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Task 2.1

Final Report: Emission Inventory Evaluation and Improvement for the Killeen-Temple-Fort Hood Area

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LIST OF ACRONYMS AND ABBREVIATIONS

AQRP	Air Quality Research Project
BDSNP	Berkeley-Dalhousie Soil NOx Parameterization
BEIS	Biogenic Emission Inventory System
BELD4	Biogenic Emission Landuse Database version 4
CAMS	Continuous Ambient Monitoring Station
CAMx	Comprehensive Air Quality Model with Extensions
CDP	Census Designated Place
CLM	Community Land Model
CMAQ	Community Multi-scale Air Quality
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTAIR	Central Texas Air Information and Research Advisory Committee
CTCOG	Central Texas Council of Governments
DFW	Dallas-Fort Worth
ECS	Equipment Concentration Site
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
EVT	Existing Vegetation Type
GHG	Greenhouse Gas
gN/km^2-hr	Grams of nitrogen per square-kilometer per hour
HAPs	Hazardous Air Pollutants
HGB	Houston-Galveston-Brazoria Area
H.R.	House of Representatives
hr	Hour
KTF	Killeen-Temple-Fort Hood
LAI	Leaf Area Index
lb	Pound
MATES	Military Equipment and Training Site
MDA8	Daily Maximum 8-Hour Average
MEGAN	Model of Emissions of Gases and Aerosol from Nature
MODIS	Moderate Resolution Imaging Spectroradiometer
NAAQS	National Ambient Air Quality Standard
NASS	National Agricultural Statistics Service
NLCD	National Land Cover Database
NO	Nitric Oxide
NOx	Oxides of Nitrogen
Pb	Lead
PFT	Plant Functional Type
PM	Particulate Matter
PM_{10}	Particulate Matter less than Ten Microns
$PM_{2.5}$	Particulate Matter less than 2.5 Microns
ppb	Parts per Billion

ppbC	Parts per Billion by Carbon
ppm	Parts per Million
QAPP	Quality Assurance Project Plan
SCC	Source Classification Code
SIP	State Implementation Plan (for the ozone NAAQS)
SO_2	Sulfur dioxide
TCEQ	Texas Commission on Environmental Quality
TexN	Texas Nonroad Model
Ton	English short ton (2000 pounds)
tpd	Ton per Day
tpy	Ton per Year
TexN	Texas NONROAD Model
TX	Texas
USAEC	United States Army Environmental Command
USAG	United States Army Garrison
USDA	United States Department of Agriculture
VOC	Volatile organic compound
WRF	Weather Research and Forecasting model
YL95	Yienger And Levy, 1995 (Publication)
yr	Year

EXECUTIVE SUMMARY

On behalf of the Central Texas Council of Governments (CTCOG), Ramboll Environ evaluated potential improvements to 2012 Killeen-Temple-Fort Hood (KTF) Area emission inventory estimates determined in the KTF Conceptual Model analysis (Kemball-Cook et al., 2015) to be uncertain or in need of further evaluation. This study reviewed emissions of oxides of nitrogen (NOx) from (1) the Fort Hood Military Base and (2) biogenic sources.

Fort Hood is a large military base with over 45,787 assigned military (not including deployed military) and family members[1]. Fort Hood is located on the border of Bell and Coryell counties in the KTF Area and may have substantial emissions from all source categories of anthropogenic emissions that can affect ozone at KTF Area ozone monitors (Kemball-Cook et al., 2015).

Fort Hood Emissions

We reviewed Texas Commission on Environmental Quality (TCEQ) 2012 emission inventory and modeling files for Fort Hood and determined that on-road vehicles, off-road equipment, and area source emissions within the boundaries of Fort Hood are underestimated. Through the Central Texas Council of Government (CTCOG) and Fort Hood's liaison to the Central Texas Air Information and Research (CTAIR) Advisory Committee, we requested additional emissions information from Fort Hood. Fort Hood provided additional emission inventory files for point sources and additional data for on-base vehicles and military tactical equipment on unpaved roads. Comparison of TCEQ 2012 point source emissions to point sources emissions provided by Fort Hood indicated only very minor differences in volatile organic compound (VOC) emissions; point source NOx emissions were identical. On-road vehicle activity and military tactical equipment emissions provided by Fort Hood are not recommended for incorporation into the TCEQ 2012 emission inventory at this time because (1) the geographical locations of vehicle activity (i.e. on-base or off-base) is unknown and (2) military tactical equipment emissions are small relative to other KTF Area emission sources.

Guidance provided by the TCEQ indicates that the extent of emission inventory improvements that can be developed for Fort Hood is constrained by national security concerns. Based on the information made available by Fort Hood and the TCEQ's guidance, we recommend no emission inventory improvements at this time. However, it is necessary to understand the impact of underestimates on Fort Hood area emissions on CTCOG's ozone modeling. As part of the fiscal year 16-17 photochemical modeling task, we will evaluate the sensitivity of ozone model performance at the Killeen Skylark monitor (CAMS 1047) and Temple Georgia monitor (CAMS 1045) monitors to emissions from the Fort Hood area.

[1] USAG Fort Hood Fact Sheet (3 March 2017), http://killeenchamber.com/assets/uploads/docs/Fact_Sheet_March_2017.pdf

Recommendations

- In accordance with TCEQ guidance and in recognition of national security constraints on the information Fort Hood is able to provide, we do not recommend further development of Fort Hood emission inventories at this time.
- Evaluate the effect of Fort Hood emissions on CTCOG's ozone modeling through a sensitivity analysis under the FY16-17 Photochemical Modeling Task.

Biogenic NOx Emissions

Biogenic NOx emissions account for nearly 25% of KTF Area-wide NOx emissions in the current TCEQ 2012 emission inventory. Ozone formation in the KTF Area is limited by the amount of available NOx (Kemball-Cook et al., 2015) so that an accurate biogenic NOx emission inventory is important for KTF Area ozone modeling. During the last biennium, TCEQ used two different models to estimate biogenic NOx emissions: the Model of Emissions of Gases and Aerosols from Nature (MEGAN; Guenther et al., 2012) and Biogenic Emission Inventory System (BEIS; Bash et al., 2015).

2012 KTF Area total biogenic NOx emissions estimated in MEGAN were 43% lower than biogenic NOx emissions estimated in BEIS. We reviewed the MEGAN model computer code and found a coding error that incorrectly decreased biogenic NOx emissions. A screening analysis of MEGAN emissions with the corrected code substantially increased KTF Area total biogenic NOx emissions estimates from MEGAN so that they were within 12% of the BEIS estimates. We notified the MEGAN model developers of the coding error and correction and were informed that the correction will be implemented in the new version of MEGAN (version 3) that is under development. Future KTF Area biogenic NOx emissions estimates prepared using MEGAN should be developed with MEGAN (version 3) so that they include the code correction.

There is no NOx monitoring at KTF Area CAMS, so a direct comparison of modeled NOx using BEIS and MEGAN inventories was not possible. Although satellite NO_2 column data have been used to infer biogenic NOx emission inventories (e.g. Vinken et al., 2014), uncertainties in satellite retrievals are very likely to complicate interpretation of differences between modeled NO_2 columns using BEIS and MEGAN biogenic inventories. Therefore, we reviewed model inputs used by MEGAN and BEIS to determine whether one model was likely to provide more accurate emission estimates for the KTF Area than the other. We analyzed vegetation distribution inputs for BEIS and MEGAN. KTF Area vegetation distribution inputs for BEIS showed a much higher prevalence of trees/shrubs while MEGAN showed a much higher prevalence of grasslands. BEIS NOx emissions are substantially smaller than MEGAN (code corrected) NOx emissions in western KTF Area because biogenic NOx emissions from trees/shrubs are smaller than biogenic emissions from grasslands. MEGAN vegetation distribution inputs for grasslands, shrubs, and trees are based on land cover data developed in Texas Air Quality Research Project (AQRP) 14-016[2] (Yu et al., 2015) which included Texas-specific analyses and quality assurance. AQRP 14-016 landcover data are based on LandFire

[2] http://aqrp.ceer.utexas.edu/viewprojectsFY14-15.cfm?Prop_Num=14-016

vegetation data which has high spatial resolution and allows for more accurate estimates of vegetation distributions than are present in the Biogenic Emission Landuse Database 4 (BELD4) implemented in BEIS. KTF Area MEGAN vegetation distribution inputs developed in AQRP 14-016 are more accurate based on the use of LandFire EVT data and Texas-specific analyses and quality assurance than BEIS BELD4 vegetation distribution inputs.

There was good agreement between MEGAN and BEIS crop coverage estimates. BEIS includes basal[3] soil NO emission factors for over 40 different crop types while MEGAN includes only two crop types. Higher crop NOx emissions in BEIS are the result of higher NO basal emission factors in BEIS, on average, over the KTF Area.

<u>Recommendations</u>

- Any future biogenic NOx emission estimates developed in MEGAN should use the code correction identified in Section 3.3. Based on communications with MEGAN developers, this code correction will be implemented in the next version of MEGAN (version 3).
- Future effort to add more detailed crop data in MEGAN and implementation of crop specific soil NO basal emission factors could improve MEGAN biogenic NOx emissions accuracy.
- BEIS inventory estimates could be enhanced by integrating Texas AQRP 14-016 grassland/savanna and trees vegetation distributions into BEIS BELD4.
- We recommend that MEGAN be used to estimate biogenic NOx emissions in the KTF Area because of the incorporation of AQRP 14-106 vegetation distribution estimates into MEGAN. We also note that BEIS includes over 40 crop types and associated basal soil NOx emission factors whereas MEGAN includes only two crop types and associated basal soil NOx emission factors. BEIS estimates of biogenic NOx emissions for crops may be more accurate than MEGAN because of the level of crop type detail in BEIS.
- There is substantial interannual variation in cropland acreage. Since crops are a substantial contributor to biogenic NOx emissions, the year upon which crop acreage estimates are based is important to biogenic NOx emissions accuracy. For baseline inventories, the basis of crop acreage estimates should be as close as possible to the baseline year. The representativeness of the baseline biogenic NOx emission inventory for a future year should also be carefully considered given potential changes to crop production between the baseline and future year.
- Monitor ongoing research on the Berkeley-Dalhousie Soil NOx Parameterization (BDSNP) since the BDSNP may be improved in the future to estimate more accurate biogenic NOx emissions than the Yienger and Levy (1995; YL95) scheme currently used in BEIS and MEGAN.

[3] basal emission factors are base emission factors, unadjusted for soil moisture, temperature, etc.

1.0 INTRODUCTION

In 2015, a Conceptual Model of Ozone Formation in the Killeen-Temple-Fort Hood (KTF) Area was developed (Kemball-Cook et al., 2015). This study evaluated causes of high ozone in the seven-county KTF Area consisting of Bell, Coryell, Hamilton, Lampasas, Milam, Mills, and San Saba Counties. Ozone source apportionment modeling of the KTF Area (Johnson et al., 2015) showed that the local KTF Area contribution to ozone reached 12-13 parts per billion (ppb) at the Killeen Continuous Ambient Monitoring Station (CAMS) 1047 and Temple Georgia CAMS 1045 monitors. The modeling results suggested that local KTF Area emissions sources can produce intermittent large impacts that are of particular concern because they have the potential to affect compliance with the National Ambient Air Quality Standard (NAAQS) for ozone.

During development of the Conceptual Model, the Texas Commission on Environmental Quality (TCEQ) 2012 emission inventory for the KTF Area was reviewed. Two emissions sources were found to require further evaluation:

- Biogenic NOx emissions were found to comprise nearly 20% of the KTF Area 2012 NOx emission inventory. This is an unusually large fraction for biogenic NOx, and may be due in part to the large portion of KTF Area land used for agriculture. Further evaluation of the biogenic NOx inventory was deemed necessary
- Emissions from the Fort Hood military base in Bell and Coryell Counties are likely underestimated in TCEQ 2012 modeling inventories and require further evaluation.

The purpose of the present study was to evaluate and provide recommendations for improvement of emission inventory estimates for these two sources of emissions.

1.1 Background on Air Quality in the Killeen-Temple-Fort Hood Area

The KTF Area is located generally north of Austin and south to southwest of the Dallas-Fort Worth-Arlington (DFW) Metropolitan Statistical Area. Killeen is approximately 60 miles north of Austin, 45 miles southwest of Waco and 130 miles south of the DFW area. Figure 1-1 displays KTF Area major roadways, urban areas, and air quality monitors. The KTF Area includes large tracts of rural lands that support ranching and agriculture, including cultivation of crops such as grass, wheat, and corn.

The US Environmental Protection Agency (EPA) sets a NAAQS for ozone in order to protect public health and welfare. Under the Clean Air Act, the EPA is required to review the NAAQS periodically. EPA's most recent review of the ozone standard was finalized on October 1, 2015, and on that date the EPA lowered the ozone NAAQS from the 75 ppb standard set in 2008 to a more stringent value of 70 ppb. Attainment designations for the 2015 NAAQS will be based on 2014-2016 data.

The TCEQ operates two ozone monitoring stations in the KTF Area that determine whether the area is in compliance with the NAAQS for ozone. The Killeen Skylark monitor (Continuous

Ambient Monitoring Station [CAMS] 1047) and Temple Georgia (CAMS 1045) are located in Bell County (Figure 1-1), and data from these monitors are used to calculate the ozone design values for the KTF Area. The Temple monitor (CAMS 651) operated during 2005-2006 only. As of the end of the 2016 ozone season, the Killeen Skylark monitor (CAMS 1047) in Bell County has a design value of 67 ppb. The Temple Georgia monitor (CAMS 1045) in Bell County also has a design value of 67 ppb.

On August 3, 2016 TCEQ approved designation recommendations for the 2015 ozone NAAQS and on September 30, 2016 Governor Greg Abbott provided these recommendations to EPA[4]. TCEQ recommended that KTF Area counties be classified as follows:

- An attainment designation is recommended for Bell County since regulatory ozone monitor data for the Killeen Skylark monitor (CAMS 1047) in Bell County is certified from 2013 through 2015 and the Temple Georgia monitor (CAMS 1045) in Bell County is certified from 2014 through 2016 as complete and meeting the NAAQS.
- An unclassifiable/attainment designation is recommended for all other KTF Area counties, which do not have ozone monitors.

The EPA has indicated that it will delay finalizing designations by one year, until October 1, 2018[5]. The designation schedule is uncertain. On June 8, 2016, the House of Representatives (H.R.) passed the Ozone Standards Implementation Act of 2016 (H.R. 4775)[6]; a parallel bill, the Ozone Standards Implementation Act of 2017 (H.R. 806)[7] was introduced in the House on February 2, 2017. If H.R. 4775 or H.R. 806 becomes law as currently written, the schedule for finalizing designations would be delayed by eight years. States would be required to submit designation recommendations in October 2024 and the EPA would be required to finalize recommendations in October 2025.

The two KTF Area monitors are in compliance with the 2015 ozone NAAQS of 70 ppb, but their design values are close to the NAAQS. Because failure to comply with the NAAQS carries adverse public health impacts and significant economic penalties, ozone air quality planning remains important for the KTF Area. Reducing emission inventory uncertainty in the KTF Area to improve ozone model accuracy is a key component of air quality planning.

[4] September 30, 2016 letter from Texas Governor Greg Abbot to EPA Assistant Administrator Janet McCabe and Regional Administrator Ron Curry: State Designation Recommendations for the 2015 Ozone NAAQS. http://www.tceq.texas.gov/assets/public/implementation/air/sip/ozone/2015Designations/TXRecommendation/2015Ozone_DesignationRecommendation_Submittal_to_EPA.pdf

[5] Letter to Governors from EPA Administrator Pruitt, June 6, 2017. https://www.epa.gov/ozone-designations/administrator-extends-deadline-area-designations-2015-ozone-standards

[6] https://www.congress.gov/bill/114th-congress/house-bill/4775

[7] https://www.congress.gov/bill/115th-congress/house-bill/806

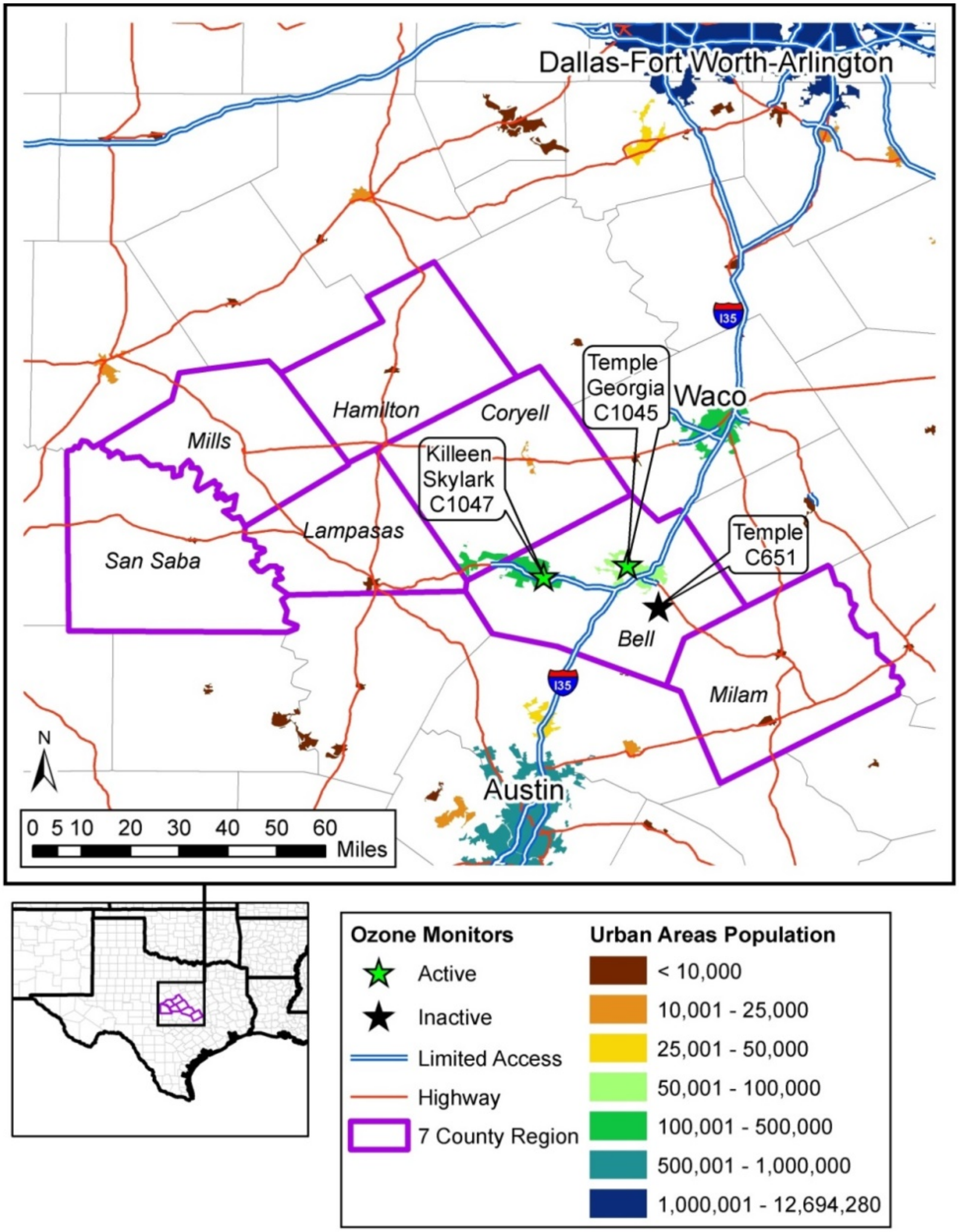

Figure 1-1. The seven county KTF Area and locations of active and inactive CAMS in Bell County. Also shown are population distributions and major roadways in the KTF Area and the surrounding region.

1.2 All Source Emissions Overview

The TCEQ 2012 emission inventory is summarized below to establish the relative importance of biogenic, point, area, on-road, and off-road sector emissions in the KTF Area emission inventory. At the time this analysis was performed, 2012 was the most recent year for which a full KTF Area emission inventory (i.e. anthropogenic and biogenic emissions) was available.

Figure 1-2 shows NOx and volatile organic compound (VOC) emissions by source category in the KTF Area for 2012. KTF-wide 2012 total emission estimates are 64.6 tons per day (tpd) NOx and 731 tpd VOC. The largest three NOx emissions source categories, on-road vehicles (23 tpd, 36%), off-road sources (16 tpd, 25%), and biogenic sources (15 tpd, 24%), account for 84% of KTF Area NOx emissions. Point sources (8.2 tpd, 13%) and area sources (1.8 tpd, 3%) together account for 16% of KTF Area total NOx emissions. Biogenic sources are the largest VOC category comprising 93% (683 tpd) of KTF Area total VOC emissions. Anthropogenic sources account for 7% of VOC emissions with contributions from: area sources (3%, 32 tpd), on-road vehicles (1%, 8.1 tpd), off-road sources (1%, 6.0 tpd), and points sources (<1%, 2.0 tpd).

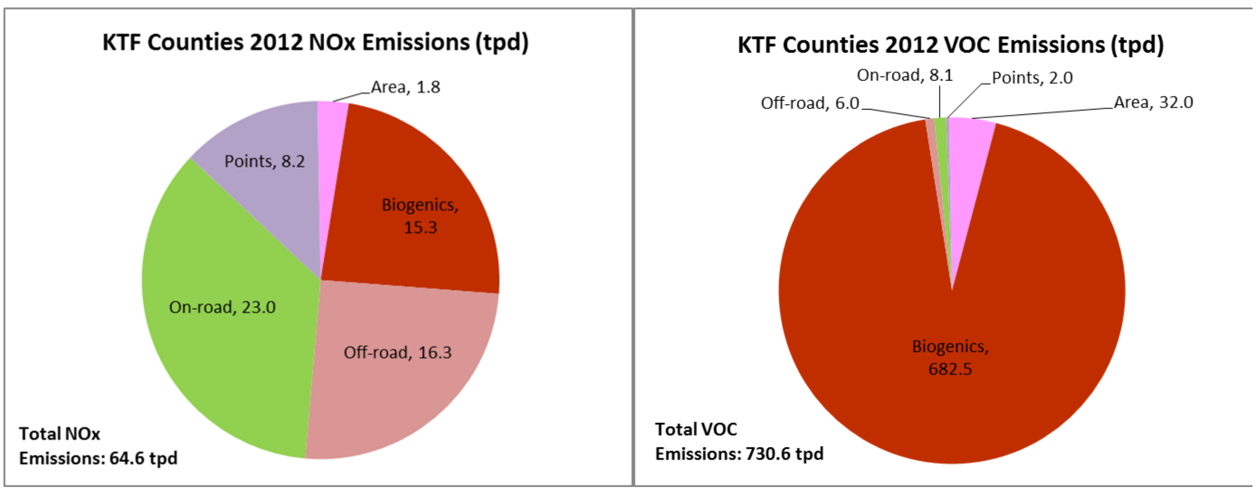

Figure 1-2. 2012 KTF Area emissions by source category for NOx (left) and VOC (right)[8,9].

Ozone formation depends on the amount of NOx and VOC present as well as on the ratio of VOC to NOx, where the ratio is taken in terms of parts per billion by carbon (ppbC) per ppb. When the VOC/NOx ratio is higher than about 10, ozone formation is limited by the amount of available NOx and reducing NOx tends to decrease peak ozone concentrations. However, if the VOC/NOx ratio is less than about 7, reducing NOx tends to increase ozone in the vicinity of NOx emission sources (e.g., an urban area) and the area is said to be VOC-limited. In this situation, ozone is suppressed in the urban area due to titration by large amounts of fresh NOx emissions. When NOx emissions are reduced, suppression of ozone by NOx is lessened and ozone increases.

[8] Emission inventory compiled from TCEQ 2012 emission inventory files downloaded October 2016 from ftp://amdaftp.tceq.texas.gov/pub/EI/2012_episodes/.

[9] Biogenic emissions based on BEIS

For the KTF Area, the emission inventory VOC/NOx ratio is 37 ppbC/ppb, which is well within the NOx-limited regime. The presence of abundant biogenic VOC emissions ensures that there are sufficient VOCs to allow ozone formation and that ozone formation is limited by the amount of available NOx. This means that accurate NOx emission inventories are critically important to understanding ozone formation in the KTF Area.

1.2.1 Biogenic NOx Emissions

Biogenic emission estimates for 2012 were developed by the TCEQ using the Biogenic Emission Inventory System (BEIS; Bash et al., 2015) version 3.61. BEIS estimates hourly, day-specific biogenic emissions that depend on photosynthetically active solar radiation and temperature as well as other inputs such as land cover and plant type. June 2012 average biogenic emissions were estimated from the TCEQ 2012 biogenic emission inventory for the KTF Area[10].

In previous emission inventories (including the emission inventory analyzed in the KTF Conceptual Model), TCEQ 2012 biogenic emission inventories were estimated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN; Guenther et al., 2012). Similar to BEIS, MEGAN estimates hourly, day-specific biogenic emissions. Both MEGAN and BEIS use the algorithm described in Yienger and Levy (1995; YL95) to estimate biogenic NOx emissions; however, there are important differences in BEIS and MEGAN default inputs and reference data sources for parameters such as vegetation distribution and NOx emission factors. MEGAN biogenic emission inventories downloaded previously from TCEQ[11] showed total biogenic NOx emissions of 8.8 tpd (downloaded July 2016) and 12.0 tpd (downloaded in spring 2015).

Biogenic NOx emissions contributions in the KTF Area are higher than in other areas of East Texas for which Ramboll Environ has analyzed emission inventories (e.g. Grant et al. 2015a; Grant et al., 2015b). This is due, at least in part, to intensive agricultural activity in the KTF Area. The nitrogen cycle is the process by which nitrogen is transformed from one form to another through processes such as fixation, ammonification, nitrification, and denitrification. Denitrification is the process by which microorganisms in soil convert nitrate or nitrite molecules into gaseous forms of nitrogen (such as nitric oxide; NO). Fertilizer application and the presence of abundant organic material in soil increase the rate of nitrogen cycling in a soil system while soil properties and water content determine the amount of nitrogen released into the atmosphere. Higher temperatures, oxygen deficient (anaerobic) conditions, and water saturation are all factors that increase nitrogen emissions to the atmosphere from soils (Sakulyanontvittaya et al., 2012). Therefore, we expect that agricultural areas where nitrogen-based fertilizers are applied to the soil to have biogenic NOx emissions and that these emissions would increase during periods of hot weather or following heavy rains when soil becomes saturated and drainage is insufficient to prevent anaerobic conditions. In 2012, there were

[10] ftp://amdaftp.tceq.texas.gov/pub/EI/2012_episodes/hgb_sip/biogenic/beis361F_2012_wrf371/

[11] ftp://amdaftp.tceq.texas.gov/pub/EI/2012_episodes/hgb_sip/biogenic/

723,979 planted acres in the KTF Area with three crop types accounting for over 75% of the planted acres: grass (52%), wheat (13%), and corn (11%)[12].

1.2.2 Fort Hood Emissions

The Fort Hood Military Base occupies 335 square miles in Bell and Coryell Counties[13] and is one of the largest military installations in the United States[13]. Fort Hood may have sizable emissions in all source categories of anthropogenic emissions. Emissions from Fort Hood military base were identified in Kemball-Cook et al. (2015) as highly uncertain and potentially underestimated for military tactical vehicles, industrial area sources (e.g. solvent usage, degreasing), and on-base civilian vehicle emissions. Figure 1-3 shows on-road and off-road NOx emissions from Fort Hood and surrounding areas. There are substantial areas on the Fort Hood base at the border of Coryell and Bell counties which have zero NOx emissions from on-road vehicles and off-road equipment. Google Earth imagery shows these areas to be populated and to have active roadways (Figure 1-4).

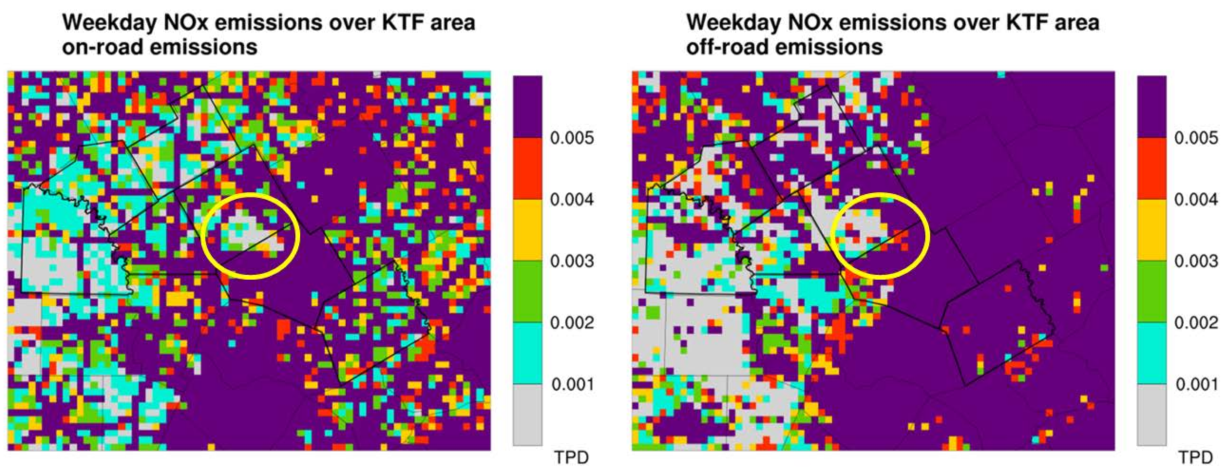

Figure 1-3. KTF Area NOx emissions from on-road vehicles (left panel) and off-road equipment (right panel)[14]. Yellow circles show approximate location of Fort Hood.

Analysis of days with a daily maximum 8-hour average (MDA8) ozone > 75 ppb at the Killeen Skylark (CAMS 1047) monitor indicated the potential importance of impacts from local emissions source(s) such as Fort Hood (Kemball-Cook et al., 2015). Our analysis focused on

[12] United States Department of Agriculture (USDA) Farm Services Agency (FSA) Crop Acreage Data. 2012 acreage data as of January 2013. http://www.fsa.usda.gov/FSA/webapp?area=newsroom&subject=landing&topic=foi-er-fri-cad

[13] Fort Hood Fact Sheet No. 0703, http://www.hood.army.mil/facts/FS%200703%20-%20Fort%20Hood%20Overview.pdf

[14] Note: Charts show grey areas for grid cells without emissions, purple areas for grid cells with emissions greater than the low emission threshold of 0.005 tpd NOx, and other colors for grid cells with emissions greater than zero and less than 0.005 tpd NOx.

gathering of emissions and activity data from Fort Hood to verify or improve the Fort Hood emission inventory while recognizing the constraints of national security considerations.

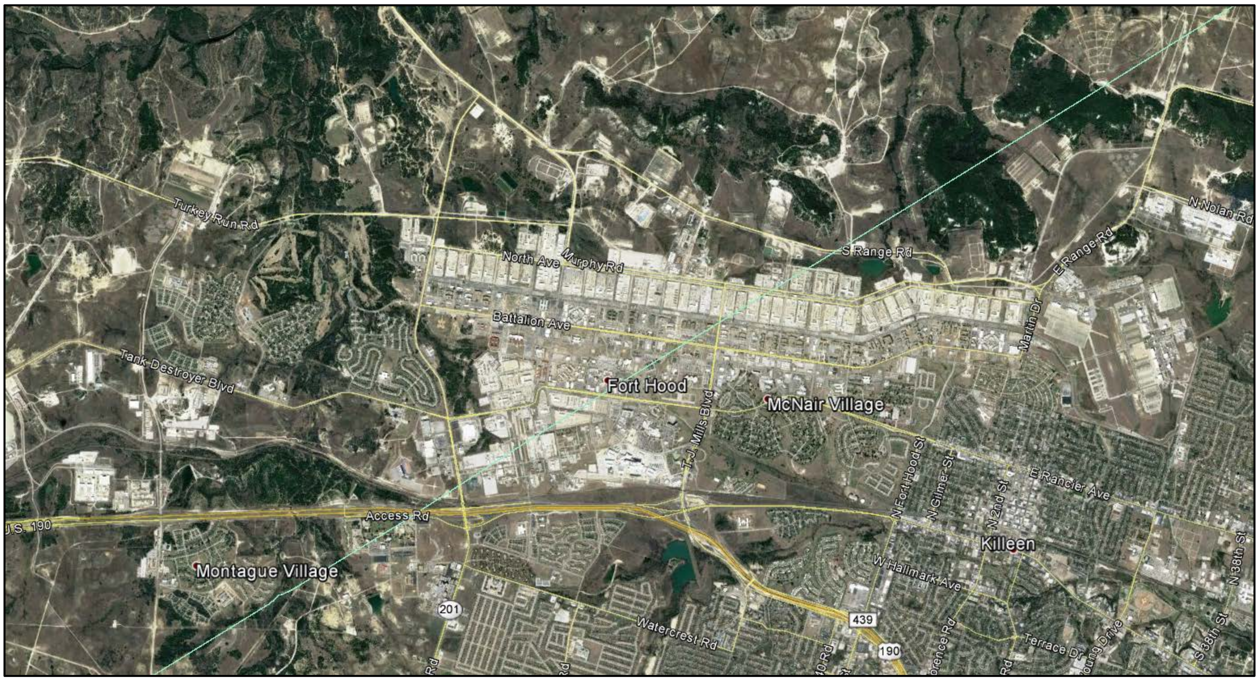

Figure 1-4. Google Earth imagery showing Fort Hood. The Bell-Coryell County Line is shown as a blue-green diagonal line.

1.3 Structure of Report

This report includes analysis of the Fort Hood emissions inventory in Section 2.0. Section 3.0 provides the KTF Area biogenic NOx emissions analysis. The report concludes with Section 4.0, which summarizes the key findings of the Fort Hood and biogenic emissions analyses and provides recommendations for KTF Area emission inventory improvements.

2.0 Fort Hood Emission Inventory

The Fort Hood Military Base is one of the largest military installations in the United States[15] and may have substantial emissions from all source categories of anthropogenic emissions. Fort Hood occupies 335 square miles in Bell and Coryell Counties (see Figure 2-1), and is the only post in the United States capable of stationing and training two Armored Divisions[15]. In 2017, Fort Hood had an on post population of 45,787 assigned military (not including deployed military) and family members. Including all assigned military, family members, civilian employees, contractors, etc., Fort Hood had an on post population of 73,934 in 2017[16].

In the Conceptual Model of Ozone in the KTF Area (Kemball-Cook et al., 2015), it was noted that (1) on-base emissions from on-road vehicles and off-road equipment in Fort Hood were not present in the 2012 TCEQ emission inventory, (2) that the extent to which Fort Hood industrial area sources (e.g. solvent usage and degreasing) are included in the current inventory was not clear and (3) the selection methodology for the reporting of Fort Hood point sources was not clear. We reviewed the most recent TCEQ 2012 emission inventory to determine whether any updates have been made by TCEQ to Fort Hood emissions since the Kemball-Cook et al. (2015) analysis. We also performed outreach to Fort Hood to determine whether additional information on emissions could be made available.

Figure 2-1. Fort Hood area (shaded brown) with county boundaries. I-35 is shown in red.

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[15] Fort Hood Fact Sheet No. 0703, http://www.hood.army.mil/facts/FS%200703%20-%20Fort%20Hood%20Overview.pdf

[16] USAG Fort Hood Fact Sheet (3 March 2017), http://killeenchamber.com/assets/uploads/docs/Fact_Sheet_March_2017.pdf

2.1 Fort Hood Emission Inventory Outreach Efforts

We worked with the Central Texas Council of Governments (CTCOG) and the Fort Hood liaison to the Central Texas Air Information and Research (CTAIR) Advisory Committee, to determine the availability of emissions information beyond what went into the preparation of the TCEQ 2012 inventory. In May 2016, Robert Kennedy (Air Quality Program Manager in the Fort Hood Directorate of Public Works), CTCOG, and Ramboll Environ staff met to discuss the Fort Hood emission inventory. In July 2016, Mr. Kennedy provided additional data on Fort Hood emissions (Personal communication; Kennedy, 2016). In July 2016, Mr. Kennedy provided three data source files to CTCOG which included the emission inventory information described below.

Point Sources[17]: This file contains Fort Hood point source carbon monoxide (CO), NOx, sulfur dioxide (SO_2), particulate matter (PM), particulate matter less than 10 microns (PM_{10}), particulate matter less than 2.5 microns ($PM_{2.5}$), lead (Pb), VOC, and hazardous air pollutants (HAPs) emissions by source. Comparison of emissions provided by Kennedy (2016) with TCEQ 2012 point source emissions for the Fort Hood Military Base facility (see Table 2-1) indicates that emissions in this file are, to a great extent, already included the TCEQ 2012 emission inventory; there is a very small quantity of VOC emissions in Kennedy (2016) that are not included in the 2012 TCEQ emission inventory, but the NOx and CO emissions match. Update of the TCEQ 2012 point source emission inventory based on the information provided by Kennedy (2016) is not warranted.

Table 2-1. Fort Hood point source emissions.

Source	Units	NOx	VOC	CO
Kennedy (2016)	tpy[A]	28.8542	36.2688	73.4259
	tpd[B]	0.0791	0.0994	0.2012
TCEQ 2012 Emission Inventory[8]	tpd	0.0791	0.1474	0.2012

[A] tons per year
[B] tpd emissions estimated by dividing tpy emissions by 365

Fuel mileage[18]: This file contains 2012 fuel consumption and mileage by vehicle. Although the data in this file contain vehicle-specific activity details, this data is not useful for estimating on-road emissions without additional information because the location where vehicle activity occurred (i.e. on-base or off-base) is not available in the data file.

Unpaved roads[19]: This file contains 2012 NOx and VOC emissions from tactical vehicles traveling on unpaved roads (see Table 2-2). It is unclear whether this is a

[17] Filename: "Table 1-3-Summary of Actual Emissions by Source Category-CY12.xlsx"
[18] Filename: "2012_Fuel-DPW_Mileage_report.xlsx"
[19] Filename: "FD001 TACTICAL VEHICLE NOX AND VOC EMISSIONS-CY12.xlsx"

comprehensive inventory for tactical vehicles. Emissions are very small relative to the total KTF Area emissions inventory totals.

Table 2-2. Fort Hood 2012 unpaved road emissions from tactical vehicles.

Vehicle Category	NOx Factor (lb/mile)	VOC Factor (lb/mile)	Total Mileage (1000 miles)	NOx Emissions		VOC Emissions	
				(tpy)	(tpd[A])	(tpy)	(tpd[A])
Wheel - LD	0.0016	0.00103	2,302	1.9	0.005	1.2	0.003
Wheel - HD	0.0161	0.00153	6,860	55.3	0.152	5.2	0.014
Track	0.2429	0.00011	219	26.6	0.073	<0.1	<0.001
Totals			**9,381**	**83.8**	**0.230**	**6.4**	**0.018**

[A] tpd emissions estimated by dividing tpy emissions by 365

Following review of the three files (described above) provided by Mr. Kennedy, Ramboll Environ determined that additional information was needed in order to use the data provided to derive emission estimates for Fort Hood that could be used for ozone modeling. In August 2016, Ramboll Environ asked clarifying questions via email (1) to confirm units of measurement and the types of internal combustion sources in the point sources inventory file and (2) to confirm units of measurement, the location of vehicle activity (i.e. on-base or off-base) and the completeness of the vehicle data in the fuel mileage file. No response to these clarifying questions was received.

2.2 TCEQ 2012 Fort Hood Emission Inventory

Based on review of Fort Hood emissions in the TCEQ 2012 emission inventory, inspection of TCEQ modeling files, and discussions with TCEQ on how the Fort Hood emissions inventory was developed, we found that several emission sources are missing or underrepresented in the TCEQ 2012 emission inventory within the boundaries of Fort Hood.

On-road vehicle emissions from vehicle traffic on roads within Fort Hood (e.g. cars, trucks, buses, motorcycles) are not present in the TCEQ 2012 inventory because mobile source emission inventories are based on traffic count data which is only collected on public roads. Military traffic on public roads outside Fort Hood is accounted for in the TCEQ inventory.

Off-road equipment emissions are estimated in the Texas NONROAD model (TexN) for many types of off-road equipment (e.g. construction, agricultural, lawn and garden equipment) based on several studies as described in TexN model User Guides (ERG, 2008; ERG, 2014). Off-road equipment emissions estimated in TexN do not include any military equipment such as tanks, armored vehicles, or helicopters, nor are there any equipment populations based on Fort Hood military post activity separate from the county-level estimates included in the TexN model (TCEQ, 2015a). Fort Hood off-road equipment emissions are not well-characterized and may be underestimated. Fort Hood includes the Military Equipment and Training Site (MATES) where 850 pieces of heavy equipment (such as transporter trucks and military tactical vehicles) are stored and supported. Additionally, 1,700 pieces of equipment are stored and supported at an Equipment Concentration Site (ECS) at Fort Hood[15]. Equipment at the MATES and ECS is expected to be a source of ozone precursor emissions; the magnitude of emissions depends on equipment characteristics as well as frequency and duration of equipment use. Emissions from vehicles and equipment that are mobile, but travel off-road, such as tanks, armored vehicles and helicopters, are not present in the TCEQ inventory. Fort Hood tactical equipment emissions on unpaved roads (see Table 2-2) were provided (Kennedy, 2016); however, the completeness of these emissions is unknown.

Military aircraft are included in emission estimates for the Killeen–Fort Hood Regional Airport which is a military/commercial joint-use facility located on the Fort Hood Military Base.

Population-based **area source** (e.g. degreasing, solvent usage) emission estimates are included in the TCEQ 2012 emission inventory, since population-based area source emissions are based on human population estimates (TCEQ, 2015b). The U.S. Census lists Fort Hood as a census designated place with a 2010 human population of 29,589[20]. The U.S. Census population is lower than recent U.S. Army Garrison (USAG) on post population estimates[16]. Differences in 2010 U.S. Census population estimates and USAG on post population estimates may result from differences in population counting methodology and on post population fluctuations. Differences in the population basis for area source emission estimates are not critical to the KTF Area NOx emission inventory since NOx emissions from area sources are expected to be small. Point source emissions provided in Kennedy (2016) also include many sources that could be classified as nonpoint sources such as surface coating and solvent usage, indicating that missing emissions in the area source inventory are likely to be small.

According to TCEQ's 2014 Emission Inventory Guidelines (TCEQ, 2015c), **point sources** must be reported to TCEQ in attainment areas such as the KTF Area when a facility's actual or potential emissions exceed 100 tpy for any criteria pollutant, 10 tpy for any individual hazardous air pollutant, or 25 tpy for aggregated HAP emissions. Fort Hood reported their 2012 point sources voluntarily since Fort Hood emissions did not exceed any reporting criteria in 2012.

2.3 Future Efforts

Fort Hood provided three datasets that were analyzed in this study. Point source emissions provided by Fort Hood showed emission quantities identical to TCEQ 2012 emission inventory estimates for NOx and CO and small differences for VOC. The other two datasets provided by Fort Hood (vehicle activity and unpaved road emissions) were not suitable for enhancing TCEQ's 2012 emission inventory. While Fort Hood has been highly cooperative, their ability to provide additional information for inventory development may be constrained by national security considerations. TCEQ has provided guidance that emissions for Fort Hood should not be estimated without participation and approval from Fort Hood. We therefore do not recommend further development of Fort Hood 2012 emission inventories at this time.

In order to evaluate the effect of missing Fort Hood emissions on air quality model performance at the Killeen Skylark monitor (CAMS 1047) and Temple Georgia monitor (CAMS 1045), Ramboll Environ will conduct a sensitivity test under the FY 16-17 photochemical modeling task. We will

[20] http://quickfacts.census.gov/qfd/states/48/4826736.html

report on the sensitivity of the ozone model to Fort Hood area emissions in the fiscal year 16-17 photochemical modeling task final report.

3.0 BIOGENIC NOX EMISSIONS

Biogenic emissions comprise a substantial fraction (24%) of TCEQ 2012 NOx emissions in the KTF Area. KTF Area has substantial agricultural production (723,979 acres in 2012[12]) which contributes to high biogenic NOx emissions.

Biogenic emissions have been estimated by TCEQ using BEIS for the most recent TCEQ 2012 emission inventory and previously using MEGAN. KTF Area NOx emissions from BEIS of 15.3 tpd were estimated in TCEQ's most recent 2012 emission inventory; previous TCEQ 2012 biogenic emission inventory estimates from MEGAN indicated smaller biogenic NOx emissions of 8.8 tpd (downloaded July 2016) and 12.0 tpd (downloaded in spring 2015). There is no NOx monitoring at KTF Area CAMS, so a direct comparison of modeled NOx using BEIS and MEGAN inventories was not possible. Although satellite NO_2 column data have been used to infer biogenic NOx emission inventories (e.g. Vinken et al., 2014), uncertainties in satellite retrievals are very likely to complicate interpretation of differences between modeled NO_2 columns using BEIS and MEGAN biogenic inventories. Therefore, we reviewed model inputs used by MEGAN and BEIS to determine whether one model was likely to provide more accurate emission estimates for the KTF Area than the other.

Since the MEGAN and BEIS model estimates of NOx emissions were substantially different, we began our analysis by reviewing model code. We found a coding error in MEGAN that incorrectly applied reductions to NOx emissions. We fixed and recompiled the MEGAN code in order to perform a screening analysis of the effect of the coding error on NOx emission estimates from MEGAN. The code correction resulted in substantial increases in NOx emissions from MEGAN, bringing MEGAN and BEIS NOx emissions estimates into closer agreement. We then focused our analysis on vegetation coverage inputs to BEIS and MEGAN; vegetation coverage inputs are critical inputs in the estimation of biogenic NOx emissions.

3.1 Biogenic NOx Emissions Estimation Overview

3.1.1 MEGAN and BEIS NOx emission estimation

MEGAN (Guenther et al., 2012) and BEIS (Pierce and Waldruff, 1991) are two commonly used models for estimating biogenic emissions. The latest version of MEGAN (version 2.1) and BEIS (version 3.61; Bash et al., 2015) include a soil NOx emission module based on the approach described in YL95 which calculates soil NOx emissions by adjusting basal NO emission factors (dependent on biome type[21]) with scaling factors dependent on pulsing (i.e. increased NOx emissions following precipitation or irrigation), soil temperature, soil moisture, fertilization application, and canopy reduction.

Different biome types exhibit dramatically different NOx emission potential as a result of different vegetation types, soil conditions, climate zones, etc. Emissions from grasslands are typically an order of magnitude higher than forests/shrubs/wetlands and emissions from

[21] A biome refers to a large ecological area with its own weather and temperature patterns and plant and animal community

cultivated croplands are as much as an order of magnitude higher than grasslands. NOx emissions are stimulated when there is a pulsing event; the magnitude of NOx emissions increase depends on the strength of the pulsing event. The strength of the pulsing event is determined by the current soil status (wet or dry) and the daily cumulative precipitation rate during the pulsing event. NOx emissions are also temperature-dependent; temperature scaling factors differ for dry and wet soil conditions by temperature range; a general rule of thumb is that NOx emissions are positively correlated with soil temperature. Canopy reductions of NOx emissions, either by diffusion through leaf stomata or direct deposition onto/through the leaf cuticle, are parameterized as a function of Leaf Area Index (LAI)[22]; larger NOx emissions reductions are associated with higher LAI values. For crops, NOx emissions are dependent on planting date; more NOx is emitted during the growing season when fertilizer is applied.

Although the soil NOx calculation module in MEGAN (version 2.1) and BEIS (version 3.61) are based on the same YL95 algorithm, there are minor implementation differences:

1. **Growing season definition.** In BEIS, growing season is defined as April 1st – October 31st regardless of location. In MEGAN, growing season is a function of location (i.e. latitude); in the KTF Area, the MEGAN growing season is estimated to be close to year-round, from early-February to early-December. Actual growing season is dependent on crop type and climate. For example, in Texas in 2009, corn had a growing season from March 1 to November 8, cotton had a growing season from March 22 to January 11, and winter wheat had a growing season from September 4 to July 12[23]. Our analysis focused on the month of June which is within the growing season for BEIS and MEGAN.
2. **Canopy reduction scaling factor.** In MEGAN, the canopy reduction factor is implemented as a function of LAI exactly as outlined in the YL95 paper. In BEIS, the canopy scaling factor varies from 0.5 to 1 based on the day of growing season to account for fluctuation in NOx losses through the canopy. For example, at early stage of the growing season (i.e. first 30 days) when the canopy starts to grow, the canopy reduction scaling factor is set to 1; as the canopy continues to develop, this scaling factor decreases from 1 to 0.5, indicating higher canopy NOx reductions.

Key inputs for estimating soil NOx emissions in MEGAN and BEIS include:

1. **Vegetation distribution data** (i.e. vegetation coverage and types across a modeling domain). MEGAN adopts the Community Land Model (CLM, Lawrence et al., 2011) plant functional type[24] (PFT) scheme with a total of 16 PFTs (Guenther et al., 2012). In contrast, BEIS uses the Biogenic Emission Landuse Database version 4 (BELD4; Bash et al., 2016) with much more detailed vegetation types (e.g. 194 tree types and 42 crop types). Both MEGAN and BEIS provide default vegetation distribution inputs. In the

[22] Leaf area index (LAI) is the ratio of green leaf area to ground surface area.
[23] Usual Planting and Harvesting Dates for U.S. Field Crops, National Agricultural Statistics Service, October 2010, http://usda.mannlib.cornell.edu/usda/current/planting/planting-10-29-2010.pdf.
[24] Individual plant species are grouped into a short list of aggregate plant functional types (PFTs) based on similar physical or other characteristics for use in modeling applications

TCEQ BEIS model setup, BEIS default vegetation distribution inputs are used. In TCEQ's MEGAN setup, updated PFT data developed in Yu et al. (2015; Air Quality Research Project [AQRP] 14-016) was used.

2. **Basal NO emission factors** (i.e. soil NO emission factors prior to any adjustments). Basal NO emission factors are available for each of 16 PFTs in MEGAN and each of close to 300 land use types in BEIS. Bash et al. (2016) notes that "variability in BEIS emission rates is greater than MEGAN 2.1 (Guenther et al., 2012) due to the more detailed representation of vegetation species." Differences in MEGAN and BEIS basal NO emission factors are greatest for crops. There are two basal emission rates for crops available in MEGAN, 40 grams of nitrogen per square-kilometer per hour (gN/km^2-hr) for corn and 68 gN/km^2-hr for all other crops. In BEIS, there are over 40 individual crop types, each with an associated basal NO emission rate that ranges from 21 gN/km^2-hr to 361 gN/km^2-hr. BEIS basal emission rates for corn (68 gN/km^2-hr [unirrigated] and 203 gN/km^2-hr [irrigated] are higher than MEGAN estimates (40 gN/km^2-hr). BEIS basal NO emission rates for other crop types are generally higher than MEGAN for irrigated crops and lower than MEGAN for unirrigated crops. In the KTF Area, there is a mix of irrigated and unirrigated crops.
3. **Meteorological inputs** including precipitation rates and air temperature are from the Weather Research and Forecasting Model (WRF) output for MEGAN and BEIS.
4. **Soil related inputs** including soil temperature, soil moisture and soil type are from WRF output for MEGAN and BEIS.
5. **Leaf area index inputs** were developed in MEGAN from 2013 MOderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Yu et al., 2015) and in BEIS based on plant genus type specific estimates (Bash et al., 2016).

3.1.2 Berkeley-Dalhousie Soil NOx Parameterization

We reviewed a third biogenic NOx emissions model to determine whether it had the potential to characterize KTF Area emissions more accurately than MEGAN and/or BEIS. Recent research on developing more accurate estimates of soil NOx emissions has focused on the Berkeley-Dalhousie soil NOx parameterization (BDSNP) scheme (e.g. Rasool et al., 2016). The BDSNP allows for the integration of detailed fertilization rate datasets and includes enhanced modeling of the soil nitrogen cycle compared to MEGAN or BEIS.

The BDSNP is a soil NOx estimation scheme which, similar to the YL95 scheme, estimates NOx emissions by multiplying a basal emission factor and several scaling factors that are functions of temperature, soil moisture and a pulsing term. The BDSNP includes refined soil moisture/temperature response which estimates smooth transitions between dry and wet soil conditions instead of sharp changes in the YL95 scheme caused by the binary categorization of soil moisture as either "dry" or "wet". Instead of relating the strength of a pulse to precipitation rate (as in the YL95 scheme), BDSNP uses the length of the antecedent dry period and soil moisture changes to determine the pulse strength. The long-term average fertilizer and manure dataset from Potter et al. (2010) or the Environmental Policy Integrated Climate (EPIC) model[25]

[25] http://epicapex.tamu.edu/epic/

is used to develop fertilizer induced soil NO emissions in BDSNP. Wet and dry deposition of nitrogen species is included in BDSNP scheme as an additional fertilizer source, which is not considered in the YL95 scheme. More details of comparisons between the YL95 scheme and BDSNP can be found in Rasool et al. (2016).

BDSNP was originally implemented as an in-line module in the GEOS-Chem global chemical transport model (Hudman et al., 2012), and was later implemented as an in-line module in the Community Multi-scale Air Quality (CMAQ) Modeling System (Rasool, et al., 2016). BDSNP has not been implemented in the Comprehensive Air Quality Model with Extensions (CAMx) model used by the TCEQ and CTCOG for ozone modeling. A standalone BDSNP is also available. Additional input data (beyond the data needed in YL95 method) are needed in the BDSNP, including wet and dry nitrogen deposition (derived from photochemical model output) and fertilizer data (e.g. Potter et al., 2010 or EPIC model estimates).

Rasool et al. (2016) analyzed three soil NOx methodology scenarios in CMAQ (YL95, BDSNP with Potter et al. [2010] fertilization, and BDSNP with EPIC fertilization). BDSNP scenarios improved air quality model ozone performance over YL95 in National Forest and National Park areas of California with dry soil conditions, but did not improve model performance in agricultural/prairie areas in the Midwest with wet soil conditions (Rasool et al., 2016). Rasool et al. (2016) model performance results for agricultural/prairie areas in the Midwest are likely to be closer to KTF Area conditions than National Forest and National Park areas of California. Ozone model performance evaluation results for the Midwest sites indicate that the BDSNP scheme should not be implemented in the KTF Area until further improvements to the model are made. Additional work to enhance EPIC model soil moisture modeling and nitrogen cycling was suggested in Rasool et al. (2016) to increase the accuracy of the BDSNP. Research on the BDSNP model is ongoing and should be monitored.

Ramboll Environ reviewed the standalone BDSNP code as well as relevant input data and estimated the time and effort required to integrate the BDSNP algorithm into MEGAN as an alternative soil NOx scheme. Incorporating the standalone BDSNP model into MEGAN would require substantial code modification. In addition, to conduct a BDSNP run for the KTF Area at 4 km resolution would require substantial effort to generate model required input data, including the soil climate data, fertilizer data, and nitrogen deposition data. Given the model's current performance and the complexity of implementation, we determined that BDSNP was not appropriate for use in the KTF Area modeling at present.

3.2 KTF Area 2012 Biogenic NOx Emission Inventory

3.2.1 MEGAN and BEIS Model Setups

2012 biogenic NOx emissions have been developed by TCEQ with the latest versions of MEGAN (version 2.1) and BEIS (version 3.61). Both MEGAN and BEIS simulations utilized meteorological data extracted from WRF simulations; the BEIS simulation is based on a WRF simulation conducted for the Houston-Galveston-Brazoria (HGB) State Implementation Plan (SIP) 2012 ozone modeling episode[26]. We note that BEIS and MEGAN simulations are likely to use different WRF simulation output; we have not evaluated the effect of different WRF simulations on biogenic emissions. For MEGAN, LAI data, PFT data, and basal emission factors were adopted from the AQRP 14-016 project (Yu et al., 2015). For BEIS, land use data were generated from the EPA 2011 National Emission Inventory (NEI, version 6.3) BELD4.

3.2.2 MEGAN and BEIS Model NOx Results

Table 3-1 summarizes the BEIS and MEGAN NOx and VOC emissions for June 2012 over the KTF Area. VOC emissions generated from the two models are similar with a relative difference of only 3.8%. However, there are substantial NOx emissions differences (40%) between BEIS and MEGAN over the KTF Area.

As shown in Figure 3-1, BEIS NOx emissions were generally highest in agricultural areas on the eastern border of the KTF area and in northern Milam and southern Bell counties (Section 3.4 provides additional analyses on vegetation distribution). NOx emissions differences between MEGAN and BEIS generally indicate higher emissions from MEGAN in the western KTF Area and higher emissions from BEIS in the eastern KTF Area. MEGAN results show a more uniform distribution of NOx emissions across the KTF Area with slightly lower emissions in the eastern half of Milam County. The spatial distribution of NOx emissions in MEGAN are not well correlated with the spatial distribution of crops (see Figure 3-2) due to a coding error in the MEGAN model (described in Section 3.3).

Table 3-1. BEIS and MEGAN June 2012 KTF Area NOx and VOC emissions.

Pollutant	Emissions (tpd)		Percent Difference
	BEIS	MEGAN	
NOx	15.3	8.77	42.7%
VOC	682.5	656.4	3.8%

26 ftp://amdaftp.tceq.texas.gov/pub/TX/camx/2012/bc12_12xxx.r6a_r4a.2012_wrf371_p2ma_i2mSNgqsfc0_f/input/met/

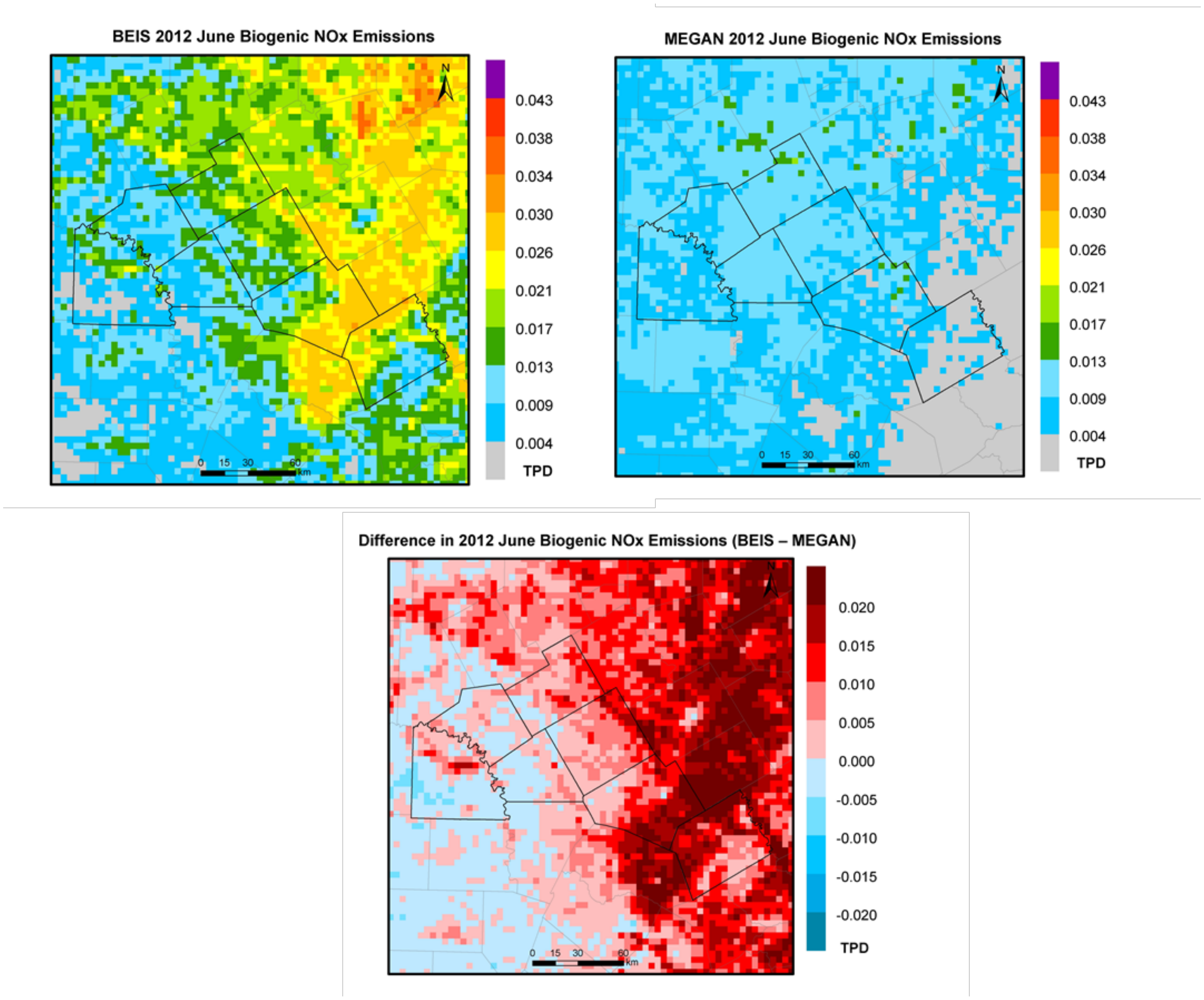

Figure 3-1. KTF Area June 2012 NOx emissions from BEIS (upper left panel), MEGAN (upper right panel), and differences between BEIS and MEGAN (bottom panel).

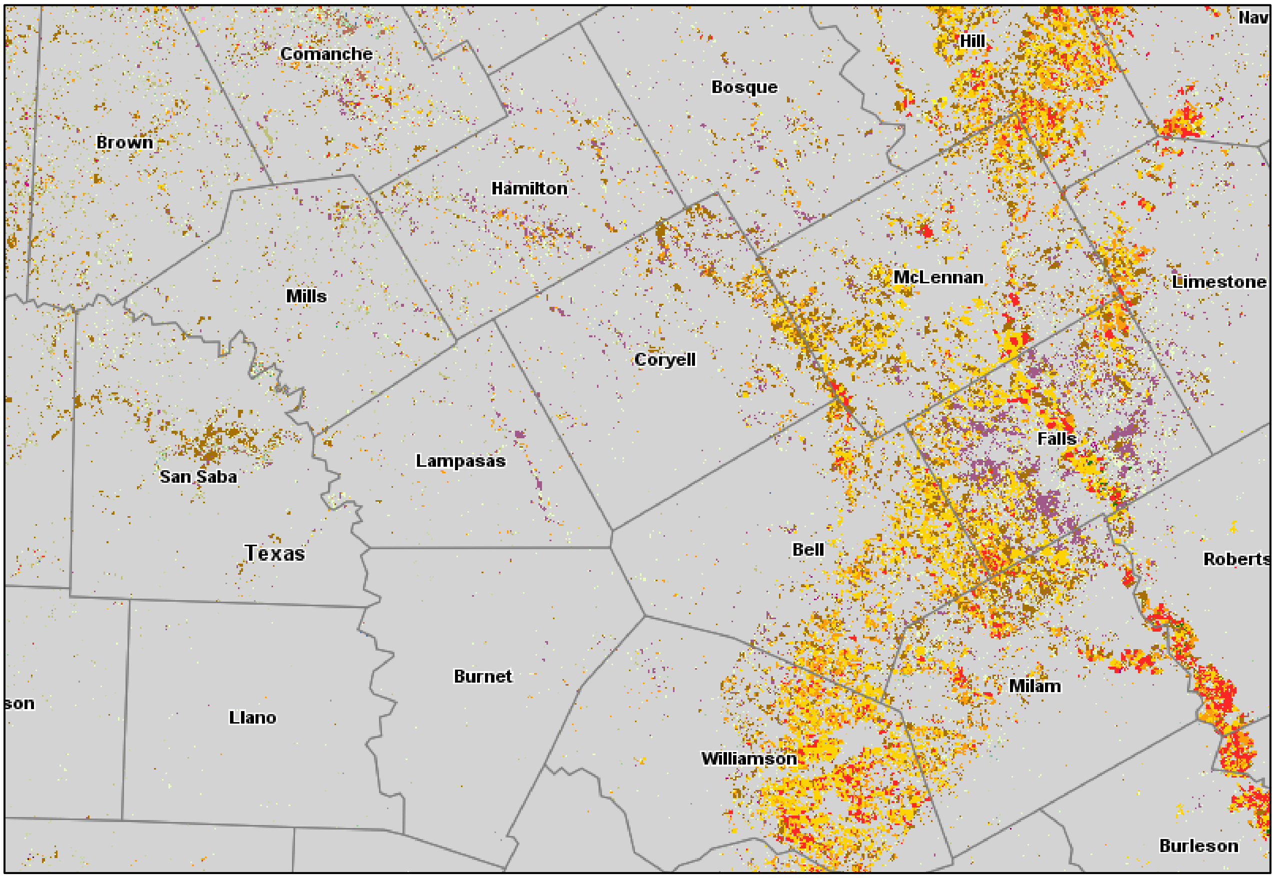

Figure 3-2. Calendar year 2012 crop areas in the KTF Area[27,28].

3.3 MEGAN Coding Error

3.3.1 MEGAN Code Review and Error Description

MEGAN (version 2.1) includes two key soil NOx emission calculation subroutines:

1. "EMPROC" calculates soil NOx emission activity factors which adjust basal emission rates in response to temperature, precipitation, fertilizer stimulation, and other factors.
2. "MGN2MECH" combines the soil NOx emission activity factors with basal NOx emission rates to generate final NOx emission rates for a given grid cell and hour.

Ramboll Environ reviewed MEGAN (version 2.1) source code[29] for "EMPROC" and "MGN2MECH" subroutines. A coding error associated with the soil NOx emission calculation was found in the "MGN2MECH" calculation step. This error appears in four lines of original source code listed below:

[27] Source: USDA Cropscape – Cropland Data Layer, https://nassgeodata.gmu.edu/CropScape/.
[28] Grey areas are indicative of areas without crops, other colors are indicative of areas with crops.
[29] MEGAN version 2.1 source code was downloaded from http://lar.wsu.edu/megan/.

a. Line 639 and 655 estimate grid cell-adjusted NOx emission rates outside of the growing season:

*Line 639: tmper(nmpsp,C,R) = inper(INO,C,R) * EF(INO,C,R) * CFNOG(C,R) * TMO2 / TMO1* n2no*
*Line 655: tmper(nmpsp,C,R) = inper(INO,C,R) * CFNOG(C,R) * TMO3* n2no*

b. Line 682 and 698 estimate grid cell-adjusted NOx emission rates in the growing season:

*Line 682: tmper(nmpsp,C,R) = inper(INO,C,R) * EF(INO,C,R) *TMO2 / TMO1* n2no*
*Line 698: tmper(nmpsp,C,R) = inper(INO,C,R) * TMO3* n2no*

In the original source code, the "inper" variable (in red text above) was incorporated into the calculation of final soil NOx emission rates "tmper". However, "inper" represents the emission activity factors for biogenic VOCs and should not be applied to soil NOx. We fixed this error by simply deleting the "inper" variable from the source code as shown below:

*Line 639: tmper(nmpsp,C,R) = ~~inper(INO,C,R) *~~ EF(INO,C,R) * CFNOG(C,R) * TMO2 / TMO1* n2no*
*Line 655: tmper(nmpsp,C,R) = ~~inper(INO,C,R) *~~ CFNOG(C,R) * TMO3* n2no*
*Line 682: tmper(nmpsp,C,R) = ~~inper(INO,C,R) *~~ EF(INO,C,R) *TMO2 / TMO1* n2no*
*Line 698: tmper(nmpsp,C,R) = ~~inper(INO,C,R) *~~ TMO3* n2no*

The impact of this coding error varies depending on the magnitude of the "inper" variable. The "inper" variable has a range from zero to one and accounts for VOC adjustments for temperature, light, LAI, etc. In MEGAN, the "inper" variable incorrectly decreases soil NOx emissions by a grid cell specific ratio. We have informed the MEGAN model developer of this correction; it will be implemented in MEGAN (version 3).

3.3.2 Screening Analysis of MEGAN Code Correction

To quantify the impact of the MEGAN code error described above on output NOx emissions in the KTF Area, two parallel MEGAN simulations were run for June 2012 over the TCEQ's 4 km modeling domain[30] using the original source code and corrected source code; all other inputs and settings were identical between the two simulations. Meteorological data were extracted from a TCEQ WRF simulation conducted in 2015[31]; LAI data, PFT data, and basal emission factor maps, were adopted from the TCEQ MEGAN setup described in Section 3.2.1.

Figure 3-3 shows KTF Area June 2012 NOx emissions generated by original and corrected source code simulations and the differences between the two. The coding error causes MEGAN to underestimate NOx emissions over the KTF Area. As mentioned above, the "inper" variable decreases emissions by a grid cell specific ratio; therefore, the magnitude of underestimation generally aligns with the magnitude of NOx emissions by grid cell. Maximum underestimation of NOx emissions is as much as 0.01 tons/day per grid cell.

[30] https://www.tceq.texas.gov/airquality/airmod/data/domain
[31] https://www.tceq.texas.gov/airquality/airmod/data/tx2012

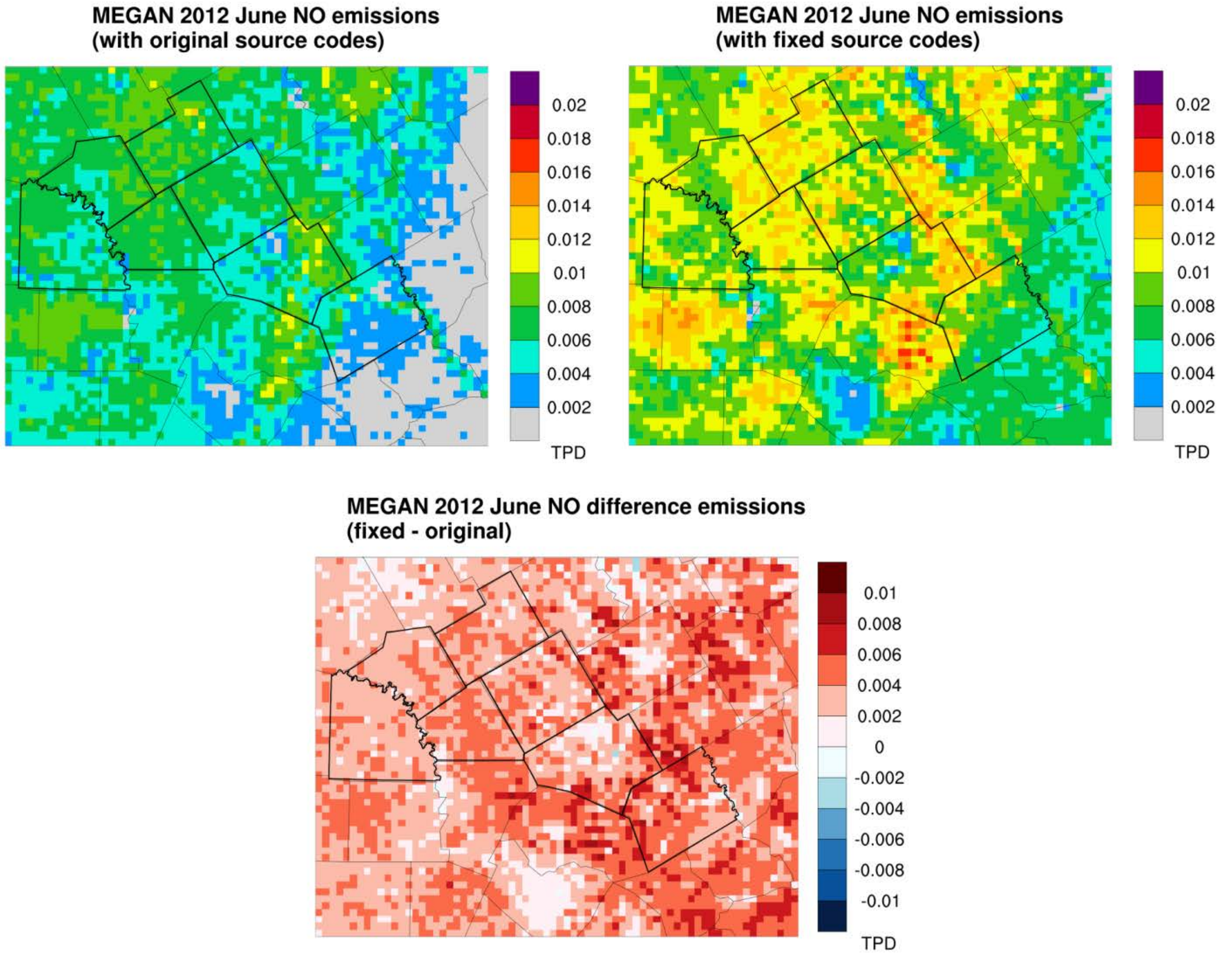

Figure 3-3. KTF Area MEGAN June 2012 NOx emissions generated by original source code (upper left panel), corrected source code (upper right panel), and differences between the two (bottom panel).

As shown in Figure 3-4 and described above, BEIS estimates the greatest biogenic emissions in agricultural crop areas. Code-corrected MEGAN results show increased emissions in areas with the greatest crop production (e.g. eastern Bell County) and areas with substantial grassland vegetation (e.g. Lampasas County). There are substantial differences (plus/minus 0.015 tpd per grid cell) between BEIS and code-corrected MEGAN NOx emissions. BEIS NOx emissions are generally higher in areas of agricultural cultivation. MEGAN emissions are higher outside of areas of agricultural cultivation, with the largest differences occurring in areas where MEGAN vegetation coverage indicates substantial grasslands (e.g. Lampasas County).

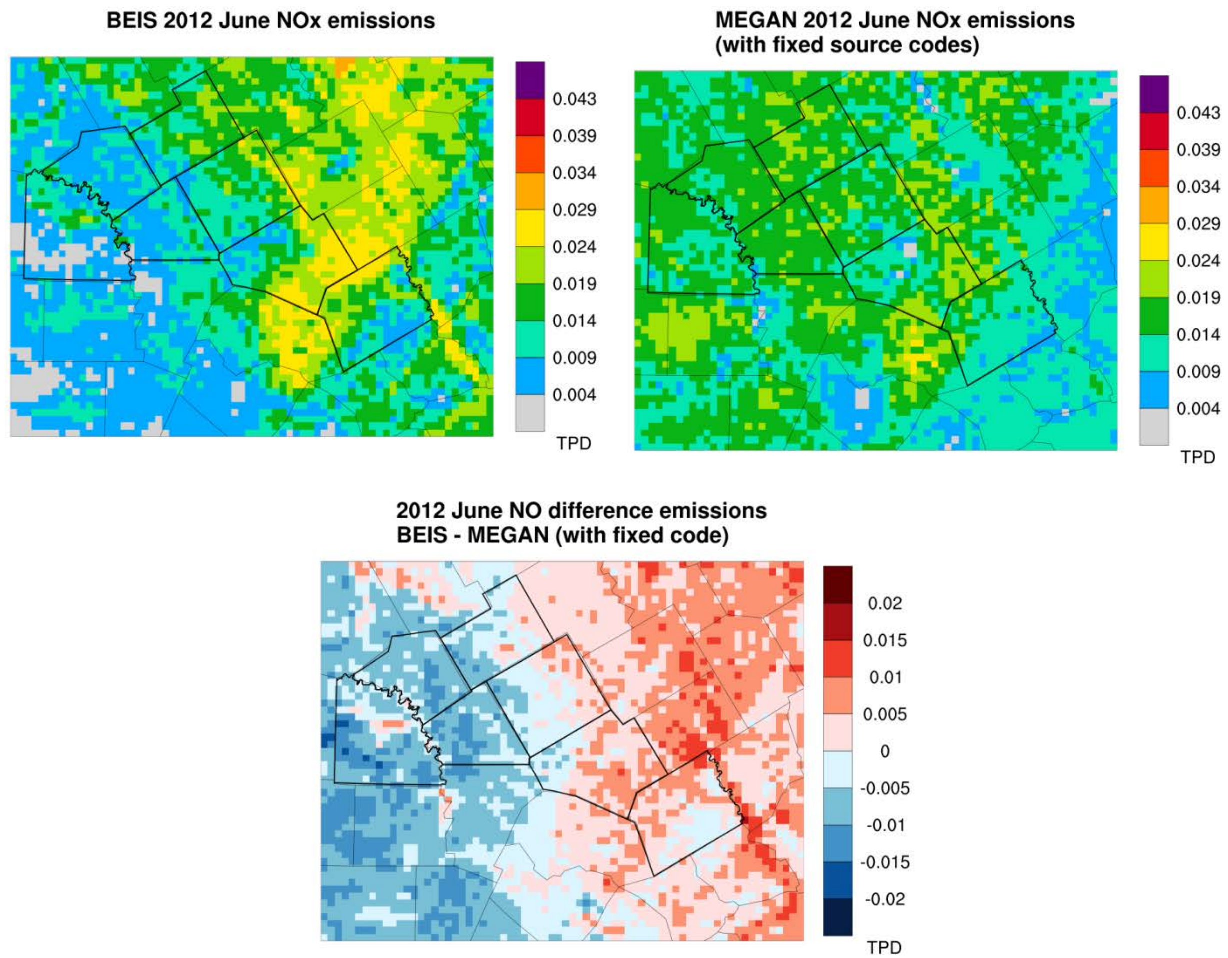

Figure 3-4. KTF Area June 2012 NOx emissions from BEIS (upper left panel), code-corrected MEGAN (upper right panel), and differences between BEIS and code-corrected MEGAN (bottom panel).

Table 3-2 summarizes NOx emissions and percent differences for each KTF Area county. KTF Area county-level, percent increases in NOx caused by the MEGAN code error range from 48% to 119%. As a preliminary extrapolation, if these county-level percent differences were applied to the TCEQ MEGAN NOx emissions, the adjusted total KTF-wide NOx emissions would be 13.8 tpd, which agrees much more closely with the BEIS estimate (15.8 tpd). Relative differences between KTF Area BEIS and MEGAN NOx results drop from 43% without the code correction to 12% with the code correction.

Table 3-2. MEGAN code correction results for KTF Area June 2012 biogenic NOx emissions.

County	NOx Emissions (tpd)			TCEQ MEGAN NOx Emissions (tpd)	TCEQ MEGAN NOx Emissions, adjusted by code correction percent difference (tpd)
	Original Code (tpd)	Code Correction (tpd)	Percent Difference		
Bell	1.1	1.8	54%	1.4	2.1
Coryell	1.1	1.7	56%	1.6	2.5
Hamilton	1.0	1.5	47%	1.4	2.1
Lampasas	0.8	1.3	57%	1.1	1.8
Milam	0.6	1.4	119%	0.7	1.5
Mills	0.9	1.3	48%	1.1	1.6
San Saba	1.2	1.8	53%	1.5	2.3
Grand Total	**6.7**	**10.7**	**59%**	**8.8**	**13.8**

3.4 Vegetation Distribution Input Analysis

Basal NO emission factors are assigned by vegetation type, i.e. by land use in BEIS and by PFT in MEGAN. The geographic distribution of vegetation type and coverage (or vegetation distribution) is a key variable driving biogenic NOx emissions.

The spatial distribution of PFTs that are implemented in MEGAN to estimate biogenic emissions were developed in AQRP 14-016 (Yu et al., 2015). In AQRP 14-016, tree PFTs were developed with 30 meter resolution 2012 LandFire[32] existing vegetation type (EVT) data and Forest Inventory and Analysis[33] tree species composition data. Shrub and grass PFTs were developed with 30 meter resolution 2012 LandFire EVT data and MEGAN (version 2.1) landcover data. Crop PFTs were developed for corn and non-corn crops with 30 meter resolution LandFire EVT data which incorporates detailed crop acreages available from the United States Department of Agriculture (USDA) Cropland Data Layer[34] database.

The spatial distribution of land use in BEIS is based on BELD4. BELD4 is based on 2001 to 2011 National Land Cover Database (NLCD), 2002 and 2007 USDA census of agriculture county-level crop data, and MODIS satellite data (Bash et. al, 2016). Vegetation species assignments are based on 2002-2013 Forest Inventory and Analysis data and crop species assignments are based on 2002 and 2007 USDA National Agricultural Statistics Service (NASS) data.

In order to make direct comparisons between MEGAN PFT and BEIS land use data, we aggregated the 16 PFTs in MEGAN and almost 300 land use types in BEIS into three aggregate vegetation types (crops, grassland/savannah, trees) based on the basal NO emission factor assigned for each PFT/land use type (Table 3-3). In general, BEIS and MEGAN basal emission

[32] https://www.LandFire.gov/
[33] http://www.fia.fs.fed.us/
[34] https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php

factor estimates for grassland/savannah and trees are similar in MEGAN and BEIS. There is a much wider range of basal emission rates for crops in BEIS and MEGAN. There are more than 40 crop types in BEIS but only two general PFTs for crops in MEGAN (corn and other crops).

Table 3-3. Aggregate vegetation types and associated NO basal emission factor ranges.

Aggregate vegetation type	NO basal emission factor in BEIS (gN/km^2-hr) [A]	NO basal emission factor in MEGAN (gN/km^2-hr) [A]
Crops	27-361	40-68
Grassland/savannah	22-27	27
Trees[B]	2-6	2

[A] grams of nitrogen per square kilometer per hour
[B] includes shrubs which have basal emission rates in MEGAN and BEIS that are in the same range as trees

The percent of cropland in each county is relatively consistent between BEIS and MEGAN (see Figure 3-5). The three counties with the highest fraction of land in crops are Milam County (47% in BEIS and 52% in MEGAN), Bell County (16% in BEIS and 14% in MEGAN), and Coryell County (10% in both BEIS and MEGAN). No other KTF Area county has more than 10% of land assigned the crop vegetation type. BEIS and MEGAN crop vegetation type spatial distributions are also similar; crops are concentrated around the border of Bell and Milam counties and are otherwise widely distributed at low levels (see Figure 3-6).

BEIS and MEGAN exhibit substantial differences in the distributions of KTF Area trees and grassland/savanna aggregate vegetation types (see Figure 3-6). There is substantially more grassland/savanna in MEGAN and substantially more trees in BEIS. A majority of KTF land area in BEIS is included in the trees aggregate vegetation type (65%), grasslands account for 20% and crops for 15%. A much smaller fraction of KTF area acreage in MEGAN is from trees (42%), grasslands account for 43% and crops account for 16%.

AQRP Project 14-016 (Yu et al. 2015) developed updates to MEGAN PFT inputs. Several figures in the AQRP 14-016 analysis showed higher trees (or shrub) coverage in previous MEGAN inputs than in the inputs developed as part of AQRP 14-016. AQRP 14-016 Final Report Figure 3-15 showed substantial decreases in shrub coverage in central and western Texas (including parts of the KTF Area) from approximately 30% shrub coverage in previous MEGAN inputs to less than 10% shrub coverage in the inputs developed as part of AQRP 14-016. AQRP 14-016 Final Report Figure 3-19 showed vegetation for a grass PFT (Warm Grass) which increased from 0-20% coverage to 20%-40% coverage across much of the KTF Area. AQRP 14-016 attributes changes in grassland and shrub coverage to the use of the LandFire[32] EVT data, which provides more detailed vegetation type information. Comparison of MEGAN to BEIS vegetation distributions (see Figure 3-6) shows a similar pattern to the comparison of new versus old PFT data in the AQRP 14-016 report. Since BEIS BELD4 land use type were not developed based on LandFire EVT data, the MEGAN grassland/savanna and trees vegetation distributions can be considered more accurate.

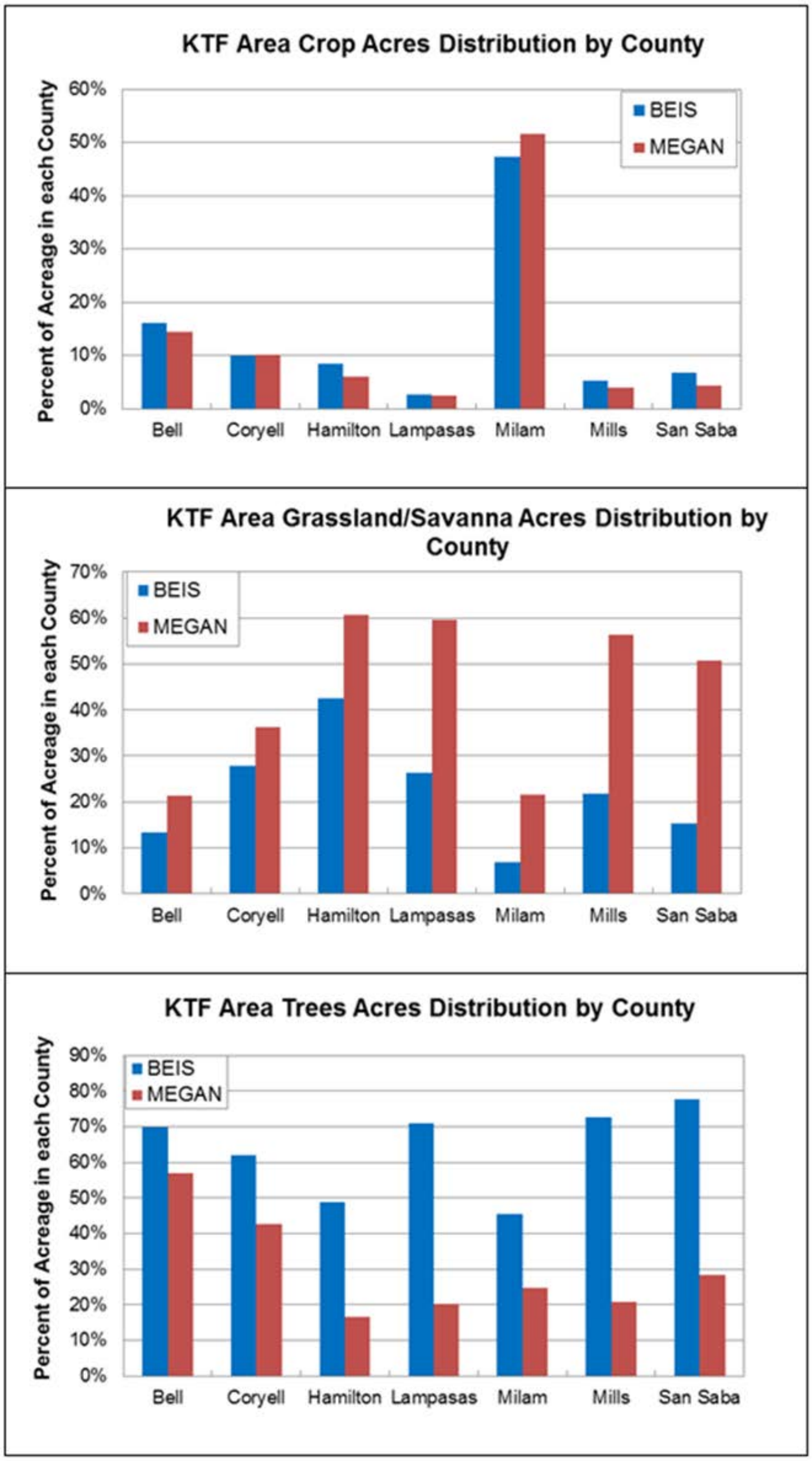

Figure 3-5. KTF Area county-level BEIS and MEGAN inputs for percent of land area by aggregate vegetation type: crops (upper panel), grassland/savannah (middle panel), and trees (bottom panel).

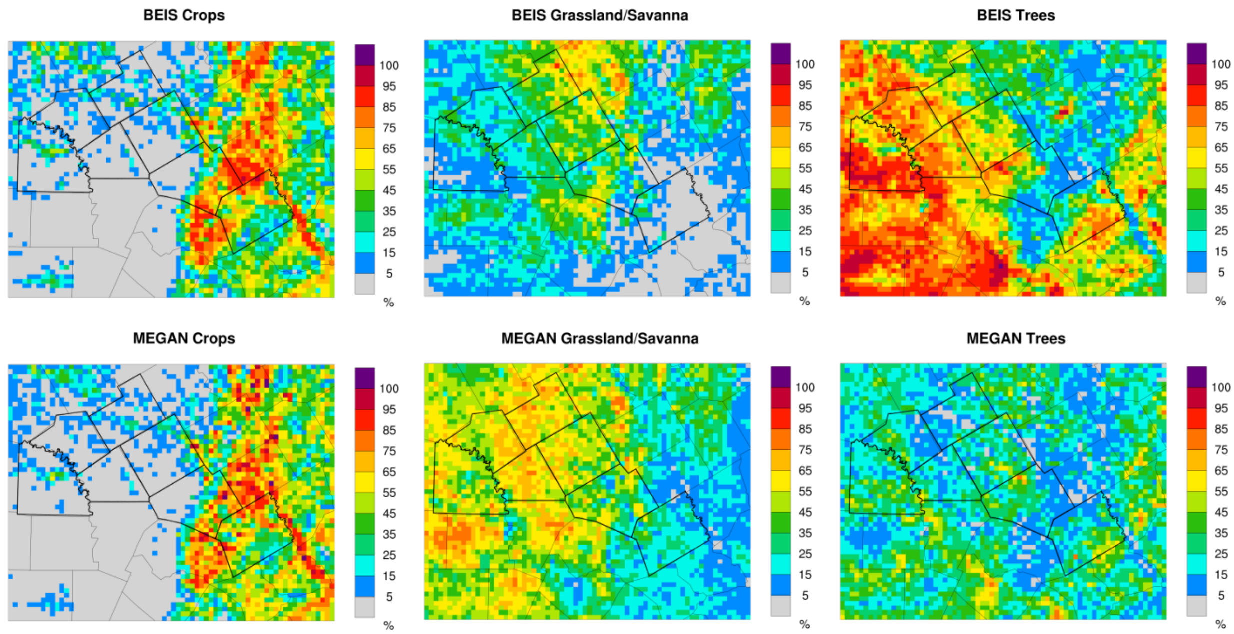

Figure 3-6. KTF Area land area distribution by aggregate vegetation type: BEIS crops (top left panel), MEGAN crops (bottom left panel), BEIS grassland/savanna (top middle panel), MEGAN grassland/savanna (bottom middle panel), BEIS trees (top right panel), and MEGAN trees (bottom right panel).

USDA NASS census estimates of cropland acres to BEIS and MEGAN crop acres. There is substantial interannual variation in cropland acreage in NASS, which indicates that the crop year basis of the BEIS land use and MEGAN PFT data should match the emission inventory calendar year. Crop acreage in MEGAN and BEIS match USDA NASS data for 2007 more closely than 2012; the reasons for differences in BEIS and MEGAN and USDA NASS data could be caused by the use of circa-2007 crop coverage data in BEIS and MEGAN or result from other source data discrepancies between MEGAN and BEIS inputs and USDA NASS estimates.

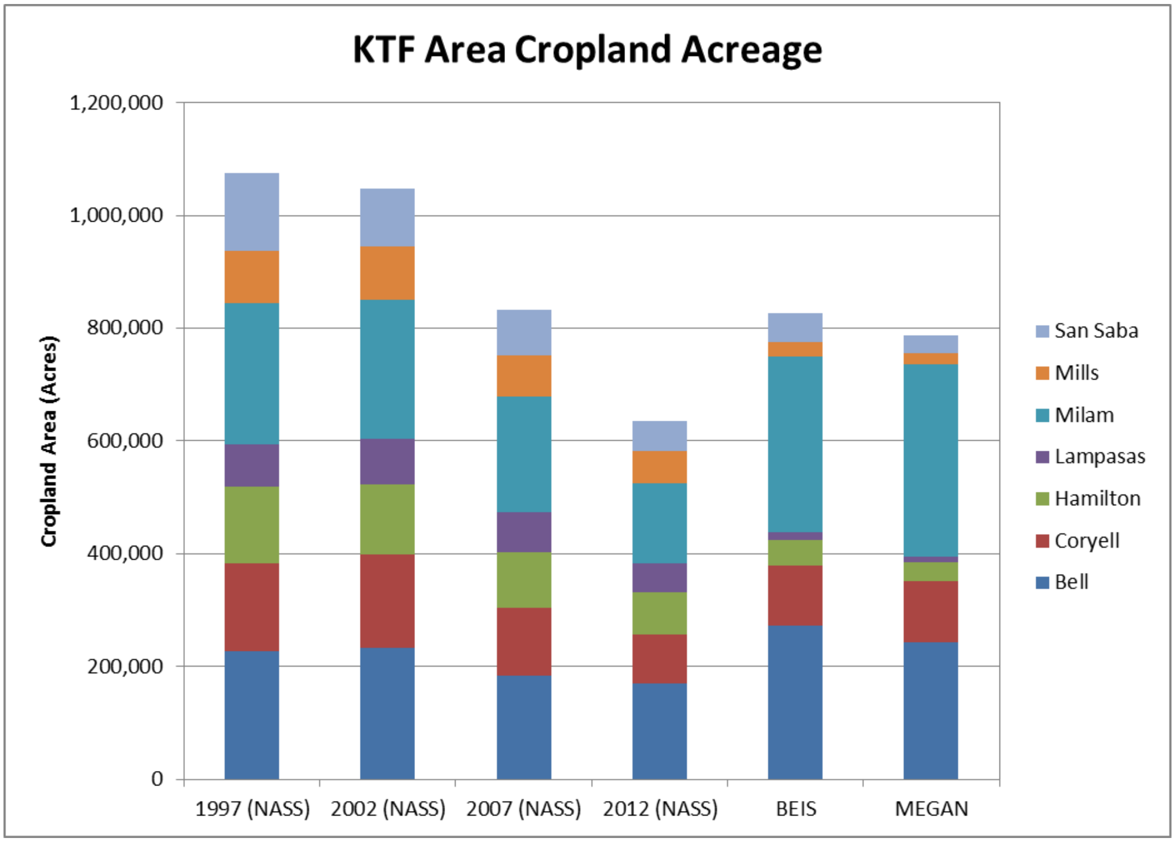

Figure 3-7. Cropland area in BEIS, MEGAN and USDA NASS[35].

3.4.1 Aerial Imagery Review

BEIS and MEGAN land-use inputs were verified for a limited number of grid cells against aerial images. Grid cells that represent the maximum and minimum crop coverage in MEGAN and BEIS in Bell and Coryell counties (total eight grid cells; see Figure 3-8) were selected for analysis. Latitude and longitude of the center of the eight grid cells were used to locate Google aerial images[36]. Figure 3-9 and Figure 3-10 show the Google aerial images for the selected grid cells in Bell and Coryell counties, respectively. Google aerial images show distinct patterns that differentiate between crops and non-crops. For the eight selected grid cells, there is close agreement between BEIS and MEGAN vegetation distribution and vegetation/land use in the Google aerial imagery. Based on this limited verification analysis, both MEGAN and BEIS vegetation distribution estimates for the most heavily cropped and least heavily cropped areas are reasonable estimates for the KTF Area.

[35] https://quickstats.nass.usda.gov/results/2A7EDB7C-B4C5-3020-9BA1-192848D81281
[36] Google Earth version 7.1.8.3036

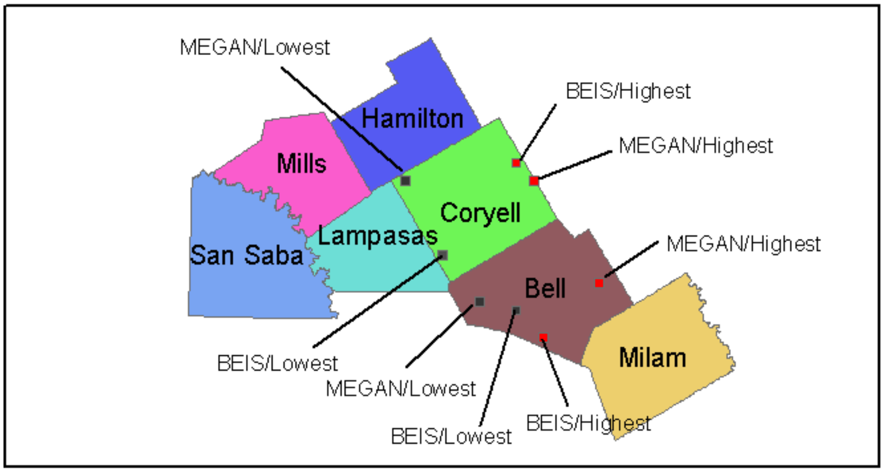

Figure 3-8. **Locations of selected grid cells in Bell and Coryell County for aerial image analysis.**

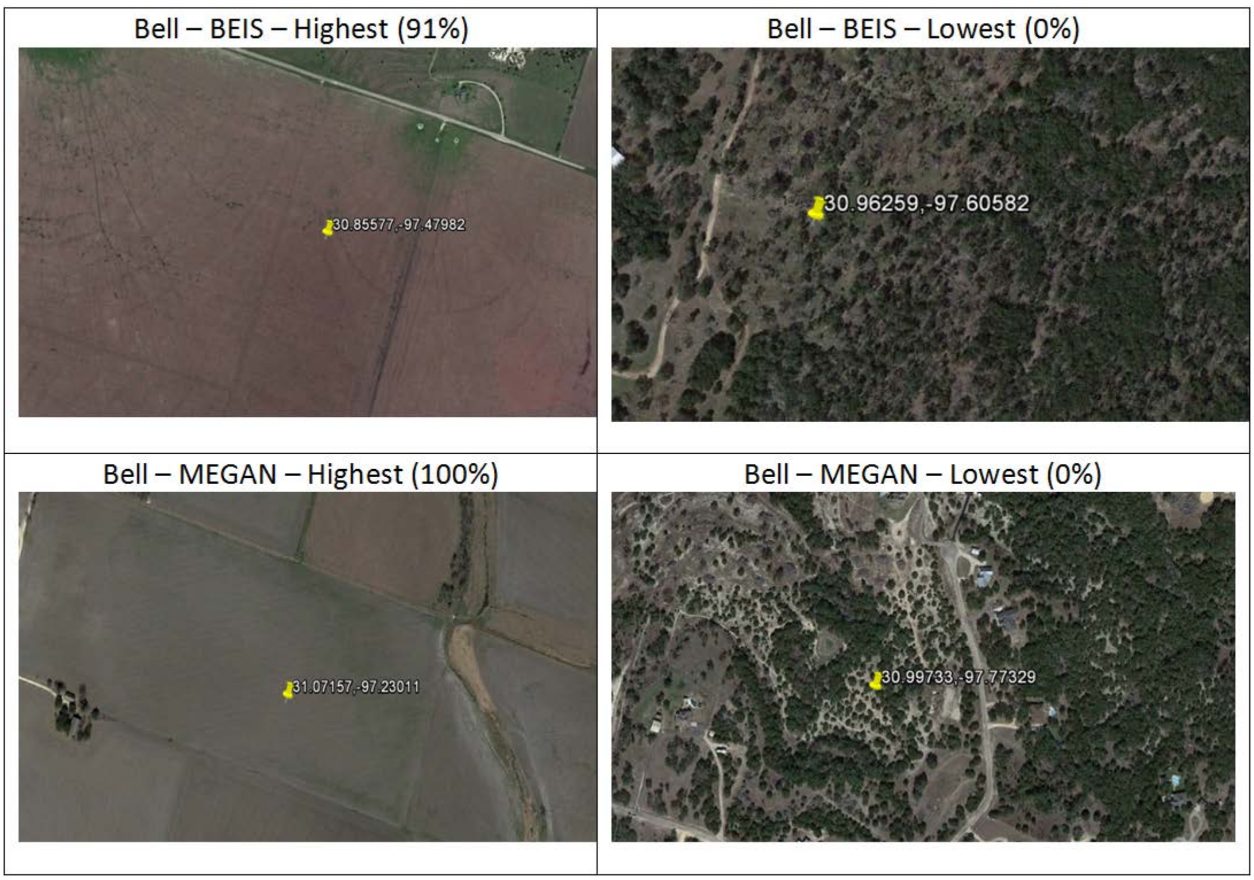

Figure 3-9. **Google Earth aerial images of select grid cells in Bell County: BEIS 91% cropland (top left panel), MEGAN 100% cropland (bottom left panel), BEIS 0% cropland (top right panel), MEGAN 0% cropland (bottom right panel).**

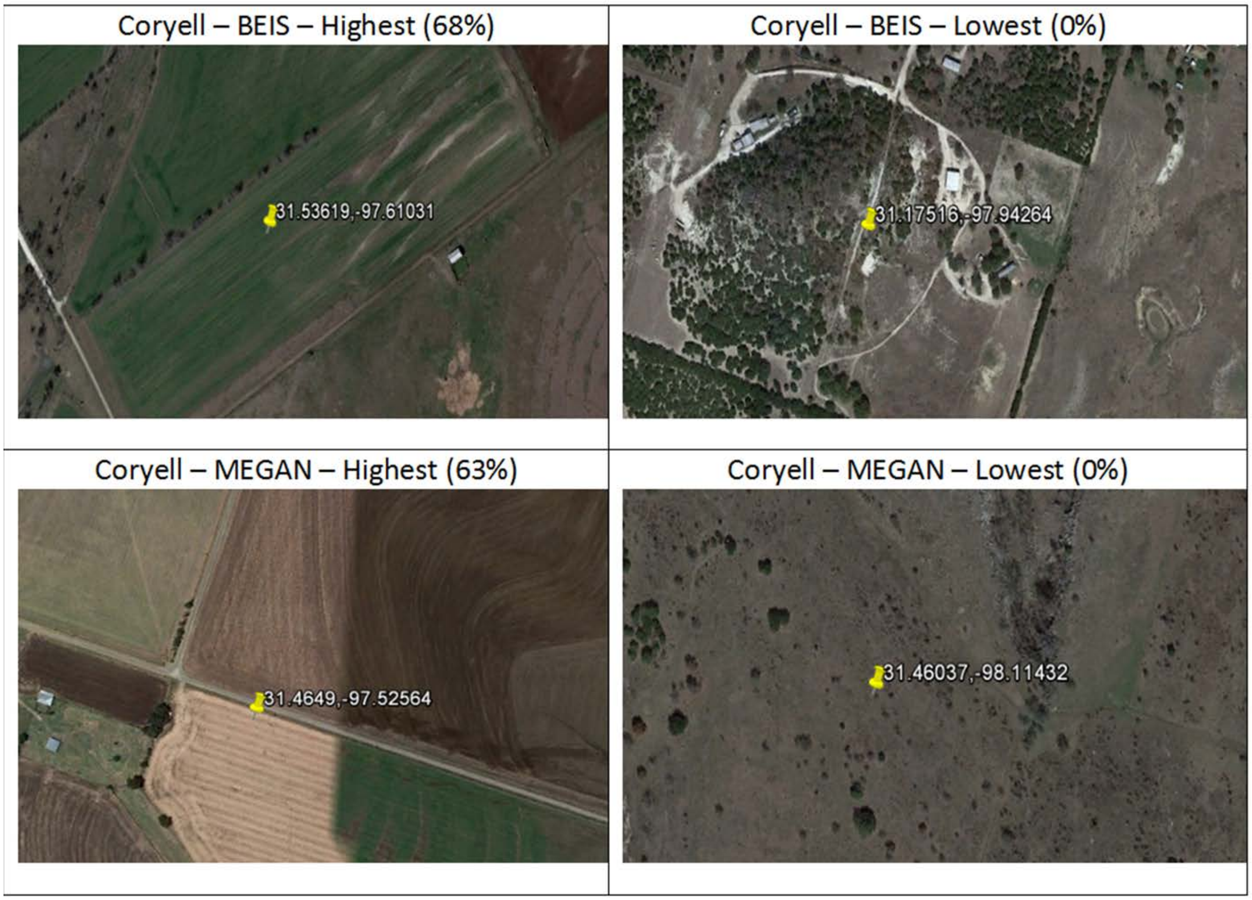

Figure 3-10. Google Earth aerial images of select grid cells in Coryell County: BEIS 68% cropland (top left panel), MEGAN 63% cropland (bottom left panel), BEIS 0% cropland (top right panel), MEGAN 0% cropland (bottom right panel).

3.5 Biogenics Summary

As shown in Table 3-4, KTF-wide biogenic NOx emissions estimated by BEIS and MEGAN agree to within 10% (when MEGAN emissions are adjusted for the code correction). NOx emissions in BEIS are well-correlated with crop distribution whereas MEGAN emissions follow grassland/savanna and crops vegetation distribution. San Saba, Lampasas, and Mills counties have much higher grassland/savanna coverage and lower trees coverage in MEGAN compared to BEIS and show biogenic NOx emission that are 33%-53% higher in MEGAN relative to BEIS. The higher fraction of grasslands in MEGAN compared to BEIS over much of western KTF Area counties (Mills, San Saba, Lampasas) contributes to higher biogenic NOx emissions in MEGAN over western KTF Area counties. Biogenic NOx emissions for KTF Area counties with the greatest crop acreage (Milam, Bell, and Coryell) show 11%-48% lower soil NOx emissions in MEGAN relative to BEIS. Since the cropland acres are similar in MEGAN and BEIS, we suspect that average basal NO emission factors from crops in the KTF Area are higher in BEIS than

MEGAN. It is possible that biogenic NOx emissions from crops are more accurate in BEIS as a result of more granular basal emission rates; biogenic NOx emissions from grassland/savanna and trees are likely to be more accurate in MEGAN than BEIS as a result of more accurate vegetation distribution for these aggregate vegetation types in MEGAN. BEIS and MEGAN both may underestimate biogenic NOx emissions with current model setups.

Table 3-4. KTF Area biogenic NOx emission by county as estimated by BEIS and MEGAN (adjusted for code correction).

	NOx Emissions (tpd)		
County	BEIS (tpd)	Code Correction Adjusted TCEQ MEGAN NOx Emissions (tpd)	Percent Difference
Bell	3.5	2.1	-40%
Coryell	2.8	2.5	-11%
Hamilton	2.2	2.1	-5%
Lampasas	1.2	1.8	50%
Milam	2.9	1.5	-48%
Mills	1.2	1.6	33%
San Saba	1.5	2.3	53%
Grand Total	**15.3**	**13.8**	**-10%**

The BDSNP has flexibility to incorporate detailed fertilization data whereas BEIS and MEGAN framework for crops currently assumes uniform fertilization rates by crop type. Recent research (Rasool et al., 2016) does not indicate that BDSNP would improve air quality model ozone performance for Texas, as currently configured, relative to YL95 as implemented in BEIS and MEGAN. However, additional research may enhance BDSNP accuracy. BDSNP model development should be monitored in the future.

4.0 RECOMMENDATIONS

We address potential improvements to the Fort Hood emissions inventory in the following recommendations:

1. We do not recommend developing emission inventory enhancements for Fort Hood at this time. Consistent with direction provided by TCEQ staff upon review of the Quality Assurance Project Plan (QAPP) for this study, national security considerations do not allow for emission inventory refinements unless emission inventory input data (e.g. equipment population, annual usage, engine characteristics) is either released by Fort Hood authorities or explicit permission is given by Fort Hood authorities to develop emission inventory input data. To date, the data available from Fort Hood has either already been incorporated into the TCEQ 2012 modeling emission inventory by TCEQ or requires additional information for developing enhancements to the TCEQ 2012 emission inventory.
2. Although changes to the Fort Hood inventory are not recommended, it is important to understand the sensitivity of KTF Area ozone to Fort Hood area emissions. As part of the fiscal year 16-17 photochemical modeling task, we will evaluate the sensitivity of ozone model performance at the Killeen Skylark monitor (CAMS 1047) and Temple Georgia monitor (CAMS 1045) monitors and the sensitivity of peak ozone in the KTF Area to emissions from the Fort Hood area.

We recommend the following improvements to the KTF Area biogenic NOx emissions inventory:

1. Any future MEGAN biogenic NOx emissions should be developed with the code correction identified in Section 3.3. MEGAN (version 3) will include the code correction.
2. Vegetation distribution analysis showed good agreement between MEGAN and BEIS crop coverage estimates. BEIS has basal soil NO emission factors for over 40 different crop types (ranging from 27-364 gN/km^2-hr) while MEGAN includes only two crop types with basal soil NO emission factors of 40 gN/km^2-hr or 68 gN/km^2-hr. Future effort to include PFTs for several crops types in MEGAN and implementation of soil NO basal emission rates by crop type could improve MEGAN biogenic NOx emissions accuracy.
3. The KTF area has much higher grassland/savanna coverage in MEGAN and much higher trees coverage in BEIS. MEGAN inputs are based on PFT distributions developed in AQRP 14-016 which rely on highly detailed LandFire EVT data to estimate PFT distribution for trees and grasslands/savanna. AQRP 14-016 noted that higher grassland/savanna and lower trees coverage is likely the result of the use of detailed LandFire EVT data; BEIS trees and grassland/savanna land use coverage is not based on LandFire EVT data. BEIS inventory estimates could be enhanced by integrating AQRP 14-016 grassland/savanna and trees vegetation distributions into the BELD4 land use database.
4. We recommend that MEGAN be used to estimate biogenic NOx emissions in the KTF Area because of the incorporation of AQRP 14-016 vegetation distribution estimates into MEGAN. We also note that BEIS includes over 40 crop types and associated basal

soil NOx emission factors whereas MEGAN includes only two crop types and associated basal soil NOx emission factors. BEIS estimates of biogenic NOx emissions for crops may be more accurate than MEGAN because of the level of crop type detail in BEIS.

5. There is substantial interannual variation in cropland acreage in NASS which indicates that the crop year basis of the BEIS land use and MEGAN PFT data should match the baseline emission inventory calendar year as closely as possible. For future year inventories, biogenic emissions are typically assumed equivalent to the baseline inventory. The representativeness of the baseline inventory for a future year should be carefully considered given potential changes to crop production between the baseline and future year.
6. The BDSNP includes potential improvements over the YL95 method implemented in BEIS and MEGAN such as the integration of more accurate fertilization rates and more accurate modeling of the soil nitrogen cycle. BDSNP model research should be closely monitored. If future research indicates implementation of the BDSNP will improve the accuracy of biogenic NOx emission estimates in the KTF Area, then study to implement/evaluate the BDSNP would be recommended at that time.

5.0 REFERENCES

Bash, J., K. Baker, M. Beaver. 2015. Evaluation of Improved Land Use and Canopy Representation in BEIS v3.61 with biogenic VOC measurements in California, Geoscientific Model Development Discussions, 8, 8117-8154. DOI: 10.5194/gmdd-8-8117-2015.

Bash, J. K. Baker, M. Beaver. 2016. Evaluation of Improved Land Use and Canopy Representation in BEISv3.61 with biogenic VOC measurements in California, Geoscientific Model Development, 9, 2191–2207. doi: 10.5194/gmd-9-2191-2016.

Eastern Research Group, Inc. (ERG). 2008. Texas NONROAD (TexN) Model Version 1.0 User's Guide. Eastern Research Group, Inc. August.

Eastern Research Group, Inc. (ERG). 2014. Texas NONROAD Model Update and Enhancement. Prepared for the Texas Commission on Environmental Quality. August.

Grant, J., S. Kemball-Cook, G. Yarwood, 2015a. "Final Report Review of Emissions for Northeast Texas: Point, Off-road and Area Sources". ENVIRON International Corporation. Prepared for the East Texas Council of Governments. January.

Grant, J., S. Kemball-Cook, G. Yarwood, 2015b. "Draft Report: Review of Hood County, Texas Ozone Pre-cursor Emission Inventory for Point, Off-road and Area Sources". ENVIRON International Corporation. Prepared for the City of Granbury. March.

Guenther A., X. Jiang, C. Heald, T. Sakulyanontvittaya, T. Duhl, L. Emmons, X. Wang. 2012. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geoscientific Model Development, 5, 1471-1492, doi:10.5194/gmd-5-1471-2012.

Hudman, R.C., N.E. Moore, A.K. Mebust, R.V. Martin, A.R. Russell, L.C. Valin, and R.C. Cohen. 2012. Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints, Atmospheric Chemistry and Physics, 12, 7779-7795, doi:10.5194/acp-12-7779-2012.

Kemball-Cook, S., J. Johnson, J. Grant, L. Parker, J. King, W. Hsieh, G. Yarwood. 2015. "Final Report: Conceptual Model of Ozone Formation in the Killeen-Temple-Fort Hood Area". Ramboll Environ. Prepared for the Texas Commission on Environmental Quality. September 2015.

Kennedy, R. 2017. Email from Robert Kennedy (US Army) to Jennifer Lawyer (Central Texas Council of Governments). July 28, 2016.

Johnson, J., J.Jung, W. Hsieh, S. Kemball-Cook, G. Yarwoord. 2015. "Final Report: Photochemical Modeling of June 2012 for the Killeen-Temple-Fort Hood Area". Ramboll Environ. Prepared for the Texas Commission on Environmental Quality. July 2015.

Lawrence, D., Oleson, K. W., Flanner, M. G., Thorton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z.-L., Levis, S., Skaguchi, K., Bonan, G. B., and Slater, A. G. 2011. Parameterization Improvements and Functional and Structural Advances in Version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3, M03001, doi:10.1029/2011MS000045.

Pierce, T., P. Waldruff. 1991. PC-BEIS: A Personal Computer Version of the Biogenic Emissions Inventory System, Journal of the Air & Waste Management Association, 41, 7, 937-941. http://dx.doi.org/10.1080/10473289.1991.10466890.

Potter, P., R. Navin, M.B. Elena, and D.D. Simon. 2010. Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interactions, 14, no. 2: 1-22.

Rasool, Q.Z., R. Zhang, B. Lash, D.S. Cohan, E.J. Cooter, J.O. Bash, and L.N. Lamsal. 2016. Enhanced representation of soil NO emissions in the Community Multiscale Air Quality (CMAQ) model version 5.0.2. Geosci. Model Dev., 9: 3177-3197. doi:10.5194/gmd-9-3177-2016.

Sakulyanontvittaya, T., G. Yarwood, A. Guenther. 2012. "Improved Biogenic Emission Inventories across the West Final Report". ENVIRON International Corporation. Prepared for the Western Governors' Association. March.

Texas Commission on Environmental Quality (TCEQ). 2015a. Personal Communication with TCEQ staff (Chris Kite). April.

Texas Commission on Environmental Quality (TCEQ). 2015b. Personal Communication with TCEQ staff (Jim MacKay). April.

Texas Commission on Environmental Quality (TCEQ). 2015c. 2014 Emissions Inventory Guidelines. Air Quality Division. January.

United States Army Environmental Command (USAEC). 2014. "Supplemental Programmatic Environmental Assessment for Army 2020 Force Structure Realignment". June.

Vinken, G.C.M., K. F. Boersma, J. D. Maasakkers, M. Adon, and R. V. Martin. 2014. "Worldwide biogenic soil NOx emissions inferred from OMI NO_2 observations". Atmos. Chem. Phys., 14, 10363–10381, doi:10.5194/acp-14-10363-2014.

Yienger, J., H. Levy. 1995. Empirical Model of Soil Biogenic NOx Emissions, Journal of Geophysical Research, 100, D6, 11447-11464.

Yu, H., A. Guenther, C. Warneke, J. Gouw, S. Kemball-Cook, J. Jung, J. Johnson, G. Yarwood. 2015. Improved Land Cover and Emission Factor Inputs for Estimating Biogenic Isoprene and Monoterpene Emissions for Texas Air Quality Simulations, September, 2015. http://aqrp.ceer.utexas.edu/projectinfoFY14_15/14-016/14-016%20Final%20Report.zip