johnswort	5.84E-04
Ilex sp.	Unidentified Holly	3.91E-04
Juniperus Media	Pfitzer Juniper	7.81E-04
Juniperus sp.	Unidentified Juniper	2.77E-02
Laburnum sp.	Golden Rain	7.03E-04
Ligustrum sp.	Privet	1.25E-03
Magnolia sp.	Unidentified Magnolia	4.26E-03
Malus sp.	Apple	6.64E-02
Myrtus communis	Common Myrtle	5.45E-04
Papaver sp.	Unidentified Poppy	4.34E-04

Table 15. Continued

Species	Common Name	$m^3 \, m^{-2}$ Vegetated Area
Parthenocissus quinquefolia	Virgina Creeper	1.55E-04
Philadelphus sp.	Mock Orange	8.46E-04
Picea pungens	Blue Spruce	4.42E-02
Pinus mugo	Mugo Pine	8.90E-04
Pinus nigra	Austrian Pine	5.44E-04
Pinus sp.	Unidentified Pine	1.05E-02
Pinus sylvestris	Scots Pine	3.85E-02
Populus tremuloides	Quaking Aspen	9.78E-02
Prunus armeniaca	Apricot	7.43E-03
Prunus avium	Wild Cherry	3.49E-03
Prunus domestica	Plum	3.08E-02
Prunus lusitanica	Portugal Laurl	1.94E-03
Prunus persica	Peach	5.55E-03
Prunus sp.	Unidentified Cherry	6.41E-02
Pseudotsug menziesii	Douglas Fir	1.73E-02
Pyrus sp.	Pear	4.69E-03
Quercus sp.	Unidentified Oak	1.32E-02
Rheum sp.	Rhubarb	3.34E-04
Rhus sp.	Unidentified Sumac	1.79E-02
Rosa sp.	Rose	7.16E-03
Salix sp.	Unidentified Willow	1.80E-03
Skimmia sp.	Unidentified Skimmia	1.71E-04
Sorbus accuparia	Mountain Ash	6.47E-02
Spiraea arguta	Bridal Wreath	3.96E-03
Symphoricarpos sp.	Snowberry	3.37E-04
Syringa vulgaris	Common Lilac	9.49E-03
Taxus baccata	Yew	1.79E-03
Thuja sp.	Arborvitae	7.74E-03
Ulmus parvifolia	Chinese Elm	4.78E-02
Ulmus sp.	Unidentified Elm	1.15E-01
Viburnum sp.	Snowball	2.90E-03
Wistaria sp.	Wistaria	2.24E-04

Table 16. Average area of ground covers per vegetated area of the residential and
commercial/industrial/transportation classes

Species	Common Name	$m^2\ m^{-2}$ Vegetated Area
Achillea sp.	Yarrow	1.45E-04
Aegopodium podagraria	Bishop Weed	3.74E-04
Alyssum sp.	Alyssum	1.00E-03
Begonia sp.	Begonia	3.43E-04
Chrysanthemum praecox	Daisy	1.37E-04
Chrysanthemum sp.	Chrysanthemum	6.18E-04
Corn	Corn	6.89E-03
Cucurbita maxima	Squash	1.43E-02
Cucurbita sp.	Pumpkin	5.63E-03
Grass	Grass	8.53E-01
Hedera sp.	Ivy	7.13E-04
Helianthus annuus	Common Sunflower	3.10E-04
Hemerocallis sp.	Daylily	6.32E-04
Hosta sp.	Unidentified Hosta	9.20E-04
Hyacinthus sp.	Unidentified Hyacinth	1.96E-04
Ipomoea tricolor	Morning Glory	1.56E-04
Lavandula sp.	Lavender	8.27E-05
Lobelia sp.	Unidentified Lobelia	3.45E-05
Lycopersicon sp.	Tomatoes	1.78E-03
Mixed Flowers	Mixed Flowers	1.16E-02
Mixed Garden	Mixed Garden	4.74E-03
Petunia hybrida	Common Garden Petunia	1.39E-03
Potentilla fruticosa	Shrubby Cinquefoil	1.41E-04
Primula sp.	Primrose	1.42E-03
Pteridium aquilinum	Bracken	1.80E-05
Rubus sp.	Raspberry	1.17E-03
Sedum sp.	Stonecrop	4.49E-05
Trifolium sp.	Clover	5.59E-05
Tulipa sp.	Tulips	3.71E-04
Vinca sp.	Periwinkle	3.95E-03
Viola sp.	Violet	1.86E-04
Vitis vinifera	Grape	2.22E-03
Weeds	Weeds	1.53E-02
Zinnia sp.	Unidentified Zinnia	1.37E-04

Table 17. Average percent vegetative cover by species for the spruce-fir class

Vegetative Species	% Vegetative Cover
Abies concolor	0.21
Abies lasiocarpa	18.68
Grasses	5.01
Picea engelmannii	2.11
Picea spp.	24.27
Pinus contorta	9.58
Pinus flexilis	0.49
Populus tremuloides	3.28
Pseudotsuga menziesii	1.43

Table 18. Average percent vegetative cover by species for the ponderosa pine class

Vegetative Species	% Vegetative Cover
Abies concolor	2.90
Artemisia tridentata	11.23
Juncus compressus	0.22
Juniperus spp.	2.46
Pinus contorta	6.96
Pinus edulis	2.46
Pinus ponderosa	24.93
Populus tremuloides	6.96
Pseudotsuga menziesii	0.22

Table 19. Average percent vegetative cover by species for the mountain fir class

Vegetative Species	% Vegetative Cover
Abies concolor	1.93
Abies lasiocarpa	10.88
Acer glabrum	0.07
Acer grandidentatum	0.71
Amelanchier utahensis	0.30
Artemisia tridentata	0.87
Baccharis salicina	0.16
Cercocarpus ledifolius	0.44
Cercocarpus montanus	0.02
Family Rosacea Shrub spp.	0.26
Grasses	6.26
Picea engelmannii	0.27
Picea spp.	6.95
Pinus contorta	0.81
Pinus edulis	0.00
Pinus flexilis	0.31
Pinus monophylla	0.06
Pinus ponderosa	2.00
Populus tremuloides	1.83
Pseudotsuga menziesii	38.00
Quercus gambelii	0.17
Salix spp.	0.32
Symphoricarpos oreophilus	0.40

Table 20. Average percent vegetative cover by species for the juniper class

Vegetative Species	% Vegetative Cover
Acer grandidentatum	0.43
Artemisia nova	2.70
Artemisia spp.	1.04
Artemisia tridentata	3.60
Atriplex confertifolia	0.04
Ceratoides lanata	0.05
Cercocarpus ledifolius	0.10
Cowania mexicana	0.20
Grasses	11.60
Juniperus osteosperma	33.32
Pinus edulis	2.21
Pinus monophylla	0.03
Populus fremontii	0.07
Populus tremuloides	0.01
Pseudotsuga menziesii	1.83
Purshia tridentata	0.03
Quercus gambelii	0.07

Table 21. Average percent vegetative cover by species for the pinyon class

Vegetative Species	% Vegetative Cover
Artemisia nova	0.13
Artemisia spp.	0.48
Artemisia tridentata	2.40
Ceratoides lanata	0.91
Cercocarpus ledifolius	2.94
Chrysothamnus spp.	0.29
Ephedra spp.	0.03
Family Compositae Forb spp.	0.43
Family Rosacea Shrub spp.	0.79
Grasses	5.11
Juniperus osteosperma	7.45
Pinus edulis	38.86
Pinus ponderosa	3.15
Quercus gambelii	0.66

Table 22. Average percent vegetative cover by species for the pinyon-juniper class

Vegetative Species	% Vegetative Cover
Artemisia spp.	0.99
Artemisia tridentata	3.88
Betula spp.	0.06
Ceratoides lanata	0.26
Cercocarpus ledifolius	0.14
Chrysothamnus spp.	0.14
Family Rosacea Shrub spp.	0.88
Grasses	2.49
Juniperus osteosperma	16.72
Pinus edulis	21.72
Pinus monophylla	0.03
Pinus ponderosa	0.17
Populus angustifolia	0.03
Pseudotsuga menziesii	0.01
Salix spp.	0.02
Symphoricarpos orbiculatus	0.11

Table 23. Average percent vegetative cover by species for the mountain mahogany class

Vegetative Species	% Vegetative Cover
Artemisia tridentata	1.94
Cercocarpus ledifolius	55.20
Family Rosacea Shrub spp.	8.16
Grasses	4.29
Pseudotsuga menziesii	1.02
Quercus gambelii	1.94

Table 24. Average percent vegetative cover by species for the aspen class

Vegetative Species	% Vegetative Cover
Abies concolor	0.51
Abies lasiocarpa	0.65
Acer grandidentatum	0.17
Amelanchier utahensis	1.25
Artemisia tridentata	0.02
Bromus spp.	2.02
Carex spp.	0.70
Elymus cinereus	0.89
Family Compositae Forb spp.	0.23
Festuca thurberi	0.47
Grasses	6.15
Juniperus osteosperma	0.00
Juniperus scopulorum	0.02
Lupinus spp.	0.91
Picea engelmannii	0.07
Picea pungens	0.03
Pinus flexilis	0.00
Populus tremuloides	60.65
Pseudotsuga menziesii	0.71
Quercus gambelii	1.36
Salix spp.	1.54
Symphoricarpos oreophilus	2.71

Table 25. Average percent vegetative cover by species for the oak class

Vegetative Species	% Vegetative Cover
Abies concolor	0.31
Abies lasiocarpa	0.44
Acer glabrum	0.21
Acer grandidentatum	11.05
Artemisia tridentata	0.38
Ceanothus spp.	1.35
Family Rosacea Shrub spp.	0.45
Grasses	4.50
Juniperus osteosperma	0.69
Juniperus scopulorum	0.09
Picea engelmannii	0.08
Pinus edulis	0.09
Populus angustifolia	2.33
Populus tremuloides	5.72
Prunus virginiana	0.24
Pseudotsuga menziesii	0.48
Quercus gambelii	50.52
Shepherdia canadensis	0.16
Symphoricarpos oreophilus	0.20
Wyethia amplexicaulis	0.45

Table 26. Average percent vegetative cover by species for the maple class

Vegetative Species	% Vegetative Cover
Abies lasiocarpa	0.42
Acer glabrum	1.88
Acer grandidentatum	16.58
Artemisia tridentata	6.18
Cercocarpus ledifolius	1.53
Cercocarpus montanus	1.90
Grasses	14.97
Juniperus osteosperma	0.31
Juniperus scopulorum	0.27
Pinus contorta	1.24
Populus angustifolia	5.54
Populus tremuloides	18.09
Pseudotsuga menziesii	1.86
Purshia tridentata	2.21
Quercus gambelii	3.32
Symphoricarpos oreophilus	6.13
Symphoricarpos vaccinioides	1.18

Table 27. Average percent vegetative cover by species for the mountain shrub class

Vegetative Species	% Vegetative Cover
Acer spp.	12.12
Artemisia tridentata	4.76
Betula spp.	3.09
Cercocarpus montanus	0.19
Family Rosacea Shrub spp.	9.95
Grasses	10.39
Juniperus spp.	1.64
Pinus edulis	1.64
Populus angustifolia	2.67
Populus tremuloides	1.06
Prunus virginiana	6.82
Quercus gambelii	5.44
Salix spp.	0.52
Symphoricarpos orbiculatus	6.82

Table 28. Average percent vegetative cover by species for the sagebrush class

Vegetative Species	% Vegetative Cover
Artemisia spp.	0.23
Artemisia nova	3.27
Artemisia tridentata	31.73
Atriplex confertifolia	0.94
Chrysothamnus spp.	3.70
Ephedra spp.	0.04
Grasses	12.60
Halogeten glomeratus	0.09
Juniperus osteosperma	1.99
Juniperus spp.	0.02
Pinus edulis	0.96
Purshia tridentata	0.10
Sarcobatus vermiculatus	1.09
Tetradymia canescens	0.03

Table 29. Average percent vegetative cover by species for the sagebrush/perennial grass class

Vegetative Species	% Vegetative Cover
Abies concolor	0.26
Artemisia campestris	0.53
Artemisia nova	0.11
Artemisia tridentata	18.59
Bromus spp.	0.11
Cercocarpus ledifolius	0.44
Cercocarpus montanus	0.39
Elymus cinereus	1.72
Grasses	21.51
Pinus contorta	0.63
Pinus ponderosa	0.09
Populus tremuloides	0.18
Potentilla spp.	0.09
Pseudotsuga menziesii	0.09
Purshia tridentata	0.26
Rosa woodsii	1.51
Symphoricarpos oreophilus	0.60
Taraxacum officinale	0.04
Wyethia amplexicaulis	0.23

Table 30. Average percent vegetative cover by species for the grassland class

Vegetative Species	% Vegetative Cover
Artemisia spp.	3.39
Artemisia nova	0.02
Artemisia tridentata	1.56
Atriplex confertifolia	0.01
Chrysothamnus spp.	0.43
Family Compositae Forb spp.	2.26
Grasses	53.85
Halogeten glomeratus	1.37
Helianthus annuus	0.56
Juniperus osteosperma	0.03
Salsola iberica	0.80
Sarcobatus vermiculatus	0.99

Table 31. Average percent vegetative cover by species for the alpine class

Vegetative Species	% Vegetative Cover
Abies concolor	3.38
Carex spp.	48.41
Family Compositae Forb spp.	16.14
Grasses	6.76
Pseudotsuga menziesii	3.38

Table 32. Average percent vegetative cover by species for the dry meadow class

Vegetative Species	% Vegetative Cover
Abies concolor	2.66
Achillea spp.	0.64
Artemisia campestris	0.38
Artemisia nova	1.17
Artemisia tridentata	1.30
Carex geophila	0.01
Carex spp.	8.14
Chrysopis villosa	0.03
Elymus cinereus	1.11
Family Compositae Forb spp.	6.91
Family Rosacea Shrub spp.	0.26
Grasses	41.24
Pinus contorta	5.46
Pinus ponderosa	0.44
Potentilla spp.	0.46
Pseudotsuga menziesii	2.66
Salix spp.	0.60
Wyethia amplexicaulis	8.59

Table 33. Average percent vegetative cover by species for the wet meadow class

Vegetative Species	% Vegetative Cover
Artemisia tridentata	0.88
Carex spp.	56.54
Family Compositae Forb spp.	18.85
Grasses	8.33
Purshia tridentata	0.38
Salix spp.	3.13

Table 34. Average percent vegetative cover by species for the spruce-fir/mountain shrub class

Vegetative Species	% Vegetative Cover
Abies concolor	13.48
Abies lasiocarpa	2.23
Carex spp.	1.61
Family Compositae Forb spp.	0.54
Family Rosacea Shrub spp.	8.64
Grasses	1.52
Physocarpus spp.	0.45
Picea spp.	2.23
Pinus contorta	30.23
Populus tremuloides	1.52
Pseudotsuga menziesii	4.85
Salix spp.	0.61

Table 35. Average percent vegetative cover by species for the mountain fir/mountain shrub class

Vegetative Species	% Vegetative Cover
Abies concolor	19.58
Abies lasiocarpa	0.49
Acer grandidentatum	2.27
Alnus spp.	1.18
Amelanchier utahensis	1.33
Artemisia tridentata	1.46
Family Rosacea Shrub spp.	19.00
Grasses	1.21
Juniperus scopulorum	0.05
Physocarpus spp.	5.92
Pinus contorta	0.27
Pinus ponderosa	6.00
Populus tremuloides	9.45
Pseudotsuga menziesii	10.11
Quercus gambelii	1.06
Symphoricarpos oreophilus	0.25

Table 36. Average percent vegetative cover by species for the aspen/conifer class

Vegetative Species	% Vegetative Cover
Abies concolor	15.51
Abies lasiocarpa	9.54
Picea engelmannii	0.09
Picea spp.	0.74
Pinus flexilis	6.20
Pinus ponderosa	4.79
Populus tremuloides	39.50
Pseudotsuga menziesii	0.05
Symphoricarpos oreophilus	2.13

Table 37. Average percent vegetative cover by species for the mountain riparian class

Vegetative Species	% Vegetative Cover
Abies concolor	2.38
Acer grandidentatum	0.60
Acer spp.	6.46
Artemisia tridentata	1.44
Betula spp.	3.36
Carex spp.	26.38
Family Compositae Forb spp.	8.14
Grasses	12.76
Populus angustifolia	6.36
Quercus gambelii	5.70
Salix spp.	10.32

Table 38. Average percent vegetative cover by species for the lowland riparian class

Vegetative Species	% Vegetative Cover
Acer grandidentatum	11.20
Grasses	41.52
Populus angustifolia	8.82
Tamarix pentandra	23.04

Table 39. Average percent vegetative cover by species for the salt desert scrub class

Vegetative Species	% Vegetative Cover
Artemisia spp.	1.82
Artemisia nova	0.46
Artemisia tridentata	0.53
Atriplex canescens	0.19
Atriplex confertifolia	9.84
Ceratoides lanata	0.97
Chrysothamnus spp.	2.13
Ephedra spp.	0.96
Family Compositae Forb spp.	0.04
Grasses	3.42
Gutierrezia sarothrae	0.05
Halogeten glomeratus	3.94
Helianthus annuus	0.02
Juniperus osteosperma	0.02
Juniperus spp.	0.01
Kochia vestita	0.86
Pinus edulis	0.01
Salsola iberica	0.05
Sarcobatus vermiculatus	2.39
Tetradymia canescens	1.63

Table 40. Average percent vegetative cover by species for the desert grassland class

Vegetative Species	% Vegetative Cover
Artemisia spp.	2.70
Artemisia nova	0.89
Artemisia tridentata	0.18
Ceratoides lanata	1.47
Chrysothamnus spp.	4.91
Grasses	29.80
Gutierrezia sarothrae	0.53

Table 41. Average percent vegetative cover by species for the greasewood class

Vegetative Species	% Vegetative Cover
Atriplex confertifolia	4.29
Family Compositae Forb spp.	0.59
Grasses	11.69
Halogeten glomeratus	2.09
Salix spp.	2.46
Salsola iberica	0.06
Sarcobatus vermiculatus	28.45

Table 42. Average percent vegetative cover by species for the pickleweed barrens class

Vegetative Species	% Vegetative Cover
Allenrolfea occidentali	13.44
Tamarix pentandra	1.78