

Greenhouse Gas Accounting of Rural Agrarian Regions: The Case of San Luis Valley

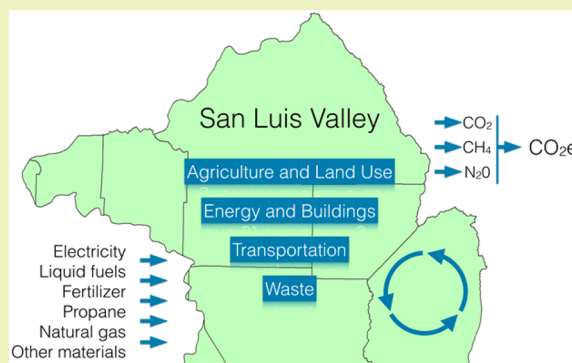
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ABSTRACT: Rural regions, with a dominant agricultural economic base, have a vastly different greenhouse gas (GHG) emissions profile than urban regions and hence require a unique accounting method. This paper presents a GHG inventorying methodology tailored specifically for rural agricultural regions. The methodology was applied to San Luis Valley (SLV) in south central Colorado with an intent to establish a clear emissions baseline and to analyze, in fine detail, the regions emission profile. The results show that SLV has an annual per capita emission of 30.5 MT CO₂e while the average for the United States is about 21 MT CO₂e. The higher per capita emissions can be attributed to the production of agricultural goods and services that are primarily exported rather than consumed in the region. Since per capita emissions might not paint an accurate picture for export based economies, we recalibrated the data on per dollar GDP basis.

We find that, on this basis, SLV emissions are almost twice that of the national average indicating that, with all things being equal, agricultural activities contribute disproportionately more towards GHG emissions. In addition, through a detailed analysis we show that SLV, with its significant solar resource base, has the potential to offset much or all of their carbon emissions. The findings from this paper offer useful insights for local stakeholders to develop plans and implement policies toward GHG mitigation.

KEYWORDS: Sustainability, GHG inventory, Emissions, Local governments, Agriculture



INTRODUCTION

Awareness in the global scientific community and in the public eye around greenhouse gas (GHG) inventories and their role in developing policy related to climate mitigation has greatly increased in the past decade.^{1,2} In addition, communities and local governments can play an important role in reducing GHG emissions as they have broad influence over activities that result in significant direct and indirect emissions within their boundary and jurisdiction. GHG inventories create a baseline that can be used to identify sectors, sources, and activities responsible for carbon emissions, assess relative contributions of emission sources, establish local climate action plans and policies, quantify benefits of activities that reduce emissions, and foster informed communication with stakeholders.³ Previous efforts to baseline communities, such as those led by the Intergovernmental Panel on Climate Change (IPCC), had primarily focused at the national level. However, now with the leadership of organizations such as ICLEI and WRI there has been a push to look more specifically at cities and urban areas because of their dense population and high consumption.^{4–6} This paper is an attempt to conduct a GHG baseline analysis on a local level but focused more on rural agrarian regions.

Typical city-scale GHG inventories account for residential, commercial and industrial energy use (primarily in-boundary buildings/facilities), and transportation. In addition, hybrid

methods account for cross-boundary contributions associated with urban material consumption (e.g., cement, fuel, food, etc.) and transportation (surface and air). Different accounting approaches, ranging from pure geographic production-based accounting and pure consumption-based accounting to hybrid geographic-plus key infrastructure supply chain accounting have been developed at the city scale.^{4,7–9} In addition to accounting for in-boundary emissions, issues related to trans-boundary emissions and life cycle supply chain emissions have been addressed.⁴ These inventories have been used for future planning in cities addressing water, energy, and material needs of urban communities.

While these studies have been influential for cities and nations in making plans and implementing actions toward reducing carbon emissions, very little work has been done on explicit accounting of GHG emissions for rural regions. According to the IPCC, land use accounts for more than 24% of the world's overall GHG emissions and agricultural production is by far the largest contributor to that sector.¹⁰ The USDA also recently published a report that shows that the agricultural sector will be one of the hardest hit by a changing

Received: June 22, 2016

Revised: August 11, 2016

Table 1. Material Flows, Emission Factors, and Total GHG Emission in the San Luis Valley

	regional material or energy flow (MFA)	data year	MFA data source	GHG emission factor (use phase)	GHG emission factor (upstream)	EF data source	total GHG emitted = MFA × EF (MT CO ₂ e)
Energy and Buildings							
electricity	434016 MWh	2012	Xcel ⁵⁰ REC ⁵¹	0.76 kg CO ₂ e/kWh	0.075 kg CO ₂ e/kWh	Xcel NREL ²⁷	361898
solar credit	198363 MWh	2012	EIA ⁴⁶	−0.83 kg CO ₂ e/kWh	0.04 kg CO ₂ e/kWh (PV) 0.02 kg CO ₂ e/kWh (CSP)	NREL ^{47,48}	−160709
natural gas	1220 MMJ	2012	Xcel ⁵⁰	0.05 kg CO ₂ e/MJ	0.014 kg CO ₂ e/MJ	NREL ²⁷	80006
propane	4.9 million gal	2012	EPA ²⁹	5.63 kg CO ₂ e/gal	2.15 kg CO ₂ e/gal	EPA ²⁹ LCA ^{52,53}	38660
Agriculture and Land Use Sector							
soil GHG emissions from crops	13009 MT synthetic N fertilizer	2010	Agro ³⁴ CSU ³⁵ CDWR ⁵⁴	IPCC tier 1 methodology	4.00 kg CO ₂ e/kg N	IPCC ⁵ Blonk ³⁶	209809
soil GHG emissions from livestock	3662 MT N applied by livestock	2012	NASS ³²	IPCC tier 1 methodology		IPCC ⁵	131966
enteric fermentation	83144 cattle 12711 sheep 221 hogs	2012	NASS ³²	50 kg CH ₄ /cattle 5 kg CH ₄ /sheep 1 kg CH ₄ /hog		IPCC ⁵	139529
manure management	83144 cattle 12711 sheep 221 hogs	2012	NASS ³²	2 kg CH ₄ /cattle 5 kg CH ₄ /sheep 1 kg CH ₄ /hog		IPCC ⁵	5666
agricultural machinery	6.7 million gal	2012	NASS ³²	9.18 kg CO ₂ e/gal diesel	2.3 kg CO ₂ e/gal diesel	REET ³⁸	77514
Transportation Sector							
personal vehicles	17.7 million gal gasoline 3.1 million gal diesel	2012	CDOT ³⁹	8.71 kg CO ₂ e/gal gasoline	2.3 kg CO ₂ e/gal gasoline or diesel	REET ³⁸	230425
large trucks	6.9 million gal diesel	2012		9.18 kg CO ₂ e/gal diesel			78886
Waste Sector							
landfills	63350 ton	2012	CDHE ⁴²	0.89 MT CO ₂ e/ton MSW		EPA ^{43,44}	56173
waste water	720 MT BOD rural septic 737 MT BOD centralized	2012	Census ⁴⁵	0.24 MT CH ₄ /MT BOD		IPCC ⁵	11567

climate.¹¹ Moreover, rural agricultural regions, although small in population have a large influence on global GHG emissions. This is a key reason why engaging with an agricultural community on GHG inventories is so important.

The sphere of influence of local government is typically limited to its geographic jurisdiction. Therefore, urban policy makers have limited ability to direct meaningful improvements to their emission profile in categories such as food, since they are consumers of food and not the producers. Therefore, engaging rural food producing regions through local carbon accounting metrics is key for fostering policy change. Since the emissions profile of agricultural regions is widely different than urban regions, there is a great need to develop context specific accounting approaches for rural regions that capture activities such as agricultural energy demand, livestock raising, and soil GHG fluxes. Further, in view of the wide variability in agricultural practices (e.g., tilling practices, crop rotations, manure management, groundwater vs surface water use), soil and climatic conditions, these inventories need to be based on local context specific, bottom-up emission factors derived from regional data.¹⁷ With a robust and descriptive region specific baseline, local decision makers can begin the process of developing plans and implementing actions toward GHG emissions reductions.

This rural GHG inventory analysis looked at an agricultural region in Southern Colorado with the names: Upper Rio Grande Basin (RGB), San Luis Basin (SLB), and in this paper referred to as the San Luis Valley (SLV). The Environmental Protection Agency took an interest in the SLV as an ideal case study for rural sustainability metric development because of its isolated geography and well-defined agricultural economy.^{12–16} The SLV is a 100-mile long and 60-mile wide upland agricultural valley surrounded by the 14 000-ft peaks of the Sangre de Christos to the East and the expansive San Juan wilderness area to the West. The valley floor sits at 7500 ft and is an ideal location for growing potatoes (it is the second largest potato producer in the United States next to Idaho) and barley (the majority of Coors beer barley is grown here). The SLV was also the first place that quinoa was grown in North America due to its Andean-like climate.

METHODOLOGY

This study presents a novel method for rural agricultural region GHG accounting and data reporting. This methodology uses the IPCC 2006 release of GHG inventory for nations as well as other GHG inventories in the field for structure and inclusions.^{4,5,18} The GHGs considered are CO₂, CH₄, and N₂O and are presented as carbon dioxide equivalents (CO₂e) based on the IPCC 2013 approach.¹⁰ The sectors of interest,

consistent with IPCC, are Energy and Buildings, Transportation, Agriculture, Land Use, and Waste. Since manufacturing makes up only about 1% of the economy in the region,¹⁹ the Industrial Processes and Product Use sector was excluded. In addition to in-boundary emissions associated with the sectors described above we also looked at upstream life cycle emissions when relevant. Further, our goal was to create an inventory that could be reproduced not just by the scientific community, but by our local community partners in the region. We spent 6 months performing a stakeholder analysis based on principles found in Community Based Participatory Research (CBPR) that led to the formation of a Community Advisory Board (CAB).²⁰ The CAB, which was composed of stakeholders from the community (farmers and ranchers), local government, conservation groups, federal lands and others from across the region provided insights into the unique nature of the area as well as aided in data collection and critical review. Moreover, because of the explicit goal of transferring this methodology to the community, we attempted whenever possible to use publicly available data, such as census data, National Agricultural Statistics (NASS), Colorado Department of Transportation (CDOT) and others, that rely as little as possible on complex computer models. The information below shows how data was collected and emission factors were selected for each of the sectors. Each sector's material flows, emission factors, and sources are summarized in Table 1.

Energy and Buildings Sector. Electricity. Annual electricity consumption in the SLV was obtained from the two utility companies—Xcel energy (Xcel) and San Luis Valley Rural Electric Cooperative (SLV-REC)—who supply electricity to the region. Total consumption was 222 023 MWh for Xcel and 211 993 MWh for SLV-REC in 2012. Further, each company provided the residential and commercial breakdown of the electricity consumption, and the amount of electricity used for agricultural irrigation. We estimated the life cycle GHG emission factors for Xcel and SLV-REC that included direct emissions from power plants as well as upstream emissions from the mining and handling of the raw resource, namely coal and natural gas. The direct emission factor for Tri State Generation and Transmission (Tri State), from whom SLV-REC purchases 99% of its electricity,²¹ was based on emission factors of individual power plants that provide electricity to Tri State.²² These power plant specific emission factors were obtained from the EPA 2012 eGRID data set.²³ The electricity grid mix from the San Luis Valley is 60% coal, 25% natural gas, and 15% renewable. The direct emissions that can be attributed to SLV-REC grid mix was determined to be 0.76 kgCO₂e/kWh while the direct emission factor for Xcel energy was determined to be 0.75 kg CO₂e/kWh.²⁴ Emissions upstream from the power plant due to mining and transport of coal and natural gas was estimated as 25% and 6% of the total emissions, respectively.^{25–28} A combined average emission factor for the region was calculated as 0.83 kgCO₂e/KWh.

Natural Gas and Propane. Community wide natural gas usage for residential and commercial purposes was directly obtained from Xcel Energy, which is the sole natural gas supplier to the SLV. The annual residential and commercial natural gas consumption was 661 and 559 million MJ, respectively. Annual propane consumption was estimated for the region based on the number and square footage of homes in the region and the number of homes using propane for heating.²⁹ In addition, this value was verified through contact with the major propane providers in the region. The life cycle

emission factor for the use of natural gas and propane in a furnace, which includes both direct and upstream emissions, was 9.35 and 7.78 kg CO₂e/gallon, respectively.^{27,30,31} In 2012, the SLV emissions from natural gas and propane use were 118666 MT CO₂e.

Agriculture and Land Use Sector. Livestock Emissions.

Methane, a strong GHG, is produced as a byproduct of enteric fermentation (digestion) in livestock and the amount of methane that is released depends on the type of digestive tract, age, and weight of the animal as well as the quality and quantity of the feed consumed.⁵ The San Luis Valley has significant livestock operations consisting mainly of cattle ranching with relatively small sheep and hog operations. For 2012, the National Agriculture Statistic Service (NASS) reports head of cattle in the region as 83 000, head of sheep as 12 700, and head of hogs as 220.³² In Chapter 11 of the 2006 GHG inventory procedures, the IPCC suggests a regionalized tier 2 approach for calculating the emission factor for cattle and a generalized tier 1 approach for sheep, goats, and swine.⁵ To reflect the variation in emission rates among cattle, instead of using the North American average of 53 kg CH₄/head as reported by IPCC, we developed a region specific emission factor by first categorizing the herd into IPCC suggested subgroups. Then using local data for climate, feeding situation, age, size, and cattle subgroup and the IPCC model, we were able to arrive at a herd specific emission factor of 50 kg CH₄/head.³³ Following IPCC tier 1 approach, the global average emission factors of 5 kg CH₄/head and 1 kgCH₄/head for sheep and hogs respectively were used. For manure management we used the IPCC tier 1 approach for each of the three animal types.⁵ Cattle manure management practices in the region produce 2 kg CH₄/head, sheep management produces 0.2 kg CH₄/head, and hogs produce 13 kg CH₄/head according to the IPCC tier 1 approach. In 2012, livestock in the San Luis valley was responsible for 145 thousand MT CO₂e.

Soil Nitrous Oxide Emissions. The use of fertilizers and managed soils is a major contributor to GHG emissions globally. This section describes the estimation of N₂O emissions from managed soil due to agricultural inputs of nitrogen (synthetic N fertilizers; N deposited by grazing animals, and decomposing crop residue). Since actual data was not available, average quantities of nitrogen applied per acre by crop type was estimated through in-depth interviews with two key agriculture consultants who work with local farmers in the Valley.^{34,35} Based on their inputs, the following average rate of nitrogen application was used in this study: 180 lbs/acre for small grains after potatoes, 80 lbs/acre for small grains after alfalfa, 220 lbs/acre for continuous small grains, 11 lbs/acre for alfalfa, and 185 lbs/acre for potatoes after small grains. Local data on N inputs through grazing animals was based on animal head counts and their feeding situation.⁵ We followed the IPCC guidelines to estimate GHG emissions from managed soils and accounted for both direct N₂O emissions from nitrification and denitrification of N inputs, as well as indirect N₂O emissions due to N volatilization, leaching, and runoff. The upstream emissions associated with the production of nitrogen fertilizer was obtained from Blonk Consultants and was found to be 4.0 kg CO₂e/kg N applied based on the North America average fertilizer mix.³⁶ In 2012 an estimated total of 28.9 million lbs of nitrogen was applied, which in turn was responsible 140 thousand MT CO₂e emissions. The total soil GHG emissions due to animal grazing and agriculture was 342 thousand MT CO₂e.

Agricultural Machinery. The on farm fuel use from tractors, farm trucks, and processing equipment was estimated using data reported by National Agricultural Statistics Service (NASS) on dollars spent on agricultural fuels in the region³² with all fuel consumption assumed to be diesel consumed on the farm. The cost per gallon for diesel was based on the reported price for western states. All fuel was road tax-exempt red diesel, so the Colorado road tax was subtracted from the regular fuel price.³⁷ The life cycle emission factor for diesel fuel was obtained from Argonne National Lab's GREET model³⁸ with the pump-to-wheels (PTW) emission factor (direct) for diesel at 9.18 kgCO₂e/gal. The wells-to-pump (WTP) emissions (upstream) were 2.3 kgCO₂e for both gasoline and diesel. In 2012 the valley consumed 6.7 million gal of farm diesel, which accounts for an annual emission of 77 514 MTCO₂e.

Transportation Sector. On-Road Cars and Trucks. Direct tailpipe emissions from on-road transportation was calculated by multiplying vehicle miles traveled (VMT) in the region by the emission factors for gasoline and diesel fuel. The total VMT in the region was collected using Colorado Department of Transportation (CDOT) static highway reports³⁹ which provided annual VMT data by county divided up into two classes, lightweight personal vehicles (DOT classes 1–3) and larger commercial vehicles (DOT classes 4–13). However, this publicly available data captures only major roadways in the region, and does not include traffic through the minor county roads, which can be significant for rural regions. In order to include the smaller roads we obtained region specific data from CDOT based on their traffic model to estimate “off grid” VMTs in the six county region. All travel within the regions boundary was allocated to the valley since there was no valid way to disassociate traffic that was just passing through, and based on the mountainous and isolated geography of the region it is safe to assume that pass through trips are minimal. The total lightweight personal vehicle traffic in the region in 2012 was estimated as 1.4 million VMT per day and the normalized personal VMT in the region yielded 30 VMT/person day which is very close to the national average of ~28 VMT/person day.⁴⁰ The total commercial large truck (classes 4–13) traffic for the region in 2012 was around 140 000 VMT/day. In order to estimate the weighted average fuel economy for the personal vehicle fleet in the region, vehicle registration data was obtained from the San Luis Valley Development Resources Group (SLVDRG).¹⁹ The average fuel economy for lightweight personal vehicles (classes 1–3) was estimated as 25.6 miles/gal. For commercial large trucks (class 4–13) the national average fuel economy of 7.3 miles/gal was used in this study.⁴¹ The GREET model was again used to derive the life cycle emission factors for gasoline and diesel. The pump-to-wheels (PTW) emission factor (direct) for gasoline was 8.71 kg CO₂e/gal, and for diesel, it was 9.18 kg CO₂e/gal. The wells-to-pump (WTP) emissions (upstream) were 2.3 kg CO₂e for both gasoline and diesel.³⁸ The on-road emissions from lightweight personal vehicles in 2012 were estimated as 230 000 MT CO₂e, and the emissions from commercial large trucks were 79 000 MT CO₂e.

Waste Sector. Landfill Emissions. There are two major solid waste facilities in the San Luis Valley: SLV Regional Landfill and Saguache County Landfill and Recycling Center. Data of municipal solid waste (MSW) generated in the region was obtained from the Colorado Department of Public Health and Environment (CDPHE) and was reported as 63 000 tons

(1.4 tons per capita) in 2012.⁴² Landfill emissions were estimated using EPA's Waste Reduction model (WARM).⁴³ SLV regional, the larger of the two sites, provided us with waste composition broken into three categories: household (87%), construction (11%), and other (2%). The WARM model required further composition detail for which we used US average data from the EPA.⁴⁴ The waste transportation portion of the analysis was omitted from the WARM model since those emissions would have already been accounted for in the **Transportation Sector**. The results from the WARM model shows landfill emissions of 56 000 MT CO₂e that can be attributed to solid waste generated in 2012.

Waste Water Treatment. The quantity of emissions from wastewater depends on the treatment type and in the case of the SLV that was either rural septic or centralized aerobic treatment. The data needed was the number of people living in the region and the percent of those people living in cities and in rural areas. It was assumed that all city population used centralized aerobic treatment and all rural population used anaerobic septic treatment. This is a critical distinction because anaerobic treatment produces higher CH₄ emissions according to IPCC. The 2012 census data showed that, of the 47 thousand people living in the Valley, 50% are in cities and 50% reside in rural areas.⁴⁵ Using the above data an emission factor of 0.24 MT CH₄/MT BOD was developed for the valley. Biological oxygen demand (BOD) in the wastewater was estimated using the average BOD concentration per person for North America (85 g/person day).⁵ The total treatment demand in the SLV was estimated at 1457 MT BOD, and the total associated annual emission was 11 567 MT CO₂e.⁵

Solar Credit. Data on utility scale solar energy production was also obtained for this study and wholly allocated in the form of carbon credits to the region. The region hosts four utility scale solar facilities with a combined total of 87 MW capacity which produced 198 363 MWh in 2012.⁴⁶ The upstream emission factors were 0.04 kg CO₂e/kWh for photovoltaic (PV) and 0.02 kg CO₂e/kWh for concentrated solar power (CSP).^{47–49} A carbon credit, based on avoided emissions, was estimated and allocated to the region based on the total kWh of utility scale solar energy produced in the valley.

RESULTS AND DISCUSSION

Total GHG Emissions of the Valley. Table 1 in the methods section provides a consolidated summary of all material and energy flows, emission factors, and data sources used in this study. For the year 2012, we estimate that about 1.27 million metric tons of carbon dioxide equivalents (MMT CO₂e) emissions can be attributed to San Luis Valley (SLV), which includes a 0.16 million metric ton carbon credit for the utility scale solar in the region. The SLV has a per capita emission of roughly 30.4 MT CO₂e while the average per capita emissions for the United States is about 21 MT CO₂e.⁵⁵ The higher per capita emissions of the Valley reflect the fact that a significant amount of economic activity in the region are associated with the production of agricultural products that are exported rather than consumed. This is typical of hinterland regions, which export agricultural products and mineral resources to urban centers. Electricity is the highest contributor to total emissions at 0.362 MMT CO₂e, followed by passenger vehicles at 0.230 MMT CO₂e, and soil GHG emissions (crops) at 0.210 MMT CO₂e (Figure 1). Soil GHG emissions, typically not accounted in city scale GHG inventories, from agricultural

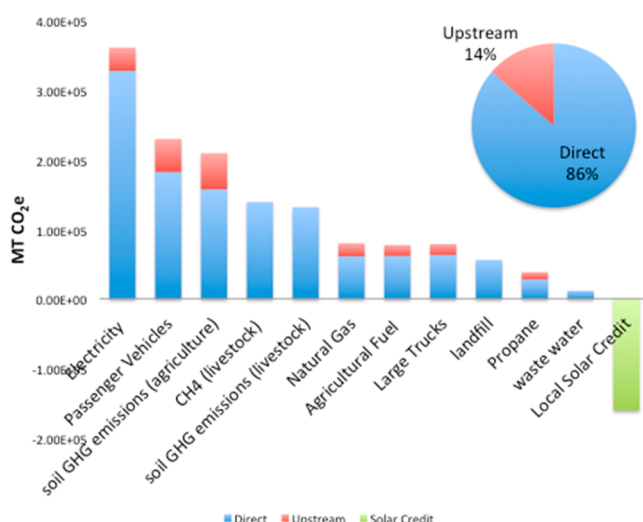


Figure 1. Total GHG inventory of the San Luis Valley in 2012.

activities and livestock raising contributes ~20% of total GHG emissions. Similarly, methane emissions from livestock contribute ~10% to the total GHG emissions of the SLV.

Upstream Emissions. Direct emissions within the valley account for about 86% of total emissions, and the remaining 14% are upstream emissions that occur outside of the geographic boundary (Figure 1). However, note that with regards to electricity the GHG emissions from power plants are categorized under direct emissions but the power plants that service the region are located outside of the geographical boundaries. The inclusion of life cycle upstream emissions coupled with direct use emissions can provide a more comprehensive emission profile for agricultural regions. Upstream emissions from fertilizer, which accounts for 3.6% of the San Luis Valley's total emissions inventory, is the largest of any of the upstream emissions. Not including upstream emissions may cause policy makers to focus on other sectors, when in fact how soils are managed and synthetic fertilizer usage could be a more impactful place to focus. If an agricultural inventory does not include upstream emissions from fertilizer they will miss a crucial piece of the picture.

Carbon Credit. The carbon credit was based on a robust accounting of electricity sources including analyzing the utility scale solar energy and attributing carbon credits based on avoided emissions. This exercise provides clarity on the current and potential future ability of the region to offset its emissions with renewables. The current utility scale solar capacity in the region (87 MW) produced 198 363 MWh in 2012 which is 44% of the regions electricity consumption and is equal to 0.16 million metric ton of avoided CO₂e emissions (see green bar in Figure 1). The current credit in this study reduced the overall GHG emissions from the region by ~10%. With this type of data, policy makers can begin assessing future scenarios based on potential emissions reductions targets. The Bureau of Land Management (BLM) in the San Luis Valley is currently proposing 4 Solar Energy Zones (SEZ) in the region. This is part of a larger federal initiative called the Solar Energy Program, which proposes that the BLM land should relax the barriers to private solar development on public land.⁵⁶ We find that even a 50% build out of the proposed BLM solar energy plan (700 MW) would see a 1.50 MMT CO₂e credit, which is more than the total emissions from the region in 2012.

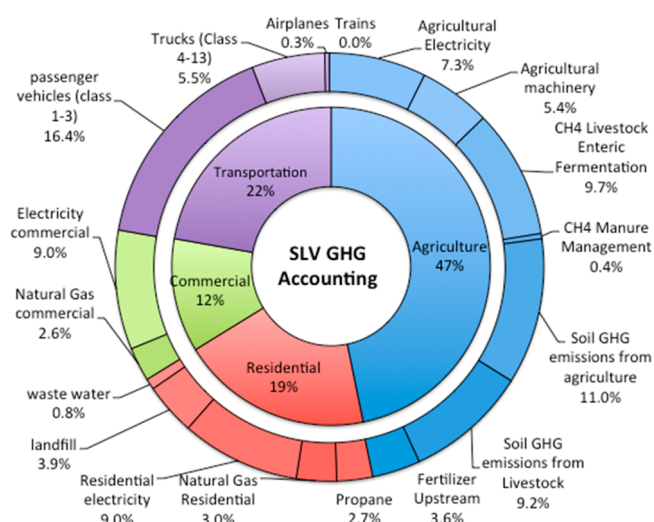


Figure 2. Breakdown of GHG emission contributions of the four major groups averaged between 2006 and 2012.

Emissions by Category. While Figure 1 shows the breakdown of the GHG emissions by IPCC sectors, Figure 2 presents the same results, organized by four major groups: agriculture, residential, commercial, and transportation. The associated calculation involved dividing electricity between agriculture, residential and commercial. In addition, agriculture and livestock soil GHG emissions, methane emissions from livestock and manure management, and agricultural machinery emissions were allocated to the agriculture category while passenger vehicles and large truck transport emissions were assigned to transportation category. The residential group included energy for buildings, wastewater treatment, and landfill emissions. We find that agriculture is the largest contributor of GHG emissions in the valley (~47%) followed by transportation and residential at ~20% each and commercial ~12%. We also find that ~43% of the agricultural footprint is associated with soil GHG emissions while electricity for irrigation contributes ~15% of agricultural emissions. Passenger vehicle transport (class 1–3) is responsible for the majority (~74.5%) of transportation emissions while large trucks account for the remaining (~25.5%). Note that the truck transportation includes truck transport for agricultural products. Building energy (electricity, natural gas, and propane) consumption dominates residential sector emissions (~75%).

Benchmarking. We now compare these regional scale results with GHG inventories related to different geographical scales (city, state, and country). By benchmarking the findings to other inventories, we can start to see how this region is unique. The results of the benchmarking exercise are presented in Table 2. Since the four scales examined, regional hinterland (SLV), city (Denver), state (Colorado), and national (USA), have very different population densities and economies, it adds clarity to analyze the results in terms of emissions per GDP in addition to emissions per capita. The SLV and Denver GHG emissions data, shown in Table 2, include upstream emissions while the inventories of Colorado and USA do not. The ranges in the SLV and Denver inventory represent the emissions without and with upstream emissions, respectively. Further, since there are certain methodological differences in each of these studies, we also present just the fossil energy use (use phase) for comparison purposes. The results from Table 2 show that the SLV has the lowest per capita emissions, among

Table 2. Benchmarking of the SLV Inventory with Other GHG Inventories^a

	San Luis Valley	Denver ⁴	Colorado ⁵⁷	USA ⁵⁵
total inventory (MMT CO ₂ e)	1.23–1.43 ^b	11.0–14.6	132	6526
fossil energy use (MMT CO ₂ e)	0.7	10.6	96.5	5072
total inventory (MT CO ₂ e/capita)	26.2–30.4 ^b	18.9–25.3	26.2	20.8
fossil energy use (MT CO ₂ e/capita)	15.5	18.9	19.1	16.2
total inventory (kg CO ₂ e/\$ GDP)	671–783 ^b	209–278	474	404
fossil energy use (kg CO ₂ e/\$ GDP)	367	202	346	314

^aThe results for GDP of the San Luis Valley and Denver County were obtained from IMPLAN working with the Business Resource System of the University of Colorado Boulder⁵⁸ while the data for GDP of Colorado and the US came from the Bureau of Economic Analysis.⁵⁹

^bThe high and low estimates of the total inventory for the SLV and Denver show results with and without upstream emissions.

the four, when considering only fossil energy use (15.5 MT CO₂e/capita). This is due to the fact that SLV has less commercial and industrial activity in comparison to urban areas. For example, in Denver commercial buildings energy use is about 9.7 MT CO₂e/capita while the corresponding number for SLV is 3.2 MT CO₂e/capita. This difference (6.5 MT CO₂e/capita) is somewhat offset, but not completely, by agricultural energy consumption (pumping energy and fuel for machinery) in SLV which was about 3.37 MT CO₂e/capita. On the other hand SLV has the highest per capita emissions when we consider the total GHG emissions (26.2 MT CO₂e/capita). This can be mainly attributed to the significant level of nonenergy related agricultural emissions (such soil N₂O emissions) associated with SLV, which is not present in Denver.

However, per capita comparisons across diverse locales (such as rural region vs urban region) provide very limited insights, since these different locales provide widely varying types of functions (food production vs services). Therefore, looking at emissions per dollar GDP as opposed to emissions per capita would be more meaningful. The SLV has the highest per GDP emissions by far of all the studies at 671–783 kg CO₂e/dollar GDP. When considering only fossil energy use, the SLV has a lower per capita GHG emissions compared to Denver and Colorado by 17% and 18% respectively. However, if we consider GHG emissions per \$ GDP as the metric we see that the SLV's emissions exceed Denver and Colorado by 30% and 6% respectively. Therefore, we conclude that the SLV is much less efficient, on a GHG emission basis, at producing capital than Denver. This is to be expected as the type of economic activities in SLV and Denver are vastly different. For example over 50% of the emissions from SLV are due to exported agricultural products, and cities (like Denver) are predominantly consumption centric and have service oriented economies. Since the urban environment relies on agricultural regions and vice versa this type of analysis can assist state level decision makers to appropriately prioritize policy and resources available for GHG mitigation purposes.

Overall we find that emissions from electricity production dominate the emissions profile of all the locales, at roughly 25% of their GHG emissions^{55,57} This information may lead practitioners to conclude that all these vastly different regions

would benefit from the same types of policies to reduce emissions from electricity. It is true that making electricity generation less dependent on fossil fuels would decrease overall emissions, but how and where that electricity is used is what is within the province of local government. If there is a state mandate to insulate homes or increase efficiency, that may make sense in urban areas where buildings account for ~50% of the emissions,^{4,8} but an entirely different set of policies should be used for SLV. In rural areas, such as SLV, where improvements to agricultural practices (agro ecological practices; low input farming⁶⁰) and land use (cover cropping) will have a much larger impact than trying to reduce energy consumption in the residential or commercial sector. Therefore, region specific inventories with highly disaggregated data as presented in this work is key for local policy makers.

Uncertainty. This study utilizes large amount of data that have an underlying uncertainty associated with them. However, information on uncertainty is rarely available for such data. We note that there exists uncertainty in the raw data (material and energy flows) such as VMTs, fertilizer application rates and liquid fuels consumed as well as in the emission factors associated with both direct emissions like wastewater treatment, landfills, natural gas burning, and upstream emissions like fuel refining. We would like to point out a specific example of uncertainty that emerged during data disaggregation regarding electricity consumption for irrigation. Though all electricity consumption in the region was accurately accounted for, the irrigation component provided by Xcel Energy, was most likely an underestimate due to the restrictions on the type of data they were allowed to provide under privacy laws. Due to this reason the irrigation portion of GHG emissions is likely a conservative estimate. Though we did our best to present a robust accounting, it is important to understand the results of the study within the overall context of possible data uncertainty.

Finally, it would be pertinent to note that GHG accounting can also be based on regional consumption (usually referred to as carbon footprint).^{61–64} But as discussed earlier, the type of accounting (consumption or production based) followed should depend on the usefulness of the inventory to provide data and insights toward mitigation strategies, which in turn is related to the sphere of influence of the relevant local governments. Therefore, for regions that are predominantly consumption oriented (e.g., cities), carbon footprinting might be appropriate since it can help formulate demand side management and consumption related mitigation strategies, while for production centric regions (e.g., SLV), an approach such as the one proposed here will offer the most value.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was funded by United States Environmental Protection Agency's office of Research and Development. This study is being conducted simultaneously with a larger investigation by our team that involves sustainability modeling and assessment in the San Luis Valley. We would like to thank our Community Advisory Board for providing support and insights that made this work possible. The authors would also

like to thank Brian Lewandowski with the Business Resource System at the University of Colorado Boulder for providing IMPLAN data. We would also like to acknowledge useful discussions with Dr. Matthew Heberling and Dr. Matthew Hopton from U.S. Environmental Protection Agency.

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